Considerations for the development of Landslide Early Warning Systems in Aotearoa New Zealand

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ABSTRACT

This guidance document outlines key considerations in the design and development of a Landslide Early Warning System (LEWS) in Aotearoa New Zealand. The document incorporates four components of an effective Early Warning System (EWS) and draws on global and national guidance for developing EWSs, such as international standards, Aotearoa New Zealand EWS guidance, LEWS-specific journal publications, and results from previous stakeholder engagement for the Earthquake-Induced Landscape Dynamics Endeavour research programme. The intended audience for this report is the emergency management sector, local government, critical infrastructure agencies, interested communities, consultancies, science agencies and land stewards involved in landslide hazard and risk management.

The development of a LEWS involves seven main activities: (1) risk assessment; (2) dissemination of knowledge; (3) establishment of a disaster preparedness team; (4) development of evacuation routes and maps; (5) development of standard operating procedures; (6) monitoring, early warning, and evacuation drills; and (7) commitment of the local government and community on the operation and maintenance of the whole system.

When carrying out these activities and designing a LEWS, we recommend:

- ✓ **Assessing the suitability of a LEWS as a risk-mitigation measure:**
  - Conduct a risk assessment to determine the appropriate risk treatment for landslide risk management (e.g. risk avoidance versus risk reduction).
  - Characterise the uncertainty present in the landslide detection, forecasting and warning system.
  - Define the acceptable level of residual risk against which to evaluate the potential LEWS and the probability of failure. This involves identifying ‘showstoppers’ or issues that could reduce the effectiveness of the LEWS and exceed the acceptable residual risk.
- ✓ **Maintaining a people-centred focus in the design of the EWS:**
  - Identify the intended user(s) and audience(s) of the EWS and understand their knowledge and perceptions of landslide hazards and risks, as well as their needs and capacities, that will influence the usefulness and usability of the LEWS.
  - Develop partnerships with the intended users and audiences to enable their involvement in the design and implementation of the LEWS from the beginning. This will empower the users and provide a sense of ownership in the system.
- ✓ **Designing appropriate thresholds and alert levels:**
  - Work with the intended users (e.g. communities) to established warning thresholds that are based on the users’ needs and capabilities.
  - Identify whether alert levels would be useful and the appropriate number of alert levels based on who the intended users are.
  - Regularly test and review the alert levels and warning thresholds to ensure continued effectiveness and relevance.
  - Understand the appropriate and possible resolution and tailoring of the warnings.

- ✓ **Conducting rigorous education and awareness campaigns:**
  - Design and carry out education and awareness campaigns with support and involvement from trusted community leaders.
  - Ensure that EWS users understand the meaning of the alert levels, forecasts and/or warnings and what to do in response to an alert level change.
  - Design and run regular evacuation drills with the community.
  - Design evacuation maps for the community following hazard mapping and risk communication guidelines.
- ✓ **Developing clear Standard Operating Procedures (SOPs):**
  - Include the procedures and guidelines for the disaster preparedness team, the individuals and the local authorities responsible for responding to alerts issued by the landslide early warning instrument(s).
  - Establish agreements and inter-agency protocols for the exchange of monitoring systems data and baseline data, e.g. for a multi-hazard approach.
  - Ensure consistency of warning language and communication responsibilities where different hazards are handled by different agencies.
- ✓ **Co-ordinate across agencies**

The LEWS also needs to be integrated within a multi-hazard EWS to ensure consistency. Developing an integrated LEWS requires co-ordination and collaboration across all agencies, governance levels and communities that have relevant information about the hazards and impacts that threaten people and assets. Such collaborative approaches allow for effective communication networks to be established and for the development of effective decision-making processes. The considerations provided in this document outline the key activities required to develop an integrated LEWS and enable warning services to empower their intended users to take appropriate action to protect themselves before, during and after a landslide-triggering event.

KEYWORDS

Landslides, debris flows, warning system, alert level, Aotearoa New Zealand, forecasts

1.0 INTRODUCTION

Aotearoa New Zealand's geographic position, environment and tectonic setting promotes a dynamic hazard-scape, as demonstrated over the past decade through various earthquake, tsunami, volcanic, weather, flooding and landslide events. A key example is the M_W 7.8 Kaikōura Earthquake, which occurred on 14 November 2016 in the upper South Island of Aotearoa New Zealand, generating tens of thousands of landslides, hundreds of significant landslide dams and damaging hillslopes that are now susceptible to failure during heavy rain and aftershocks (Massey et al. 2018; Rosser et al. 2021). In response to this event, a research programme was initiated, called 'Earthquake-Induced Landscape Dynamics'[1], funded by the Ministry of Business, Innovation & Employment (MBIE) through the 2017 Endeavour fund. As part of this research programme, a number of tools and guidelines have been developed to manage the risk from such events, including these considerations for developing Landslide Early Warning Systems (LEWS) in Aotearoa New Zealand.

This document incorporates four components of an effective early warning system (EWS) (WMO 2018) and draws on global and national guidance for developing EWS, such as international standards (ISO 2018a, 2018b), the Multi-Hazard EWSs (e.g. Basher 2006; WMO 2018) checklist, Aotearoa New Zealand EWS guidance (e.g. Leonard et al. 2008; Potter et al. 2018b), LEWS-specific journal publications and results from previous stakeholder engagement for the Earthquake-induced Landslide Dynamics Endeavour research programme (e.g. Glassey and Saunders 2021; Massey et al. 2021a). It is set within a wider risk-management framework, as described in Section 2.0. Although we draw on international literature and guidance, the considerations provided are framed in an Aotearoa New Zealand context for landslide hazards. Appendix 1 provides a summary of the key guidance documents that we draw on and situate into the Aotearoa New Zealand context for designing a LEWS.

The intended audience for this report is the emergency management sector, local government, critical infrastructure agencies, occupiers of buildings, consultancies, science agencies and land stewards involved in landslide hazard and risk management. In this report, we aim to:

- Identify considerations for how an EWS could be developed for landslides in Aotearoa New Zealand.
- Identify key information and decision points needed throughout the development process.
- Integrate international standards and guidance with Aotearoa New Zealand policies and practise as applicable.

The introduction section outlines Aotearoa New Zealand's Warning System and describes what is unique about landslides that needs to be considered when establishing a LEWS. We then introduce the international guidance on EWS that we draw on throughout this report. We finish this section with an outline of the rest of this report.

While this report focuses on the considerations for developing a LEWS, it is important to integrate such a system into a multi-hazard EWS that forecasts and warns for the primary hazards that can trigger the landslides, the landslides themselves, and the secondary hazards the landslides can produce.

1 https://slidenz.net/data-tools/

1.1 Aotearoa New Zealand's Warning System Process

To help mitigate risks to various hazards, Aotearoa New Zealand has a National Warning System (NWS; Figure 1.1) that is maintained by the National Emergency Management Agency (NEMA). The NWS issues warnings to Civil Defence & Emergency Management (CDEM) Groups based on information and advice received from responsible agencies about warnable hazards. Under Section 119 of the National CDEM Plan (2015), which sets out the roles and responsibilities of everyone involved in reducing risks and preparing for, responding to and recovering from emergencies, the following lead agencies are entrusted with the responsibility of monitoring specific hazards and issuing or supporting the issue of warnings or advisories for specific hazards at the national level:

> ***119 Principles***
>
> *(1) Monitoring, identification, and analysis of geological and meteorological hazards and threats and subsequent issuing of hazard information is to be undertaken at all times by the following agencies:*
>
> > *(a) the Meteorological Service of New Zealand Limited (severe weather); and*
> >
> > *(b) GNS Science (earthquake, volcanic activity, and landslides); and*
> >
> > *(c) the [NEMA] (tsunamis).*
>
> *(2) Relevant government agencies, CDEM Groups, local authorities, and lifeline utilities are to maintain arrangements to receive and respond to hazard information.*

Furthermore, roles and responsibilities of science and research providers during readiness and response are also laid out in Section 85 of the National CDEM Plan (2015). Lead and support agencies may access a range of science and research organisations, shown in Table 1.1, during an emergency to provide definitive scientific advice or to communicate risk (those organisations include universities, Crown research institutes and private organisations).

Table 1.1 Roles and responsibilities of science and research organisations during readiness and response according to the National CDEM Plan (2015).

Organisation	Role
GNS Science	*(2) GNS Science –* *(a) manages the GeoNet system for the detection of earthquakes, land movement, volcanic activity, and the potential for local-source tsunamis; and* *(b) assesses the threat of tsunamis with the support of a multi-agency tsunami experts panel; and* *(c) provides advice to the [NEMA] on the issuing of national advisories and warnings about geological hazards; and* *(d) provides scientific advice to the NCMC, agencies, and CDEM Groups as needed; and* *(e) contributes to the management of public information on geological hazards and associated emergencies.*
MetService	*(3) The Meteorological Service of New Zealand Limited –* *(a) maintains a weather forecasting service and issues weather warnings to the public; and* *(b) contributes to the management of public information about weather hazards and associated emergencies; and* *(c) issues, as necessary, volcanic ash advisories for the civil aviation industry; and* *(d) provides scientific advice to the NCMC, agencies, and CDEM Groups as needed.*
Regional Councils and Unitary Authorities	*(4) Regional councils and some territorial authorities monitor rainfall, lake and river levels, and volumetric flows for flood prediction and management*
NIWA	*(5) National Institute of Water and Atmospheric Research Limited –* *(a) provides public information on –* *(i) climatic and seasonal risks (including drought); and* *(ii) marine geological, seafloor, and coastal hazards and processes; and* *(b) provides scientific advice to the NCMC, agencies, and CDEM Groups as needed; and* *(c) provides representatives on the tsunami experts panel.*
MBIE	*(6) The Ministry of Business, Innovation, and Employment, during and after an emergency, may take additional steps to –* *(a) integrate consistent and coherent scientific advice to agencies and CDEM Groups; and* *(b) divert existing funding or allocate new funding to ensure that the appropriate technical resources in core physical and social science, engineering, and risk management are available nationally to support the needs of agencies and CDEM Groups.*

Additionally, a Regional CDEM Group and its members must “establish the means within its group area, in line with national guidelines and in collaboration with its supporting agencies, to provide timely warning of hazards, and public information about them”, amongst other functions (Section 6.4, MCDEM 2015).

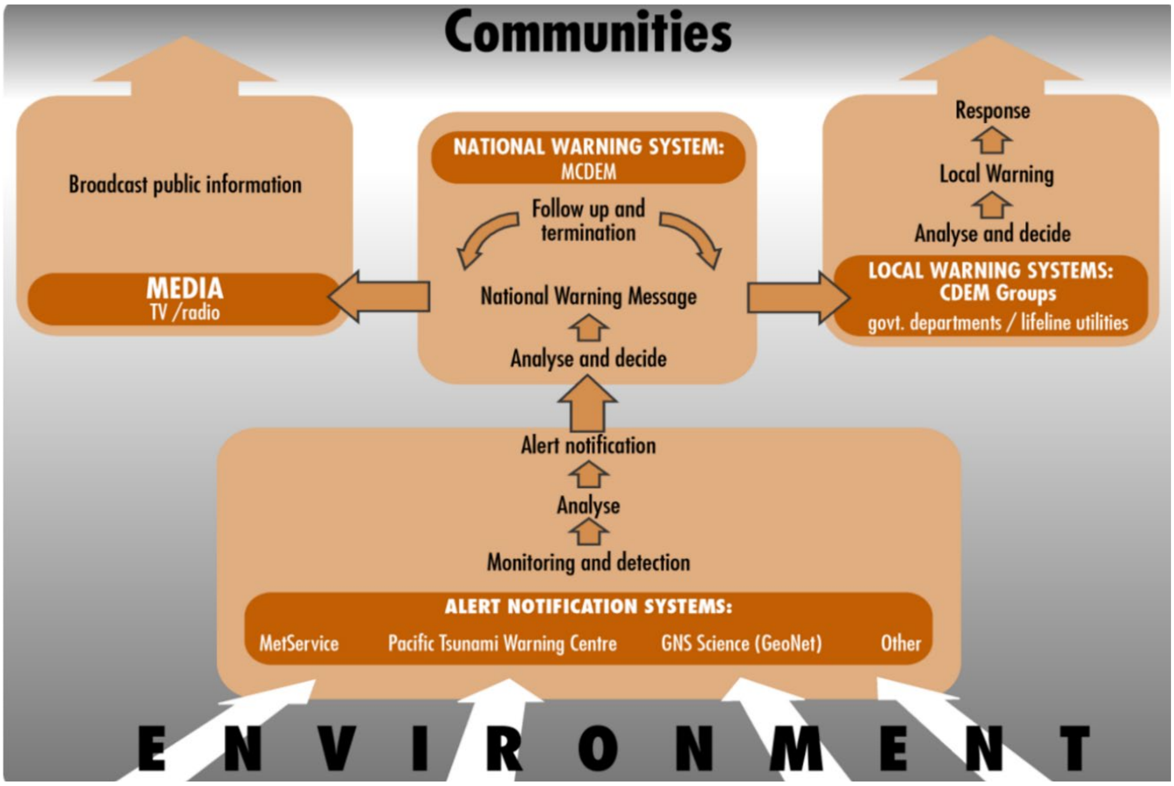

Figure 1.1 Aotearoa New Zealand's National Warning System (from MCDEM 2015). Note that, on 1 December 2019, the National Emergency Management Agency (NEMA) replaced the Ministry of Civil Defence & Emergency Management (MCDEM).

1.2 Landslide Early Warning Systems

Managing risks is a priority of the National Disaster Resilience Strategy (MCDEM 2019b). Disaster risk management involves applying disaster risk reduction policies and strategies to prevent new risk, reduce existing risk and manage residual risk (MCDEM 2019b). The aim is to build resilience and reduce losses from disasters (MCDEM 2019b).

There are three broad risk treatment options, further described in Section 2.0, that must be assessed for suitability in reducing the landslide risk, in which the EWS system is the final measure:

1. Modify human activity.
2. Modify the risk.
3. Accept the risk and warn people. An EWS should be the last option for risk mitigation due to the uncertainty and probability of failure present within these systems (see Section 2.0 for more).

LEWSs are also important during the recovery of an earthquake, rainfall or other triggering event due to the active and ongoing nature and multiple failures of landslides. For example, following the 2016 Kaikōura Earthquake that produced multiple landslides (Massey et al. 2018; Massey et al. 2020b), particularly along State Highway 1 (SH 1), there was a risk of re-activation of landslides through heavy rainfall. Anyone using SH 1 following the earthquake during heavy rainfall was in danger of more material coming down. An EWS using heavy rainfall forecasts to close roads where the risk of re-activation was high could have been put in place to protect road users.

1.3 The Challenges for Landslide Early Warning

Landslides pose a unique challenge for EWS design due to the complex processes involved with landslide occurrence (Thiebes and Glade 2016). For example, there is significant variation in the scale of landslide prediction and early warning (e.g. slope-, local- and regional-scale). The resolution of a LEWS can determine which stakeholders must be involved in the design and implementation of the EWS and required/available resources and vice versa.

The triggering mechanisms, type and speed of the landslides (Hungr et al. 2014) and geological make up also influence which forecasting, detection and alerting mechanisms are the most appropriate to use. Forecasting is described as both the “core element” of an EWS, and the “most problematic” component, particularly for landslide hazards (Intrieri et al. 2013). This is because landslides are typically a secondary hazard, produced after or by a primary hazard such as rainfall or seismic shaking.

The predictability of landslides is influenced by the uncertainty in the forecasting of these primary hazards. For example, forecasting rainfall-induced landslides requires hydrometeorological information such as rainfall intensity, duration, and location (e.g. Rosser et al. 2021), while earthquake-induced landslide forecasts require information on shaking intensity, duration and location (e.g. Massey et al. 2021a). Forecasting tools for rainfall-induced and earthquake- induced landslides in Aotearoa New Zealand are being developed (e.g. Massey et al. 2021a; Rosser et al. 2021). Landslides can also produce tertiary hazards such as landslide dams, which in turn require their own EWS that must be designed with extensive community involvement (e.g. Becker et al. 2007).

The thresholds for landslide warnings can influence how much time people have to prepare and evacuate (i.e. lead time). It is important, and difficult, to identify the appropriate thresholds, as ones that are too high may result in lead times that are too short and potentially a ‘miss’ (i.e. a landslide event occurs for which there was no warning [Intrieri et al. 2013]). Alternatively, a threshold that is too low may result in false alarms, which can undermine trust in the LEWS. Defining thresholds involves defining acceptable risk criteria in the initial risk assessment process (Intrieri et al. 2013; Nadim and Intrieri 2011). More on thresholds is described in Section 3.2 and 3.3.

These factors all influence the timeliness of warnings and thus the amount of lead time given to the warning recipients. Providing enough lead time for people to take appropriate protective actions is a challenge with LEWS, particularly in the case of rapidly moving mass movements. Given the uncertainty in forecasting landslides, many LEWS rely on early detection or a mass movement beginning to occur in order to provide enough warning to anyone in the path to evacuate (Massey et al. 2020a). The amount of time needed to detect and alert people, as well as the amount of time for people to receive and interpret the warning and evacuate, must thus be shorter than the travel time of the landslide.

The next section (Section 2.0) introduces the risk-management process for landslides based on the Joint Australian New Zealand International Standard *Risk Management – Principles and guidelines* (ISO 2009). Section 3.0 provides considerations for developing a LEWS based on key guidance documents and standards, such as the ISO 22327:2018 *Security and resilience – emergency management – guidelines for implementation of a community-based landslide early warning system* (ISO 2018a), the World Meteorological Organization (WMO) Guidelines on multi-hazard EWS (WMO 2018, 2021), international literature and case studies in Aotearoa New Zealand where relevant.

2.0 LANDSLIDE RISK MANAGEMENT AND RESILIENCE

The landslide risk-management process (Figure 2.1) involves a risk assessment in which:

1. The scope is defined.
2. A quantitative risk analysis is completed using information about the landslide hazard and the people and assets nearby.
3. The risk is evaluated against risk tolerability thresholds.
4. The risk treatment is implemented based on the risk evaluation to reduce, transfer or otherwise alter the risk (AGS 2000; ISO 2009).

Saunders et al. (2013) describe a comprehensive overview of risk-based planning, and Massey et al. (2020a) provide an overview of landslide risk analysis approaches and methods for assessing the applicability of a multi-staged debris flow EWS in Matatā. de Vilder et al. (forthcoming 2024) further provide landslide planning guidance for reducing landslide risk.

2.1 Landslide Risk Treatment

There are three general risk treatment approaches for managing landslide risk:

1. **Modify human activity:** An initial assessment of the risk of human activity in the landslide-prone area, combined with land-use planning principles and policy, should inform decisions around whether human activity should occur in or be removed from the area (Saunders and Glassey 2007, 2009).
2. **Modify the risk:** If feasible, engineering approaches such as stabilisation measures can mitigate the risk of landslide hazard occurrence and resulting impacts (ISO 2009).
3. **Accept the risk and warn people:** Where the level of risk and consequences is deemed acceptable and an EWS is deemed a feasible mitigative approach, the warning system should be designed using a people-centred approach and integrated with other hazard warnings (UNISDR 2015; WMO 2018).

When selecting appropriate risk treatments for landslide risk management, avoiding the risk (treatment 1) is usually preferred (Guo et al. 2020). However, in many cases the development and infrastructure may already be in place and/or resettlement is not a viable solution (Thiebes and Glade 2016). Thus, other treatments must be considered, including engineering protection measures such as removing potential landslides, slope stabilisation measures or other similar measures that can reduce the likelihood or reduce the consequences. EWSs can be used in any of the treatment measures to ensure remediators are not at risk and also as a last measure to protect people and mobile property, such as vehicles, by providing advanced notice for people to evacuate (Thiebes and Glade 2016).

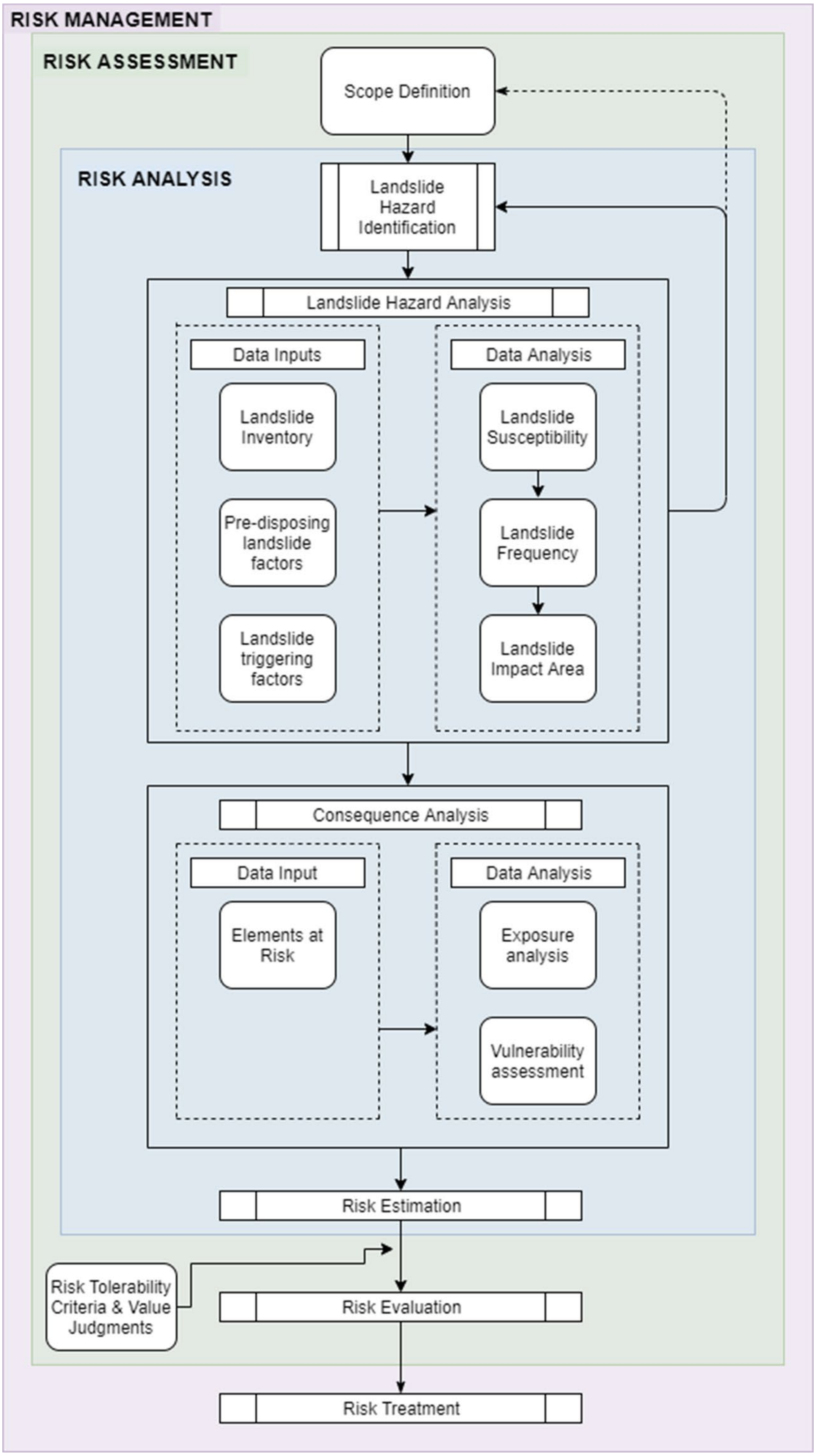

Figure 2.1 Landslide risk management framework (AGS 2000; Massey et al. 2020a).

Risk treatment does not conclude the risk-management process. Monitoring and review should be built into the risk-management process and planned for by assigning responsibilities for the associated tasks (ISO 2009). The purpose is to identify any possible changes that may alter the risks (AGS 2000). Monitoring and reviewing should be carried out through the implementation to provide opportunities for reassessments that ensure the continued appropriateness of the risk-treatment plan (AGS 2000).

2.2 Residual Risk Acceptance of Landslide Early Warning Systems

The consideration of an EWS as a treatment for landslide risk must **explicitly consider and accept the failure rate of the EWS and the consequences** of such (i.e. the probability of injury/death). This involves evaluating the effectiveness of each EWS component and determining their probability of failing. Massey et al. (2020a) applied the effectiveness evaluation framework shown in Figure 2.2 to the potential for a debris flow in the Awatarariki catchment in Matatā.

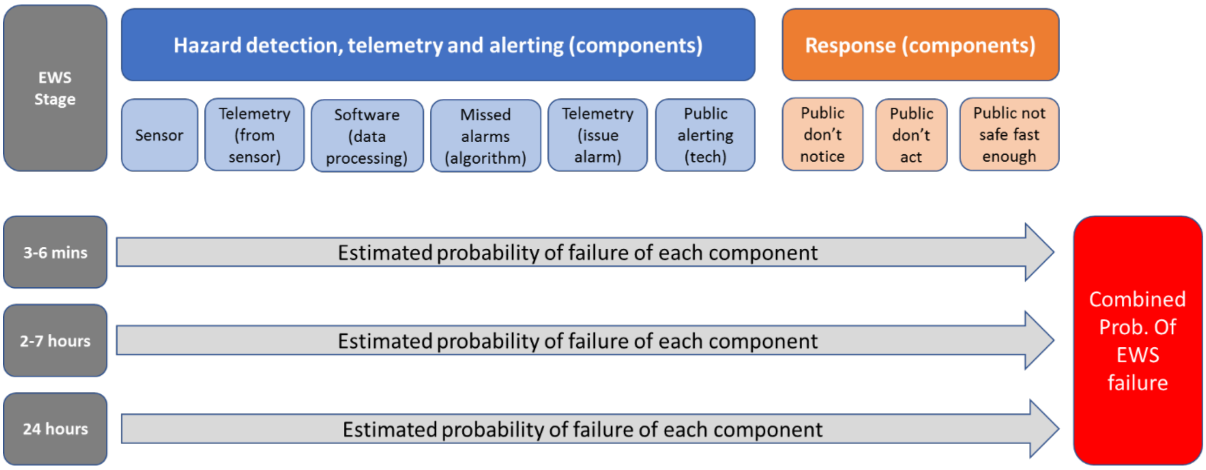

Figure 2.2 Effectiveness-evaluation framework of a public-facing early warning system for debris flows on the Awatarariki Fan (Massey et al. 2020a).

In the effectiveness-evaluation framework, the components listed in Table 2.1 were assessed for their probability of failure. Massey et al. (2020a) applied this framework to 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 process and results of this evaluation are further detailed in the report (Massey et al. 2020a). Massey et al. (2020a) identified and discussed several 'showstoppers' (i.e. issues that could reduce the effectiveness of the LEWS, listed in Table 2.2) to aid in the determination of whether a LEWS would be a suitable or unsuitable risk mitigation approach.

Based on these showstoppers, the recommendation from Massey et al. (2020a) was that a LEWS for the Awatarariki Fan did not align with the Regional Council's precautionary approach and thus was not a suitable risk-mitigation measure.

In the case where the probability of failure and showstoppers do not exceed the residual risk acceptance threshold and an EWS is deemed a feasible mitigative approach, the considerations provided in the next section for developing a LEWS in Aotearoa New Zealand may be used.

Table 2.1 Components assessed for the consideration of a public debris flow early warning system on the Awatarariki Fan (Massey et al. 2020a).

Assessed Component	Description/Justification
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 = tripwire(s).
Telemetry	(A) To transfer data from the instruments on site, e.g. from the rain gauges and trip wires, and get it to 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. (B) 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, e.g. with less than a minute for sirens/lights to operate after the tripwire triggers. This time might be slightly longer for text messages to be issued.
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.
Missed alarms	This relates to an event that the algorithm misses and only relates to the rainfall data streams, as the tripwires would be linked directly to the public alerting technology, thus not needing any data-processing algorithm.
Public alerting (technology)	Such as door knocking, voice sirens (with instructions about what to do), US Federal audible sirens, home-made sirens and flashing lights.
Public don't notice	The public might not see the alert, e.g. text message or flashing lights or hear the sirens.
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 three-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.
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 three-minute stage due to the certainty at that time about the hazard. However, if people leave it too late, e.g. at the three-minute stage, then flooding may prevent them from evacuating.

Table 2.2 'Showstoppers' for developing a debris flow early warning system on the Awatarariki Fan (Massey et al. 2020a).

Showstopper	Evidence from Evaluation
‘Public don’t act’ dominates the probability of failure of the EWS under scenarios Worst Case and Middle.	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. In this scenario, 50–60% of people in the hazard zone may still be present when the hazard occurs 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. 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. In these scenarios, 90% of people may still be in the hazard zone when the hazard occurs.
‘Public don’t notice [the alert]’ and ‘public not safe fast enough’ dominate the probability of failure of the EWS.	The tripwire has a very ‘short fuse’, 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.
Evacuation impediments/ obstructions	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. 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.
Uncertainty	Section 1.7 of the Bay of Plenty Regional Council’s Regional Policy Statement calls for a ‘precautionary approach’ where uncertainty exists.

3.0 CONSIDERATIONS FOR DEVELOPING A LANDSLIDE EARLY WARNING SYSTEM

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 General Assembly 2016)

EWSs are recognised in target 'G' of the Sendai Framework for Disaster Risk reduction 2015–2030, which aims to "substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to the people by 2030" (UNISDR 2015). There is a focus on EWSs addressing, and being able to warn for, multiple hazards in an environment (WMO 2018). There is also a shift toward warning systems becoming 'people-centred', which requires the involvement of the target audience in developing the warning system (Basher 2006; WMO 2018). A people-centred multi-hazard EWS:

> *"empowers individuals and communities threatened by hazards to act in sufficient time and in an appropriate manner to reduce the possibility of personal injury and illness, loss of life and damage to property, assets and the environment."* (WMO 2018)

EWSs have four key components: (1) disaster risk knowledge; (2) detection, monitoring and warning services; (3) communication and dissemination mechanisms; and (4) preparedness and response capabilities (Figure 2.1; Basher 2006). In addition to the four components of an EWS, which are supported by guidance from the WMO (2018) and the Sendai Framework for Disaster Risk Reduction (UNISDR 2015), the International Organization for Standardization (ISO) has provided the *Guidelines for implementation of a community-based landslide early warning system* (see ISO [2018a]). These guidelines identify seven main sub-systems of a LEWS, many of which fall within the four EWS components portrayed in Figure 3.1. These seven sub-systems are:

1. Risk assessment.
2. Dissemination of knowledge.
3. Establish disaster preparedness team.
4. Develop evacuation route and map.
5. Develop SOPs.
6. Monitoring, early warning and evacuation drill.
7. Commitment of the local government and community on the operation and maintenance of the whole system.

These sub-systems are incorporated into the respective EWS component portrayed in Figure 3.1.

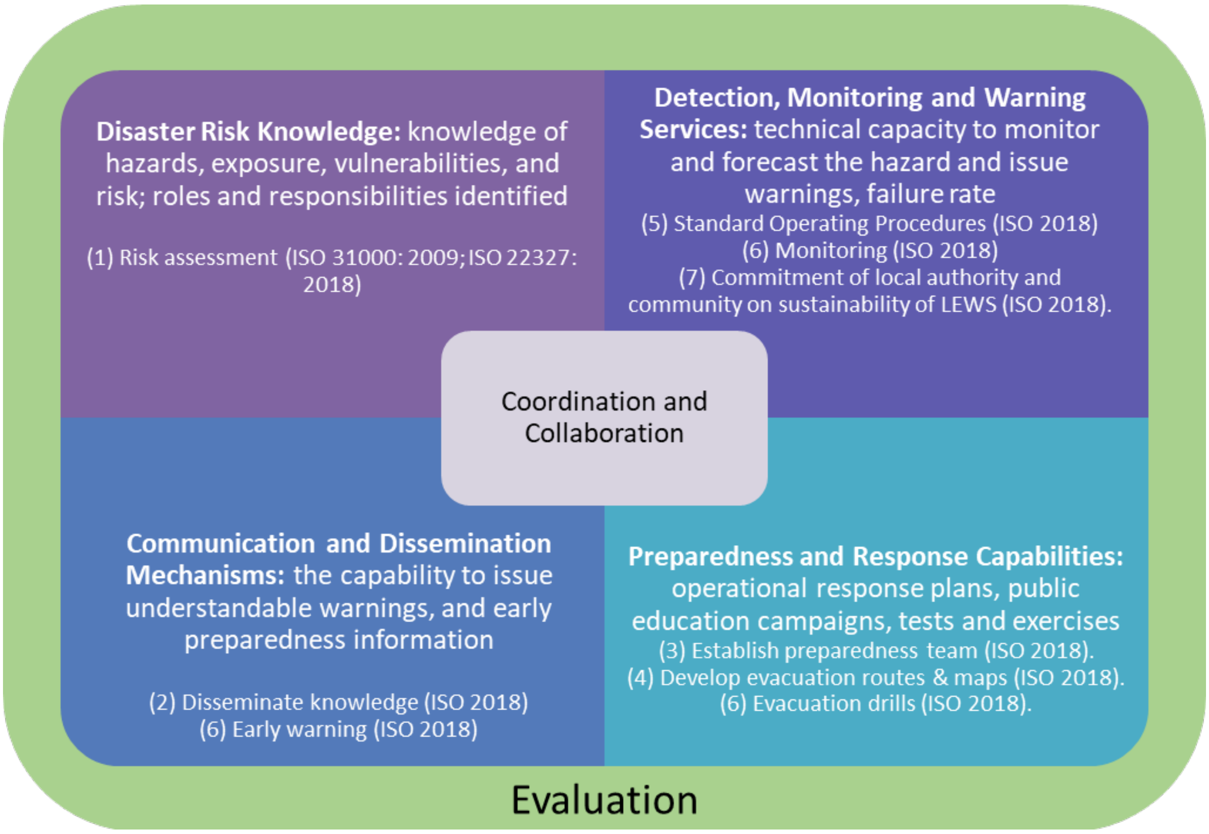

Figure 3.1 The four operational components of an early warning system (adapted from Garcia and Fearnley [2012]; ISO 2018a; WMO 2018). The numbers refer to the steps identified in the *Guidelines for implementation of a community-based landslide early warning system* (ISO 2018a). The outer rectangle demonstrates the role of evaluation for all EWS components, and the inner rectangle shows the importance of co-ordination and collaboration for integrating these components into an EWS.

Poor linkages between these components have been major causes for EWS failures resulting in disasters (Garcia and Fearnley 2012). Linking these four components into an integrated EWS requires co-ordination and collaboration across agencies and governance levels that have relevant information about the hazards and impacts that threaten people and assets (Garcia and Fearnley 2012; Golnaraghi 2012). This can enable the development of effective decision-making processes that include local contexts and define roles and responsibilities (Garcia and Fearnley 2012).

The following sub-sections describe considerations for each of the four EWS components shown in Figure 3.1 in the context of a LEWS. The purpose of this section is to describe the components that are needed to design and implement a LEWS and to provide specific examples from landslide-related research and practise both within and outside of Aotearoa New Zealand.

3.1 Disaster Risk Knowledge

Developing risk knowledge and establishing the context is foundational to the appropriate design and implementation of an EWS (WMO 2018). Developing risk knowledge involves the systematic collection of data to support multi-risk assessments (WMO 2018). This includes hazard, exposure, vulnerability and capacity (MCDEM 2019b; WMO 2018). Defining roles and responsibilities is also a prerequisite to implementing an EWS. Each of these steps for building risk knowledge and establishing context will be discussed next.

3.1.1 Hazards

Understanding the hazard is key to informing the risk assessment. Landslides are a geophysical hazard that can cause "loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation" (UNDRR [2023]). In line with the risk assessment component of the risk-management process shown in Figure 2.1, the landslide hazard assessment involves understanding the characteristics of the hazards, such as location, severity and intensity, frequency, magnitude and extent, triggers (e.g. rainfall, earthquakes / ground shaking), underlying geology, hydrology, soil properties and history (Andersson-Sköld et al. 2013). Much of these data are stored in historical inventories (Andersson-Sköld et al. 2013; Fathani et al. 2016), although acquiring inventory data continues to be a challenge (Smith et al. 2021).

3.1.1.1 Landslide Databases and Inventories

GNS Science maintains the New Zealand Landslide Database, which holds all data routinely collected on landslides by GeoNet, GNS Science's monitoring programme, through monitoring of reports made by the media, Waka Kotahi New Zealand Transport Agency (NZTA), the New Zealand Automobile Association, GeoNet landslide response activities and GNS Science staff (Rosser et al. 2017). Further work is underway with Toka Tū Ake EQC (New Zealand's Earthquake Commission), Auckland Council, GNS Science, Waka Kotahi NZTA and KiwiRail to develop a new collaborative national landslide database for Aotearoa New Zealand that will be accessible to local and regional councils, Crown entities and geotechnical consultants (Toka Tū Ake 2020). A universal open-access rock avalanche case study database is also under development for mapping out rock avalanche impact zones (Mitchell et al. 2021). Additionally, the United States Geological Survey (USGS) has developed a global open-access earthquake-induced landslide database (Tanyaş et al. 2017). Such landslide databases are fundamental in understanding the hazard in a collaborative and co-ordinated way for application to EWSs. Furthermore, they could be a home for information along the value chain, including information relating to impacts on various environments, perceptions and responses.

3.1.1.2 Landslide Mapping

The historical data in such landslide inventories are used to populate subsequent hazard maps and inform hazard and impact models (Glade 2001; Smith et al. 2021). Pardeshi et al. (2013) documented a plethora of landslide mapping techniques in a global literature review. These methods include multi-variate techniques for forecasting landslides; physical process-based models for determining relative importance of landslide causative factors in slope instability; remote sensing for detecting, mapping and monitoring landslides; and Geographic Information Systems (GIS) for mapping, monitoring and forecasting landslides (Pardeshi et al. 2013). Deterministic approaches have been used to develop landslide hazard maps and models, although a need for probabilistic approaches has been identified to account for inherent uncertainties of various factors contributing to slope instability and the likelihood of landslide occurrence (Li et al. 2022; Refice and Capolongo 2002; Xie et al. 2004).

Much work is being carried out to understand, map and forecast landslide hazard occurrence in Aotearoa New Zealand:

- Landslide inventories have been created resulting from the 2016 Kaikōura Earthquake (Massey et al. 2018, 2020b), the 1968 Inangahua Earthquake (Hancox et al. 2014), the February 2004 North Island rainstorms and floods (Hancox and Wright 2005), and other events, including ex-Tropical Cyclone Gabrielle most recently (Massey and Leith 2023).
- Landslide magnitude-frequency relationships have been derived for different levels of ground shaking and the spatial susceptibility to earthquake-induced landslides determined (de Vilder et al. 2021; Hancox et al. 2002).
- Various models were used to develop an earthquake-induced landslide forecast tool (Massey et al. 2021a), discussed further in Section 3.2.3.
- Empirical-probabilistic runout methods were applied to estimate the potential runout distance for various landslide types in Aotearoa New Zealand (Brideau et al. 2021a).

3.1.1.3 Primary, Secondary and Tertiary Landslide Hazards

The complexity and difficulties of understanding landslide hazards and their impacts are compounded by the fact that many landslides are triggered by other hazards (i.e. primary hazards) such as rainfall and earthquakes. As such, accurate information for these primary hazards is also required to support landslide hazard modelling (Allstadt et al. 2018; Crozier 2005). Allstadt et al. (2018) presented evidence of the influence that ShakeMaps have over earthquake-induced landslide hazard maps following the 2016 Kaikōura Earthquake. Robinson et al. (2018) utilised ShakeMaps produced by USGS and GeoNet earthquake records to produce near-real time landslide hazard models using empirical analysis to model landslide impacts during the live response to the 2016 Kaikōura Earthquake.

Landslides can also produce secondary and tertiary hazards, such as natural landslide dams. These dams can cause upstream flooding, followed by outburst floods if/when the dam fails (Robinson et al. 2018). Flooding from these dams has the potential to devastate nearby communities (Becker et al. 2007). Assessing the formation, failure modes and longevity of landslide dam hazards involves initial breach and inundation modelling, high-resolution topographic surveys of the dam and downstream area, measuring the volume and geometry of the dam and lake and modelling the dam breach and flood/debris inundation to determine the area of impact (Morgenstern et al. 2021). The results of this process can then inform risk and impact modelling by overlaying the results onto asset layers (e.g. spatial layers of infrastructure networks, buildings). This requires understanding of the exposure, vulnerability and capacities of the assets (i.e. the built and natural environments) and people.

3.1.2 Exposure, Vulnerability and Capacities

Understanding the underlying exposure, vulnerability and capacities further contributes to the risk assessment and mitigation, as prescribed by the ISO (2018a) guidelines for implementation of a community-based landslide early warning system.

3.1.2.1 Exposure

Exposure refers to the location of assets relative to the hazard in space and time (Paulik et al. 2020). Exposure can be determined by overlaying the spatial hazard layer(s) (including the likelihood and frequency of occurrence) with the asset layers, such as building footprints, population distribution, transportation networks and infrastructure footprints (e.g. Jaedicke et al. 2014; Nowicki Jessee et al. 2020; Paulik et al. 2020; Promper et al. 2015).

Exposure changes over space and time. Up-to-date population and asset information is important for conducting accurate risk assessments. Out-of-date exposure datasets can result in inaccurate risk assessments and lead to over-warning or under-warning (Harrison et al. 2022b). During the recovery phase, people may be displaced, and up-to-date exposure data can help to determine whether EWSs are needed and in what form.

Methodologies for integrating dynamic exposure risk assessments have been documented in the literature (e.g. Gallina et al. 2016; Shabou et al. 2017) and integration of dynamic exposure of humans and assets requires collaboration across sectors (e.g. social science, engineering, critical infrastructure and natural sciences [Harrison et al. 2022b; Merz et al. 2020]). Examples of some sources of dynamic human exposure are CCTV footage to identify where people are and their response behaviours to a hazard (e.g. Lambie et al. 2016, 2017; Vinnell et al. 2022b), population movement via cellphone data (Harrison et al. 2021) and remotely sensed data, such as frequently updated satellite imagery or aerial imagery collected by drones and/or helicopters (Aubrecht et al. 2017; Fekete 2020; Tellman et al. 2021). Furthermore, exposure datasets continue to be developed and expanded for Pacific Island countries, including the Cook Islands, Fiji, Papua New Guinea, Samoa, the Soloman Islands, Tonga, Tuvalu and Vanuatu (Glassey et al. 2011; Lin et al. 2014, 2020).

3.1.2.2 Vulnerability

Vulnerability is the susceptibility of an individual, community, asset or system to experience some level of impacts from hazards (UNDRR 2022). Vulnerability is determined by physical, social, economic and environmental factors or processes (UNDRR 2022). Landslide vulnerability is multi-dimensional with two primary assessment approaches. The first dimension is geophysical- and engineering-based approaches (Glade 2003), where the geophysical susceptibility (or vulnerability) to landslide occurrence is determined by geophysical/geological factors or processes, such as slope stability and/or seismic activity (e.g. Sharma et al. 2012). The engineering approach is also used to assess the vulnerability of built structures to landslide-related damage (Glade 2003). This can be done using fragility functions and vulnerability curves in risk models, which combine hazard intensity with vulnerability (determined by the characteristics of assets such as buildings, road networks, vehicles, etc.) to determine degrees of damage or impact indicators (Schmidt et al. 2011), described further in Section 3.1.3.

Human vulnerability makes up the other dimension to landslide vulnerability, which relates to demographic characterisations (e.g. age, gender, physical disability, health, socio-economic status), policy, land use, urbanisation, risk perceptions, awareness and education (Glade 2003). For example, landslide vulnerability in the Chittagong Hill Districts of Bangladesh was found to be determined by poverty, social injustice, lack of planning regulations, illegal hill-cutting issues and a lack of traditional knowledge amongst urbanised populations (Ahmed 2021). Furthermore, risk perceptions and preparedness of communities and individuals may be a factor for vulnerability to landslides, where areas or people with low levels of risk perception and preparedness tend to experience higher-than-average levels of damage (Glade 2003).

Vulnerability information is typically created through conducting vulnerability assessments that combine key datasets such as demographic, ecological, land-use, building and infrastructure data (Terti et al. 2015) and through surveys to understand people's risk perceptions and communities' vulnerabilities and complexities (ISO 2018a). The inputs, methods and results of vulnerability assessments vary by spatial and temporal scale. For example, Ahmed (2021) used a participatory approach to conduct a community-scale vulnerability assessment to identify and understand the drivers behind landslide vulnerability in the Chittagong Hill districts of Bangladesh. Antronico et al. (2020) sought to understand regional levels of risk perception and vulnerability to landslides through a qualitative survey in Calabria, Italy. At a global scale, Nowicki Jessee et al. (2020) used the United Nations Human Development Index as a vulnerability proxy for their development of a global dataset and model of earthquake-induced landslide fatalities.

Vulnerability indices are typically developed to incorporate social data into quantified risk assessments (e.g. Balica et al. 2012). Environmental Health Intelligence New Zealand (EHINZ) at Massey University has developed social vulnerability indicators for natural hazards in Aotearoa New Zealand for 2018, which are freely available through online web maps and downloadable data files from EHINZ ([2023]).

In Aotearoa New Zealand, there are datasets relating to the vulnerability of dwellings to landslides (Massey et al. 2019), of residential buildings to rainfall-induced landslides (e.g. Wolter et al. [2022], with more in preparation) and of buildings and life to earthquake-induced landslides (Massey et al. 2013). A quantitative risk analysis was recently completed using case studies from the Kā Roimata o Hine Hukatere Franz Josef Glacier and Te Moeka o Tuawe Fox Glacier valleys, on the west coast of the South Island, where de Vilder et al. (2022) calculated exposure based on the probability of a person occupying the tracks or roads if they spend an amount of time per year walking or driving on the tracks. Vulnerability was calculated using landslide volumes and the ability of an individual to take evasive action depending on the landslide volume (de Vilder et al. 2022). Fragility functions are also in development at GNS Science for rainfall-induced landslides.

3.1.2.3 Capacities

Capacities can be defined as the combination of all the strengths, attributes and resources available within an organisation, community or society to manage and reduce disaster risks and strengthen resilience (MCDEM 2019b). Capacity information can include risk mitigation and response plans and agencies using disaster risk knowledge to inform their management practises. Examples of capacities in Aotearoa New Zealand for landslides are Gisborne District Council and Ngāti Rangiwaho collaborating with GNS Science on a case study of landslides affecting cultural heritage sites and infrastructure to reduce impacts. Capacities of residents might include their available resources, such as whether they have operational vehicles for evacuating on receipt of a warning or being able to afford alternative accommodation or insurance. Capacities of response agencies would include staff availability, financial resources to afford the necessary elements of an EWS and knowledge and awareness to gather information, implement and respond to such systems. More work is needed to gather and use capacity information to inform the disaster risk knowledge function of an EWS.

3.1.3 Risk Assessment

The risk assessment should be based on the ISO 31000 described in Section 2.0 (ISO 2018b). Some of the tools and approaches, including the data required to conduct risk assessments, are described next.

A risk assessment involves combining the above information about the hazards and their likelihood, exposure and vulnerability in a meaningful way to assess and convey the level of risk to people, buildings and/or infrastructure, as well as potential flow on-effects, including economic loss, disruptions and health impacts and the accompanying uncertainty (Beven et al. 2018; Lee 2015). Various methods and tools are available to carry out the risk assessment and communicate the outputs, such as (but not limited to) risk models, participatory risk assessment approaches, geospatial analyses and risk matrices. Risk models and geospatial analyses are ways of quantitatively or semi-quantitatively assessing risk.

Risk models use fragility functions and vulnerability curves to associate hazard intensity with levels of damage and losses to produce quantitative outputs, such as economic losses and numbers of injuries and deaths (Schmidt et al. 2011). RiskScape[2] is an Aotearoa New Zealand -based example of a risk model that operates on a modular framework, where inputs are exchangeable under the hazard, asset and vulnerability modules (Schmidt et al. 2011).

Semi-quantitative risk assessments can also be carried out using GIS by combining landslide susceptibility maps with exposure and vulnerability layers, as was done for landslide risk assessments in Kuala Lumpur City (Althuwaynee and Pradhan 2017) and Greece (Psomiadis et al. 2020). Crawford et al. (2019) found that communicating the outputs of risk models using visualisations (e.g. maps) and tables can support risk-based decision-making for natural hazards in Aotearoa New Zealand.

Risk matrices support decision-makers in determining a level of impact based on the likelihood of the hazard occurring and the severity of the consequences (e.g. White et al. 2016). A recognised limitation of risk matrices is the inherent limitations of communicating the underlying uncertainty around the hazard likelihood and severity (White et al. 2016).

3.1.3.1 Dynamic Risk in an Early Warning System

In the context of an EWS, it is important to note that risk changes over space and time due to the dynamic nature of vulnerability and exposure, as well as changes in the hazard characteristics and triggering factors. As an example, the location of people tends to change according to the time of day. The risk relating to a landslide close to a residential area may be lower during the day, when most people are away from home and at work, and higher at night. The risk relating to a landslide impacting an arterial road might be higher during rush hour or to a railway during set times of operations. Having dynamic exposure data can be very helpful in relation to warnings. Similarly, dynamic hazard data, such as relating to rainfall intensity or aftershock forecasts with spatial shaking potential, can inform the design of a LEWS through the significant change in the likelihood of a landslide occurring. It is critical to account for this dynamic nature of risk when carrying out risk assessments so that the warnings are relevant to the current societal, geographical and geophysical conditions and context (Harrison et al. 2022b).

3.1.4 Organisational Arrangements

It is important to establish the roles and responsibilities for the various agencies and stakeholders involved when designing an EWS. In most cases, multiple agencies would likely be involved in one or more EWS component (WMO 2018). Section 1.1 indicates roles and responsibilities for the National Warning System and natural hazard management in Aotearoa New Zealand. Additional arrangements must be made to facilitate communication and collaboration across the various agencies involved to enable knowledge transfer and data and information sharing. Adopting the Co-ordinated Incident Management System (CIMS)[3] is a good example of striving to achieve an effective co-ordinated response across agencies. Strong relationships between key science and research agencies, such as GNS Science, and decision-makers and warning service providers, such as MetService, councils, CDEM and NEMA, are particularly important for the effective communication of landslide hazard and risk information in Aotearoa New Zealand. Further recommendations integrating science and government for hazard and risk management and communication are summarised in Table 3.1.

2 https://riskscape.org.nz/

3 https://www.civildefence.govt.nz/resources/coordinated-incident-management-system-cims-third-edition/

Table 3.1 Recommendations for integrating science and government for hazard and risk management and communication (Donovan and Oppenheimer 2012; Scolobig 2015).

Topic	Recommendations
Government structures and complexity	• It is important to have clear channels for providing advice and to have few steps/people in between the communicator/scientist and the recipient/ decision-maker. • Personal contact and long-term relationship building is important. • Continuity in expert advice to Civil Defence personnel is important and can be achieved via regular, frequent meetings with such personnel to keep them informed and to maintain personal contact.
Data usage and distribution	• Making data openly available increases transparency and healthy debate. • Data availability is important for risk assessments.
Public preparation and awareness	• The role of cultural cognition in risk judgments requires further research. • Expectations, emotions and lifestyle factors all affect worldviews, and these may be threatened by risk. • A gradual building up of preparedness was found to help people adjust to and prepare for hazards such as earthquakes.
Roles and responsibilities	• Making residents more responsible for their decisions about evacuation to align with people-centred EWS and new approaches where the public is a central element and resource in disaster risk management. These approaches are based on the assumption that involving people in decisions and actions is empowering and results in more effective disaster risk-reduction processes. • Setting responsibility frameworks through legislation and institutional frameworks to improve communication protocols.

The key point of this section is that when developing a LEWS, be familiar with the appropriate roles and responsibilities for a particular location, including those providing the science advice, monitoring, warnings, mitigation plans and responses. EWS documentation needs to specify these roles and responsibilities to ensure that they are clear with no room for ambiguity.

3.2 Detection, Monitoring and Warning Services

Detection, monitoring and warning requires using appropriate and reliable technology for the continuous, automated detection and monitoring of landslides and other hazards (Basher 2006). Examples of detection mechanisms include sensors for measuring landslide initiation in the potential landslide source area, such as tripwires strung across the flow path, radar and river stage gauges to measure flow height and geophysical sensors that monitor acoustic vibrations and ground shaking associated with the rapid movement of the debris downslope (Massey et al. 2020a). In addition to these ‘conventional’ detection methods, aerial photogrammetry, remote sensing, terrestrial laser scanning and high-resolution Digital Elevation Models, coupled with machine-learning techniques, offer more modern geospatial techniques (Mohan et al. 2021). A landslide dam EWS would require different detection mechanisms, such as lake-level monitors, to detect any rise or rapid fall in lake level; regular inspections of the dam and landslide area for seepage and spillway erosion; or further debris falls (Becker et al. 2007).

Five key actions are required for this component: (1) understand previous and/or existing systems; (2) co-design the system; (3) develop the detection and monitoring system; (4) develop forecasting tools; and (5) establish agreements, plans and protocols. These components will be described next.

3.2.1 Understand Previous and Existing Systems

Developing a new EWS requires understanding the current EWS capabilities and identifying how a new EWS supports current systems and fills a gap in the existing services. This includes considering EWSs for all other hazards.

3.2.1.1 State of Early Warning Systems in Aotearoa New Zealand

Examples of various natural hazard EWSs in Aotearoa New Zealand, as well as some of the associated agencies that are involved in the decision-making process for issuing warnings, are listed in Table 3.2.

Understanding the current state of practise for EWSs in Aotearoa New Zealand provides context around what EWSs are operational for the various natural hazards that present risks to society. This helps to identify gaps in the current state of practise and also provides cases and frameworks for best practise for developing a new EWS. For example, the process for assessing the need for an eruption-induced lahar in the Whangaehu Valley at Mt Ruapehu and for developing the resulting Eastern Ruapehu Lahar Alarm Warning System (ERLAWS) is well documented (e.g. Becker et al. 2018; Keys and Green 2008; Massey et al. 2010) and provides a case study of how the system was co-developed with various agencies. Alternatively, understanding the current structure of the severe weather and flood EWS (e.g. Harrison 2022; MetService c2023; Rouse 2011) may be useful for developing an EWS for rainfall-induced landslides, as it would depend on forecasts or warnings for rainfall that are issued by MetService.

Table 3.2 Summary of the various natural hazard early warning systems in operation in Aotearoa New Zealand. * This is not an exhaustive list of the agencies that can be involved in the decision-making process for issuing an early warning for the hazards listed below.

Hazard(s)	Scale, Location	Examples of Agencies Typically Involved in the EWS Decision-Making Process*	Sources
Tsunami	Coastal; location depends on source of tsunami	NEMA, GNS Science, CDEM Groups	Tan et al. (2021)
Severe Weather	Location depends on forecasted track of severe weather patterns	MetService, CDEM Groups, regional and/or local councils	Harrison (2022), MetService (c2023)
Floods	Location depends on forecasted track of severe weather patterns	Regional and/or local councils, CDEM Groups, MetService	Harrison (2022), Rouse (2011)
Landslide	Landslide-specific, Brewery Creek landslide, Clyde Dam Reservoir	Contact Energy, no other information found	Macfarlane (2009)
Lahar (ERLAWS)	Whangaehu Valley, Mt Ruapehu	Department of Conservation, CDEM Groups, regional and/or local councils	Becker et al. (2018), Keys and Green (2008), Massey et al. (2010)
Swells	Coastal; location depends on the origin(s) of the factors contributing to the swells (e.g. pressure changes due to weather systems at sea) and anticipated impacts	MetService, CDEM Groups	Harrison (2022), WREMO (2020)

3.2.1.2 State of Overseas Landslide Early Warning Systems

Much work has been done overseas to design, implement and operationalise LEWSs at different spatial- and timescales with different landslide triggers (e.g. rainfall, earthquake) and thresholds. Empirical rainfall thresholds, in combination with rainfall measurements and quantitative rainfall forecasts, remain the most frequently applied concept for most regional LEWSs (Pecoraro et al. 2019; Thiebes and Glade 2016). Furthermore, most LEWSs deal with a single landslide type (Pecoraro et al. 2019). This is because an operational LEWS at the slope scale requires site-specific choices for its design and management depending on the characteristics of the landslide under surveillance (Pecoraro et al. 2019). The technical characteristics and social aspects of integrating regional- and local-scale LEWSs into risk management, communication and alerting strategies, and risk governance are summarised in Table 3.3 based on a global literature review (Thiebes and Glade 2016).

Table 3.3 Summary of key findings of the state-of-practise review of landslide early warning systems conducted by Thiebes and Glade (2016).

Regional-Scale LEWS	
The importance of clarifying expectations	A regional EWS for debris flow in San Francisco, USA, was discontinued in 1995 due to technical problems and lack of funding. Other difficulties included the completely different expectations of the involved parties (e.g. the National Weather Service and USGS). Another challenge was effective communication of warnings, as it was observed that people entered hazardous areas due to the lack of knowledge and understanding of the risks.
Integration in overall landslide risk management	Since 2003 in Hong Kong, landslide forecasting has been made with respect to spatially varying landslide susceptibility. Public warnings are only issued if more than 15 landslides are expected based on experience with this number of landslides where at least one major event causes substantial damage. Warning dissemination uses various channels, including TV, radio, internet and a telephone hotline. A rainfall radar system was added to the LEWS to extend lead time and allow for the preparation of emergency actions.
Live modelling of landslide forecasts	The standard approach within LEWS is to use a threshold or a set of thresholds that are used for the respective warning. However, within some LEWS, the live integration of models allows for taking a more dynamic approach.
Combination of spatial and temporal forecasts	Landslide susceptibility maps give a relative probability of spatial landslide occurrence, and rainfall thresholds describe the temporal probability. The combination of spatial and temporal landslide forecasting remains a challenge. Some researchers have published ideas on how to carry out spatio-temporal landslide forecasting and to utilise this for LEWS (e.g. Bell et al. 2014; Segoni et al. 2015).
Local-Scale LEWS	
Terrestrial laser scanning (TLS)	TLS has revolutionised geomorphological research. It plays an important role in engineering applications, e.g. in open-pit mining, and all major developers of TLS equipment also have monitoring software available in their portfolios. Fixed TLS and automatic calculation of point-cloud differences were installed in an experimental warning system for deep-seated landslides.
Debris flow EWSs	EWSs for debris flows are less focused on the process onset itself and concentrate more on the detection of the process as it happens. Geophones, radar distance measurements or video cameras are frequently applied. LiDAR measurements were tested at the Illgraben debris flow catchment in Switzerland to assess material composition and the volume and velocity of debris flows.

Local-Scale LEWS	
Integration of models	Most current local-scale LEWSs base their alert thresholds on monitored landslide characteristics, in particular, displacement rates, and the magnitude of landslide-triggering factors such as rainfall and pore water pressures. These thresholds are primarily based on past experiences of landslide activations, expert judgement, or are derived by the application of quantitative predictive models. Few case studies aim to directly integrate monitoring data into numerical models, which has been described as the basis of the next generation of LEWSs. For the La Saxe landslide in Italy, integration of monitored displacement rates into a predictive model allowed for the successful forecast of a partial slope failure 10 hours before it happened, with uncertainties around acceleration phases.

Similarly, Pecoraro et al. (2019) conducted a global review of operational local LEWSs to document the monitoring strategies that were implemented for them. This review provides several user-friendly tables that summarise the characteristics of the local LEWSs for technicians, experts and stakeholders involved in the design and operation (Pecoraro et al. 2019). To view the tables, see Pecoraro et al. (2019). Here, we summarise the key findings of the review regarding key considerations and good practise for implementing local LEWSs and keeping them operational. These considerations are visualised in Figure 3.2 and summarised in Table 3.4.

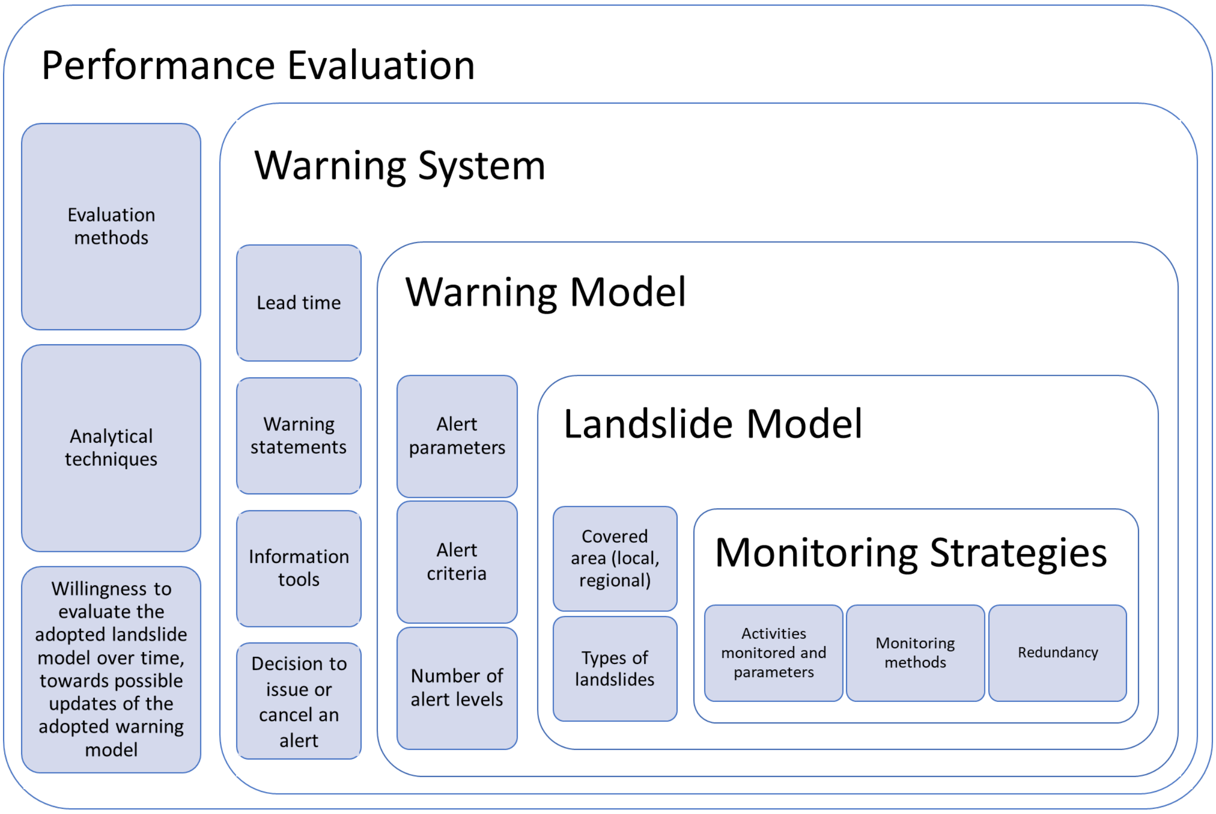

Figure 3.2 Considerations for designing a localised LEWS based on a global literature review conducted by Pecoraro et al. (2019). The considerations are grouped by the five key activities that Pecoraro et al. (2019) described.

As shown in Figure 3.2, the monitoring data inform the landslide model(s). The warning model includes the landslide model and defines a set of decision-making procedures required for issuing alerts. The warning system embeds the landslide and warning model and includes other essential elements of the risk-mitigation strategy, such as lead time, alert dissemination, communication and education, community involvement and an emergency response plan.

Performance is defined as the system capability to detect a landslide event in a timely manner (Pecoraro et al. 2019). Considerations for each of these activities in a local LEWS are summarised in Table 3.4. Many of these considerations will be elaborated on in subsequent sections in this report.

Table 3.4 Summary of findings from a global literature review of operational local landslide early warning systems from Pecoraro et al. (2019). The table is organised by five key activities (monitoring strategies, landslide model, warning model, warning system and performance evaluation) described by Pecoraro et al. (2019) for designing and operationalising local LEWS. Considerations for each activity are described in the context of the literature review results from Pecoraro et al. (2019) and provide opportunities for learning and establishing good practise.

Monitoring Strategies	
Activities monitored and parameters	• Monitored parameters are indicators or factors related to the slope or landslide of interest that can be quantified and observed with time. A key issue for any local LEWS is the understanding of the behaviour of such site-specific parameters and the evaluation of their role as early warning indicators. • Most systems are based on deformation monitoring, expressed in terms of displacement, velocity, acoustic emissions, cracking, acceleration and strain. This is because most of the monitored landslides were previously recognised and show evidence of active deformation. • In most cases, the main indicator compared with threshold criteria is the cumulated displacement; velocity and acceleration are more commonly used as kinematic indicators for landslides in rock. A large number of local LEWSs also monitor triggering parameters, such as rainfall data. • In systems that monitor groundwater conditions, pore water pressures and water levels are the most commonly monitored parameters.
Monitoring methods	• Monitoring methods can be classified into six categories: (1) geotechnical, (2) hydrologic, (3) geophysical, (4) geodetic, (5) remote sensing and (6) meteorological. • The monitoring methods are correlated to the site-specific conditions of the slope to be monitored and to the parameters investigated.
Redundancy	• Redundancy is crucial for developing monitoring strategies; thus, many LEWSs employ more than one monitoring method.
Landslide Model	
Covered area	• All systems in the review are designed to operate at a local scale.
Types of landslides	• Debris flows and rockslides are the most investigated type. Most LEWSs deal with a single landslide type. This is because a LEWS that is operational at slope-scale requires site-specific choices for its design and management depending on the characteristics of the landslide under surveillance.
Warning Model	
Alert Parameters	• The primary alert parameter used in the adopted warning models is displacement, in terms of rate of movements, velocity and acceleration. Displacement provides direct evidence of the state of activity of the landslide. • Meteorological parameters are also considered because a significant number of mass movements are weather-induced landslides. • In most systems, parameters not explicitly included in the warning model are also monitored.

Warning Model	
Alert criteria	• May be defined as a functional relationship between the investigated landslide and the monitored parameters (e.g. displacements, rainfall). • Most systems use empirical models, which can be further subdivided into heuristic methods and correlation laws.
Number of alert levels	• Most local LEWS employ two or three alert levels. However, at the beginning of the 2000s, a significant number of systems began using four alert levels or more. The highest number of alert levels was adopted in Mt Ruapehu from base level to level 5, the latter associated to a risk with a conditional probability of 100%.
Warning Systems	
Lead time	• The review found that LEWS can be classified into three main categories: alarm systems (with a lead time of seconds or minutes), warning systems (more than one hour lead time) and forecasting systems (more than one day lead time). Note that terminology in Aotearoa New Zealand may differ to this global review. • In the review, most alarm systems deal with debris flows. Warning systems typically deal with active landslides that move slowly but can be characterised by movement rates rapidly increasing before a general failure stage.
Warning statements	• The design depends on the audience, e.g. internal messages meant for politicians, scientists, government institutions, civil protection agencies or infrastructure authorities, versus the people and communities exposed in pre-defined areas. • Clear roles and responsibilities according to emergency plans are necessary.
Information tools	• Warning messages, warning signals, phone calls, internal tools. • Warning messages sent out as an SMS are the most used tool because the messages are pushed from the warning agency to the end users, reducing the latency between a decision to alert to message receipt. • Warning signals such as traffic lights and sirens are employed on road and railway lines crossing mountainous regions. • Manually and automated phone calls are used in old local LEWSs. Internet-based tools such as webpages and emails have been adopted more recently. • Communication strategies were found to be rarely redundant in the LEWS.
Decision to issue or cancel an alert	• Warnings are almost always issued manually by an individual or group.
Performance Evaluation	
Evaluation methods	• Comparison between landslide activity and warnings issued, comparison between predicted and reported landslides, and/or reliability analysis through timeframe analysis and/or statistical indicators.
Good practise	• System managers demonstrate a willingness to evaluate the adopted landslide model over time, toward possible updates of the adopted warning model.

Redundancy of the monitored parameters and monitoring methods, considering multiple thresholds, and performance evaluation are also important features to include in a LEWS (Pecoraro et al. 2019). These aspects can improve the efficiency and effectiveness of a local LEWS (Pecoraro et al. 2019). Redundancy of the monitored parameters and monitoring methods is crucial and can provide useful data to be considered in the decision-making phase and a continuous check on the working conditions of the instruments (Pecoraro et al. 2019). Using multiple thresholds can increase the efficiency of the system by supporting the decision to issue or not issue a warning (Pecoraro et al. 2019). Performance evaluation is critical in understanding the performance of the system within the overall risk management framework (Pecoraro et al. 2019).

3.2.2 Develop the Monitoring and Detection Systems

It is not always possible to forecast or predict when and where a landslide will occur; thus, various detection mechanisms tend to be relied on for a LEWS. For example, rapid debris flows can provide little warning time between landslide initiation and impact on people, buildings and/or infrastructure (Massey et al. 2020a).

3.2.2.1 Monitoring

Landslide monitoring helps to understand the landslide mechanism and to identify thresholds for landslide forecasting and early warning (Chae et al. 2017). Real-time monitoring of active landslides can help to minimise their impacts by detecting indications of any major activity that might lead to sliding (Shafique et al. 2016). The systems used for detection and monitoring, which could be automated, should allow for strict quality control of the data under international standards when these are available (WMO 2018).

The spatial and temporal resolution of the monitoring network should be determined based on the nature of the landslide hazard(s); the results and implications of the risk assessment; and addition criteria such as simplicity, robustness, reliability and cost (Pecoraro et al. 2019).

The monitoring devices installed to support the EWS should include (ISO 2018a):

1. Rain gauges to measure the intensity of rainfall within a certain period.
2. Surface deformation meters to identify the deformation on the land surface in a certain period. The common devices used are extensometer (monitoring the relative distance between two points on the crack) and tiltmeter (the gauge for changes in the inclination of the land surface).
3. Key ray surveying to measure the shortening of a line oriented downslope (installed in the Clyde Dam reservoir landslides [Macfarlane 2009]).
4. Robotic total-survey stations to measure the angle and distance to survey reflector prisms at hourly intervals (as part of a high temporal and spatial landslide monitoring system installed in Taihape in June 2006 [Massey et al. 2016]).
5. Repeated terrestrial laser scanning to measure range, colour and intensity of an object and develop 3D models, such as digital elevation models for monitoring dome/slope stability and calculating volume (Haerani et al. 2016; Prokop and Panholzer 2009).

Additional tools can be used to improve measurement accuracy (ISO 2018a):

1. Underground deformation meters to measure the deformation underground through the movement of the sliding plane within a certain period of time (inclinometer, pipe strain gauge, multi-layer movement meter).
2. Groundwater-level meters to measure changes in groundwater level in the landslide zones, mounted inside the borehole.
3. Pore water pressure sensors to measure changes in pore water pressure on the landslide mass, installed in the borehole.
4. Soil moisture sensors to measure the changes of water level in the landslide mass.

5. Survey stakes to monitor mass movement in a horizontal direction of motion (wooden, bamboo or other stake materials).
6. Other monitoring, including the use of fibre geophysics tools, ambient vibrations, seismometers and InSAR.

General monitoring approaches fall into two categories: in-situ ground-based monitoring techniques and remote-sensing techniques (including passive and active sensors). Monitoring of earthquake-induced landslides appears to benefit from remote sensing using satellite and aerial imagery, GIS technology and accelerometer monitoring tools (Doi et al. 2019; Lin 2008; Wang et al. 2020; Wasowski et al. 2011). A list of monitoring methods and tools is available from a global literature review of landslide monitoring for EWSs by Pecoraro et al. (2019). Landslide monitoring sensors are further described in a global review of the state of the art of landslide monitoring by Chae et al. (2017).

An example of a landslide monitoring network in Aotearoa New Zealand is that for a large deep-seated translational landslide in Taihape that was formed over 1800 years ago (Massey et al. 2007). The landslide encompasses about 45 ha of land upon which households and a school were built (Massey et al. 2007). A near-real-time monitoring network was installed to record movement-triggering events and link discrete periods of landslide movement to the triggering event (Massey et al. 2007). The monitoring network consists of:

- Reflectors to monitor movement with high spatial resolution.
- A robotic total-survey station to seek and measure the location of each reflector with high temporal resolution.
- Tipping-bucket rain gauges on the toe and near the back scarp of the landslide.
- Vibrating wire piezometers to monitor groundwater acting along the slip plane.
- A strong motion accelerograph to monitor earthquake-triggered movement (Massey et al. 2007).

The science of landslide monitoring continues to advance and grapple with limitations and challenges relating to data acquisition and analysis (e.g. collecting enough data points at appropriate time intervals), which has implications for warning lead time and false alarms (Carlà et al. 2017). To that end, effective landslide monitoring programmes depend on “their appropriate calibration and contextualization” of the local on-site conditions and characteristics and “the back-analysis of monitoring data from past slope instabilities” (Carlà et al. 2017).

3.2.2.2 Detection

Early detection devices should be placed in areas that have the highest risk and largest number of people affected as determined by the risk assessments and identified landslide risk zones (ISO 2018a). Installation of the equipment should be co-ordinated with the community to increase the sense of ownership and responsibility for the equipment’s condition and to increase the likelihood of people taking mitigation actions (ISO 2018a). The type of early detection and danger levels should be appropriate to the geological conditions and the scale of landslide (ISO 2018a).

3.2.2.3 *Community-Based Monitoring and Detection*

Citizen science and crowdsourcing are additional methods that can be used for detecting and monitoring landslides and other hazards (Cieslik et al. 2019; Harrison et al. 2022a). For example, the NASA (National Aeronautics and Space Administration [USA]) Landslide Reporter[4] project provides a platform for people to report landslide occurrences to a global database. Recently, GNS Science requested reports of landslide occurrence across Aotearoa New Zealand following ex-Tropical Cyclone Dovi from 12 to 13 February 2022 (GeoNet 2022), and Auckland Council deployed a crowdsourcing application to collect landslide reports.[5]

Forecasting is 'common' among local and indigenous communities' disaster risk-reduction activities (Hadlos et al. 2022). The rich knowledge of the landscape and processes at play in the communities' localities makes it possible for the communities to identify environmental cues or signals that a landslide may be imminent. For example, portions of local communities in Sri Lanka were found to be aware of unusual earth cracks as a pre-indicator for landslides (Dasanayaka and Matsuda 2019).

3.2.3 Develop Forecasting Tools

Providing reliable forecasts for an EWS involves processing and analysing data, generating models and forecasts based on accepted scientific and technical methodologies and disseminating the outputs within international standards and protocols (WMO 2018). New data analysis and processing, modelling, prediction, and warning products should be integrated easily in the system as science and technology evolve (WMO 2018). Archival processes must also be in place for forecasts and warnings (WMO 2018).

Landslide forecasting utilises historical data and monitoring, along with other hazard data such as rainfall and/or seismic shaking, as they are typically triggered by these hazards. For example, a LEWS was developed in Indonesia using rainfall forecasts to predict and warn for rainfall-induced landslides (Hidayat et al. 2019).

3.2.3.1 *Landslide Forecasting Tools in Aotearoa New Zealand*

Scientists at GNS Science have developed an earthquake-induced landslide forecast tool to produce advisory information for GeoNet, emergency managers, regional and district councils, infrastructure managers, major landowners such as the Department of Conservation, insurers such as Toka Tū Ake EQC, and the public (Massey et al. 2021a). It is a spatial forecast that shows the probability of a landslide being generated given a certain earthquake shaking. Plans, as outlined by Massey et al. (2021a), for the broader project and science team are to sequentially create the following forecast tools, with customised outputs for specific users:

1. Earthquake-induced landslide forecasts for GNS Science duty officers, a range of agencies and the public.
2. Rainfall-induced landslide forecasts for GNS Science duty officers, a range of agencies and the public.
3. Landslide runout forecasts.
4. Earthquake-induced landslide forecasts for commercial users.
5. Rainfall-induced landslide forecasts for commercial users.
6. Global landslide forecasts for commercial customers.

4 https://www.nasa.gov/solve/landslide_reporter
5 https://landslides.nz/report-a-slip/

A rainfall-induced landslide forecast tool is also being developed utilising rainfall intensity derived from rain radar. Opportunistic testing of the relationship between radar intensity and landslide occurrence took place during Cyclone Gabrielle of February 2023, although more formal testing is still required.

Additionally, the team at GNS Science has developed the Rock Activity Rating System (RoARS) tool, which is a regional-scale model to forecast the increase in rockfall rate after an earthquake and the time it takes to return to pre-earthquake 'baseline' rates (Massey et al. 2022). This can be useful for monitoring a road, railway line or river and whether a blockage can be expected.

Another tool developed by the GNS Science team is the Fahrböschung (F-) angle tool to estimate a runout angle for determining runout distance (Brideau et al. 2021a, 2021b). This can help determine whether the runout will be hazardous, for example, for travel to a house or across the road, and assess the urgency in evacuating or developing an EWS.

3.2.3.2 Global Forecasting Tools

A global-scale prediction tool has been developed overseas to estimate the distribution of coseismic landslide hazard within minutes of the occurrence of any earthquake worldwide for which a USGS ShakeMap is available (Nowicki Jessee et al. 2018). Nowicki Jessee et al. (2020) built on this global-scale prediction tool by using the United National Human Development Index as a vulnerability proxy to produce estimates of human impact (e.g. injuries and deaths) from earthquake-induced landslides. Vulnerable communities can use the outputs from the tool developed by Nowicki Jessee et al. (2020) to improve land-use planning, structural design and emergency response. It may also be used to identify areas that need an EWS.

3.2.4 Co-Design the System

Developing an integrated people-centred EWS requires co-ordination and collaboration across the various stakeholders and levels that have the relevant knowledge and information about hazards, risk and the people and assets that are threatened (Garcia and Fearnley 2012; Golnaraghi 2012). Thus, all stakeholders must be involved in the design of a LEWS to capture and consider the diverse views and expectations of the EWS and to define roles and responsibilities (Scolobig et al. 2017). Any confusion or lack of consideration of these aspects can cause the EWS to fail (Scolobig et al. 2017; Thiebes and Glade 2016).

3.2.4.1 Identifying Partners for Co-Design

When designing an EWS, it is important to consider all socio-technical aspects of the EWS. This requires co-design with all actors that hold the required knowledge, data and technical capabilities to implement the system, as well as the users, such as technical users, emergency planners and responders and the public. Important actions in the co-design process are:

- Co-determine the purpose of the warning system and desired/possible actions (Leonard et al. 2008).
- Identify and integrate detection, monitoring and alerting capabilities (Keys and Green 2008; Leonard et al. 2008).
- Identify the users of the EWS (Brown et al. 2021; Potter et al. 2021).
- Identify the thresholds and/or variables that stakeholders need to know, as well as triggers for action (Leonard et al. 2008).
- Clarify roles and responsibilities (Harrison et al. 2022b; Potter et al. 2021).
- Understand current and future capabilities and funding (Scolobig et al. 2017).

It is especially necessary to develop and strengthen partnerships with the local Iwi/hapū in the landslide risk area when scoping, designing and implementing a LEWS. Such a partnership facilitates knowledge sharing across partners that can result in a locally relevant and effective EWS that is book-ended with community-based preparedness and response plans.

Additional likely actors and partners that would be involved in the EWS are portrayed in Figure 3.3, grouped by sector.

Figure 3.3 Groups of partners and stakeholders likely to be involved in designing a landslide early warning system in Aotearoa New Zealand.

As an example, the development of the ERLAWS for Mt Ruapehu was implemented by the Department of Conservation, with involvement from Ruapehu District Council, Taupō District Council, Ngāti Rangi, Transit New Zealand (now Waka Kotahi NZTA), Genesis Energy, police and the media (Keys and Green 2008). The EWS design process began with the initial consideration of engineering interventions to mitigate the risk at the crater following the prediction of another dam-break lahar (Keys and Green 2008). Ngāti Rangi, a local iwi, strongly opposed interference at the crater rim based on tikanga: concepts of mana, kaitiakitanga and respect for land and natural processes (Keys and Green 2008). Following this, public and agency submissions to the draft environmental and risk assessment from local and national sources further supported options to allow for the lahar to occur naturally but develop alarm and response systems to improve land-use planning (Keys and Green 2008). Detection sensors and triggers were integrated with Genesis Energy and response plans were established with district councils and police to clarify roles and responsibilities (Keys and Green 2008). The effectiveness of the EWS was regularly evaluated through public surveys of the public perceptions of risk and warnings at the ski fields on Mt Ruapehu (Leonard et al. 2008). The co-development approach enabled the transfer of knowledge and development of inter-agency relationships and also provided for a mitigation strategy to evolve (Keys and Green 2008).

3.2.4.2 Engagement and Co-Design Approaches

Social science approaches are available to facilitate the co-design and co-development of a LEWS. GNS Science has utilised stakeholder engagement methods for developing an earthquake-induced landslide forecast tool (Glassey and Saunders 2021). These methods include growing partnerships with the Regional Advisory Group (RAG) and National Advisory Group (NAG), both of which were established to ensure that outputs and tools of the broader MBIE-funded Earthquake-Induced Landscape Dynamics Endeavour research programme are useful, useable and used for earthquake-induced landslide risk mitigation (Glassey and Saunders 2021; Massey et al. 2021a). After initial mapping of outputs and tools, stakeholders, and end-users, targeted engagement using an iterative process for tool development commenced (Glassey and Saunders 2021; Massey et al. 2021a).

The engagement methods included providing presentations on the landslide forecast tool during its development at various end-user forums. Following these presentations, a questionnaire was sent by GNS Science to all members of the RAG and NAG. Feedback was provided from the Department of Conservation, Environment Canterbury, Toka Tū Ake EQC, Kaikōura District Council, NEMA, Waka Kotahi NZTA and West Coast Regional Council (Massey et al. 2021a). The questionnaire asked respondents to identify potential users of the landslide forecast information, uses for the forecast information, preferred format of the forecast information (e.g. PDF versus GIS layers), how soon after an earthquake the forecast information would be needed, and whether any 'guidance' or 'what to do messages' should be included in the advisory product (Massey et al. 2021a). Questions also asked about uncertainty and how best to present the outputs, e.g. either as a probability map or in relation to the area or population exposed to the hazard (Massey et al. 2021a).

Questionnaire respondents identified similar users to those shown in Figure 3.3, with more specific users identified. Specific details were identified by the participants, including using probability maps, developing runout models, and the desire to have data-sharing agreements in place for the forecast outputs (Massey et al. 2021a). The results from this questionnaire were then used to improve the design of the landslide forecast tool outputs and products to match the users' needs (see Massey et al. [2021a] for more details).

In a different example from Austria, Scolobig et al. (2017) utilised a discourse analysis methodology to understand conflicting perspectives of and technical policy options for designing a LEWS. The discourse method they used consisted of three stages portrayed in Figure 3.4. From this process, three design options for a LEWS were identified that each reflect the values and perspectives of the stakeholders and the problems and solutions that the stakeholders identified: (1) a minimal and cost-effective warning system, (2) a technical expert warning system and (3) a resident-centred and integrated warning system.

The results from this process demonstrate that a stakeholder engagement process need not be based on a 'best' technical solution, and the results of this process provide a foundation for subsequent stakeholder deliberations (Scolobig et al. 2017). This study further provides evidence of the need to understand and resolve governance challenges associated with EWSs and the requirement for understanding the plurality of values and preferences through engagement and co-design (Scolobig et al. 2017).

1. Establish Background Context

- Demographic information from the census.
- History of landslides from municipal archives and news articles.
- Legislation, regional and municipal policy.
- Local visits to understand the existing systems.
- Informal discussions with civil servants, elected representatives, residents.

2. Stakeholder Engagement and Discourse

- Semi-structured interviews with federal authorities; the mayor; heads of technical, planning and environment departments; emergency management, geology and civil engineering experts; scientific researchers; firefighters and civil protection officers; members of voluntary organisations; residents.
- Topics discussed: early warning system design and emergency management, responsibility allocation, warning communication and decision-making chain, community preparedness, funding for the early warning system, local capacities.

3. Analysis and Design Options

- Qualitative thematic analysis of interviews, looking for key issues of risk awareness, responsibility allocation, costs, funding, technology, emergency planning, resident engagement, communication, transparency.
- Discourse analysis using the theory of plural rationality (also referred to as cultural theory) to understand stakeholder perspectives.
- Three design options were identified: (1) a minimal and cost-effective warning system, (2) a technical expert warning system and (3) a resident-centred and integrated warning system.

Figure 3.4 Stakeholder engagement and co-design process for identifying design options for a local landslide early warning system in Austria (Scolobig et al. 2017).

3.2.5 Establish Agreements, Plans and Protocols

Commitment of the authorities and community is required to ensure the sustainability and longevity of the LEWS (ISO 2018a). Plans and processes can be established based on discussions with all agencies that are required in all components of the warning system, for example, for monitoring networks, alert levels and evacuation or other required actions (WMO 2018).

The commitment, roles, functions and responsibilities must be documented so that each agency involved is empowered to carry out these duties. Memorandums of Understanding (MOU) and SOPs can help to formalise the standardised process and roles and responsibilities of all agencies involved (WMO 2018). SOPs should:

- Contain the procedures and guidelines for the disaster preparedness team, individuals and local authorities responsible for responding to alerts issued by the landslide early warning instrument.
- Be prepared based on the discussions and agreements of each division under the direction of relevant stakeholders to follow the flow of warning information delivery mechanism and evacuation commands (Figure 3.5) (ISO 2018a).

The SOP may contain alert levels at which the criteria, action(s) by the preparedness team, action(s) by individuals and action(s) by the local authority are clearly defined in the SOP (ISO 2018a).

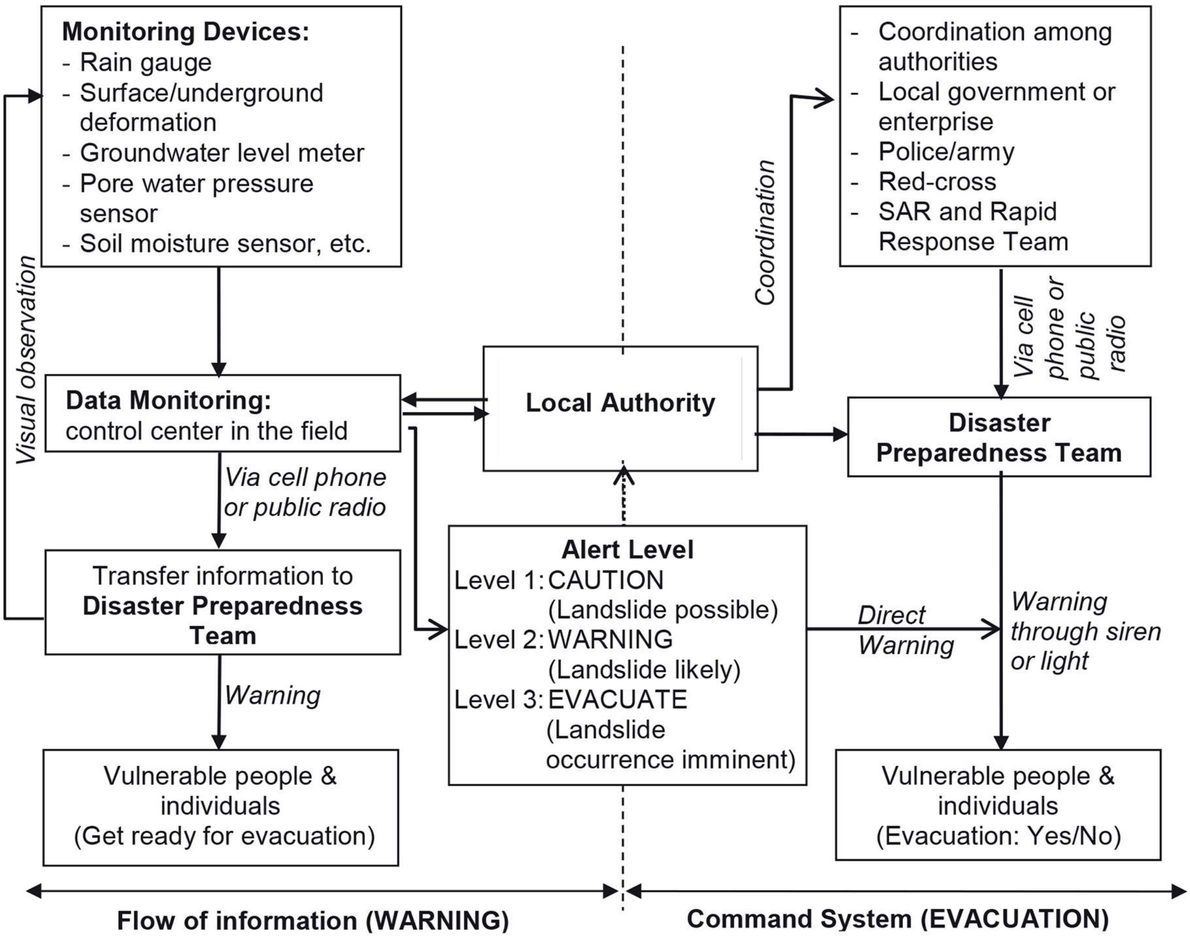

Figure 3.5 Example of the flow of warning information and evacuation instructions laid out by a standard operating procedure (ISO 2018a).

The following activities should be considered for implementing a LEWS (WMO 2018):

- Establish agreements and interagency protocols:
  - for the exchange of monitoring systems data and baseline data needed for certain data products (e.g. topographic data and shaking data for modelling earthquake-induced landslides).
  - to ensure consistency of warning language and communication responsibilities where different hazards are handled by different agencies.
- Establish a multi-hazard co-ordination strategy to obtain mutual efficiencies and effectiveness among different warning systems.
- Ensure that warning system partners, including local authorities and the media, are made aware of and respect which organisations are responsible for generating and issuing warnings.

3.3 Communication and Dissemination Mechanisms

Communication and dissemination mechanisms make up the third component of an EWS (WMO 2018). The key activities are to develop and utilise existing communication networks and channels, develop effective warning messages and train personnel and implement the system.

3.3.1 Develop and Utilise Existing Communication Networks and Channels

Regional, national and local communication systems must be pre-identified and appropriate authoritative voices established (WMO 2018). The use of multiple communication channels is necessary to ensure that as many people as possible are warned, to avoid failure of any one channel, and to reinforce the warning message. There is difficulty with notifying dispersed populations, such as in rural areas. Thus, systems must be appropriate to the population density and be available to the majority of people (Wright et al. 2014). Official alerts should reach 70% of the population, and a further 30% can be expected to receive the alert from those who were officially warned (Mileti and Kuligowski 2008; Wright et al. 2014).

Various channels and formats are available to disseminate warnings. Figure 3.6 illustrates the various options and trade-offs in terms of delivery time versus level of information and audience reach and comprehension versus data volume (WMO 2021). A comparative analysis of 29 public-alerting mechanisms is also available in *Public Alerting Options Assessment Information for the CDEM Sector [IS 10/09]* (MCDEM 2009). Key considerations to make when selecting the most appropriate alerting methods and channels as identified by Wright et al. (2014) are summarised in Table 3.5. In some cases, agreements are required to utilise private sector resources (e.g. mobile-cellular satellite, television, radio broadcasting, amateur radio, social media, mobile phone alerts) for warning dissemination (WMO 2018). Maintenance and upgrade plans must also be built into the design of a LEWS (WMO 2018).

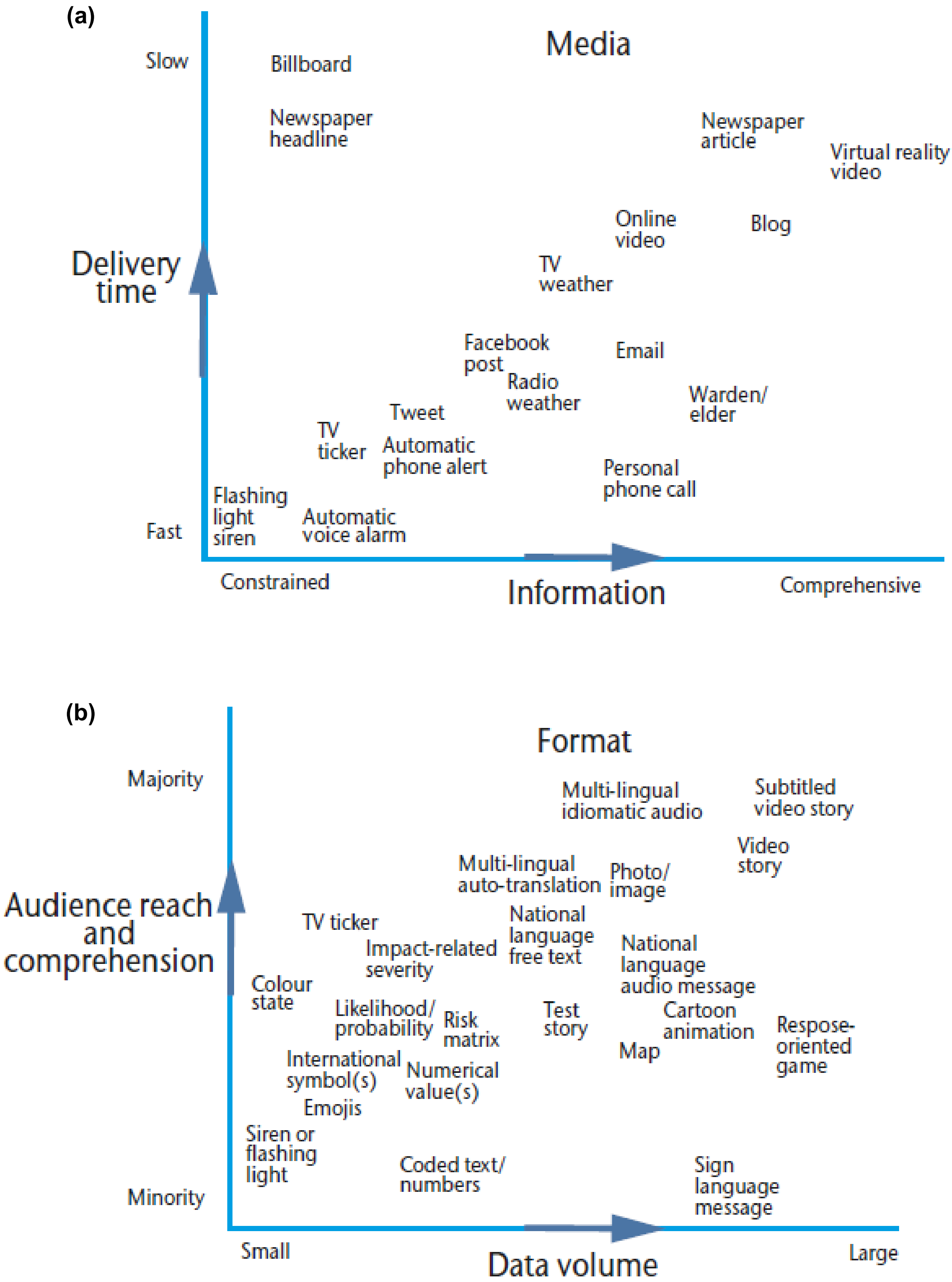

Figure 3.6 Media (a) and formats (b) for disseminating warnings (WMO 2021).

Table 3.5 Aspects and considerations to make when selecting alerting methods and channels (Wright et al. 2014).

Aspect	Considerations
Timeframes	• What monitoring capability exists for each hazard, who monitors it and is it monitored 24/7? • What constitutes a problem or potential problem and who makes this decision? • When issuing an alert, is it intended to signal an 'advisory' or a 'warning'? • How is decision-making and the timeframe between detecting to alerting to impact planned for? • How long are precursory periods planned for by emergency managers and the public? • How to ensure that alerts are received against a backdrop of activity? • How to respond to escalation and reduction of hazard activity? • How to respond to false alarms and provide information?
Spatially varied hazards	• Hazards events potentially affecting a region have varied possible spatial extends within the region. Flooding and slope instability can affect specific areas over most of the region. • Several hazards can potentially affect any part of the region equally.
Ability to apply nationally	• The ability to apply alerting options consistently throughout Aotearoa New Zealand depends on the appropriateness of the system to the national hazard profile; the capacity of the alerting agencies to implement it; and the capacity for communities to receive the alerts, make appropriate decisions and effectively respond.
Notify at least two thirds of those at risk throughout the area	• Aim for the first official alert to reach 70% of the population. A further 30% can be expected to receive the warning through their social networks. • Alerts must be distributed throughout the population to allow for the informal warning to spread effectively.
The coverage of the system will overlap	• Unless the proportion of coverage overlap amongst systems is clear and guaranteed, one (or preferably more) alerting system(s) should by itself reach 70% of the population even if multiple alerting channels are present.
Use multiple systems	• All systems have a potential failure. Use multiple systems for redundancy and to diversify alert delivery to reach different demographics.
Geographic targeting and population density	• Some alerting systems can be physically targeted to specific geographic audiences (e.g. sirens, loudspeakers, cell broadcast, some mobile apps, emergency mobile alerts). • Other options with a single region-wide application can contain area-specific messages (e.g. radio, television, internet). • At times, at-risk populations can increase markedly in certain locations (e.g. tramping huts in summer, crowds at sports events).
Who is being warned and when?	• Consider whose needs have to be served in the alert system. Is the alert intended for emergency management agencies, citizens, community groups, societal institutions, media and/or businesses? • Different sub-populations have differing levels of vulnerability and respond differently to alerts. Ensure that each group knows what the alerts mean and that they have capacity to act upon them. • Account for the activities that individuals might be involved in at the time of the alert, as this can affect how quickly they can receive an alert and respond to it.
Other sources of information	• The media constitutes a significant influence on people's perceptions of hazard characteristics and their consequences and can exercise a strong influence on people's beliefs and attitude towards alerts.

The commonly used alerting methods for LEWSs are provided in Table 3.6, along with the advantages and disadvantages of each.

Table 3.6 Advantages and disadvantages of common alerting methods used in landslide early warning systems based on a literature review by Massey et al. (2020a).

Alerting Method	Advantages	Disadvantages
Door knocking with verbal notification	Ensures clear communication and direct delivery of the required responses, with minimal confusion.	The notifications take time to deliver.
Text messaging (SMS) and email	Can rapidly deliver clear messaging with advice.	Rely on mobile phone networks and/or internet connectivity.
Sirens and flashing lights	Do not rely on phone networks and can be rapidly triggered if a tripwire is broken, with no need for processing data from instruments and running models.	Can cause confusion about how to act and thus require intensive public education and awareness so that audiences know how they should act if the sirens or lights are activated (Tan et al. 2021).

Alerting authorities use standards and protocols to transmit warnings. The Common Alerting Protocol (CAP) is an international standard format for emergency alerting and public warning, developed by the International Telecommunication Union. It is an XML-based open, non-proprietary digital message format for exchanging emergency alerts (MCDEM 2018). The CAP is designed for 'all hazards', that is, hazards related to weather events, earthquakes, tsunami, volcanoes, public health, power outages, and many other emergencies (WMO 2018). If multiple alerting platforms will be used, then inter-operability of the platforms with each other and with other alerting options is critical. The CAP can facilitate this inter-operability. A Technical Standard is available from NEMA to represent the current collection of specifications and recommended practises related to the standardisation of public alerts in Aotearoa New Zealand using the CAP standard (see MCDEM [2018]).

3.3.2 Develop Effective Warning Messages

The purpose of an EWS is to provide the most important information to warning audiences to allow them to make informed decisions to protect themselves and their assets. This requires communicating the results of the complex models and forecasts in the form of meaningful messages and advisories (Guzzetti et al. 2020). The content and format of effective warning messages should be developed using an evidence-based approach and should be relevant and suitable to the audiences of the warning system.

3.3.2.1 Designing Warning Messages

People may or may not respond to a warning in the way they were directed to for many reasons (Potter 2018). A warning receiver's characteristics (Figure 3.7) influence how prepared they are for hazardous events and how they respond to warnings (Lindell and Perry 2012; Potter 2018). Receiver characteristics include:

- age
- gender
- primary language
- mental models (i.e. general understandings and misconceptions)

- physical abilities (e.g. strength, hearing, vision)
- economic resources (e.g. money, vehicles), and
- social resources (e.g. family, friends, co-workers, neighbours [Lindell and Perry 2012; Potter 2018]).

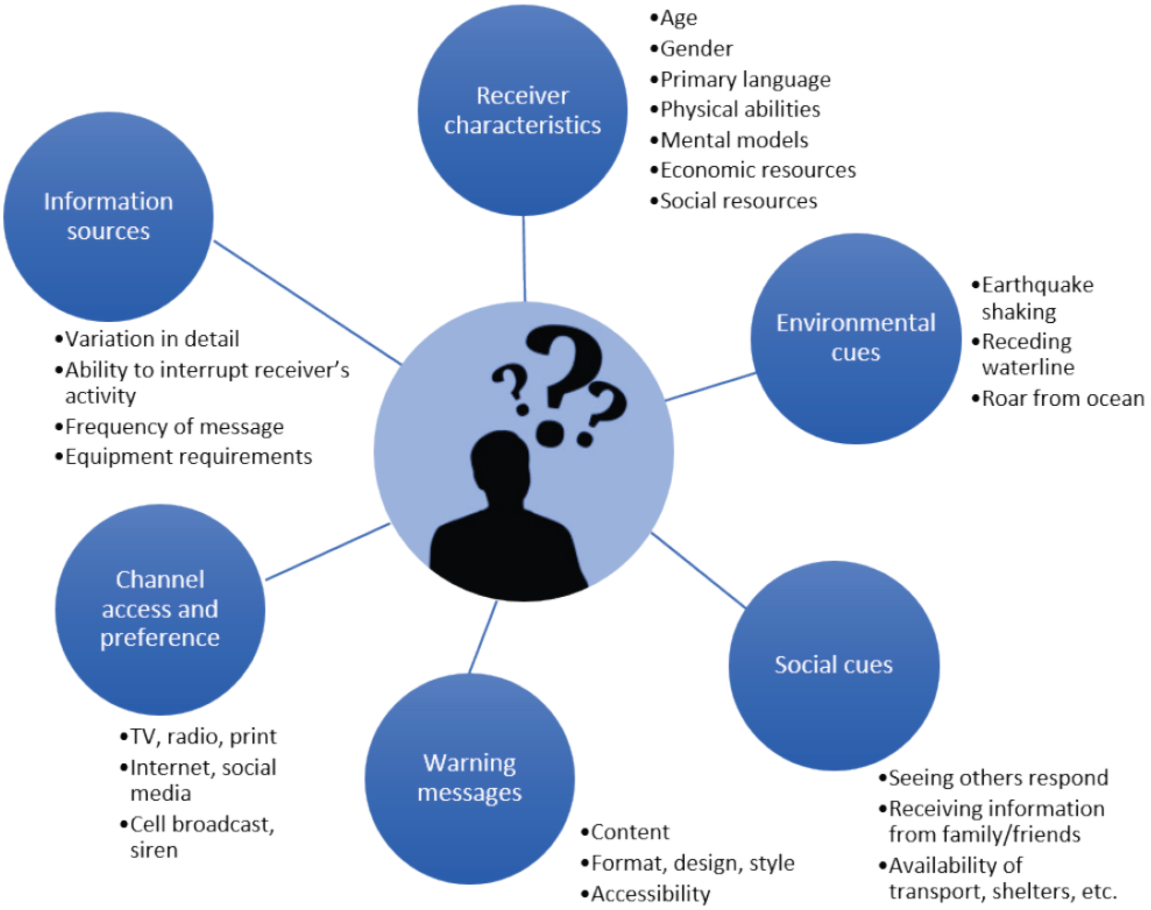

Figure 3.7 Factors that influence pre-decisional processes toward protective actions. Based on the Protective Action Decision Model (Lindell and Perry 2012). Examples of each influence are provided (image and text source: Potter [2018]).

When a hazard is occurring or is about to occur, environmental cues (Figure 3.7) can influence a person to respond (Lindell and Perry 2012; Potter 2018). For example, environmental cues that a landslide, rockfall or debris flow is imminent or occurring can include:

- doors and windows of a house not closing
- new cracks appearing in the cladding and/or on paved surfaces
- changes to the hills immediately above or in the ground around a person's property, or
- bulging ground (see Carey 2022).

Some environmental cues are difficult for people to understand and link to the threat, but social cues (Figure 3.7) can also prompt a person to respond (Lindell and Perry 2012; Potter 2018). These can include:

- seeing others respond to the hazard
- receiving information about the hazard from other members of society, and
- having resources available to aid response (e.g. transportation or public shelters [Lindell and Perry 2012; Potter 2018]).

Channel access and preference also influence the response to a threat (Lindell and Perry 2012). Channels (such as radio, TV, print media, social media, siren, cell broadcast alerts and face-to-face) vary in the level of detailed information they contain, the precision of the message, the number of people they are received by and how much it interrupts their activities, the frequency that the message is disseminated, the ability to verify that the message has been received, and the equipment requirements (Potter 2018). Information sources vary in terms of whether the message is disseminated directly to members of the public or through intermediate sources (such as the media or community leaders) (Potter 2018). In the previous section (3.3.1), we summarised the public-alerting options for Aotearoa New Zealand.

It is recommended that warning authorities ensure that warning messages are targeted, specific, accurate, clear, culturally appropriate, consistent, informative, have doable outcomes, and contain all the right elements (e.g. source, guidance, hazard, impacts, location and time), as shown in Figure 3.8 (Potter 2018). Figure 3.8 also shows that the suggested order of the elements varies depending on the length of the messages. However, it is more important that the message is clear.

Messages with up to 150 characters should use the following order:	Messages between 151 and 500 characters should use the following order:	Messages between 501 and 1395 characters should use the following order:
• Source	• Source	• Source
• Guidance	• Hazard	• Hazard
• Hazard	• Impacts	• Impacts
• Impacts	• Location	• Guidance
• Location	• Time	• Location
• Time	• Guidance	• Time
• Link to further information	• Link to further information	• Link to further information

Figure 3.8 Order of messages: templates (Potter 2018).

3.3.2.2 Consistent Messaging

Writing communication and warning plans ensure the consistency and relevancy of the warning messages. NEMA has provided nationally agreed, consistent messages for all Civil Defence organisations and emergency services to use (see NEMA 2023).

The consistent messages provided by NEMA are presented in two parts. Part A provides consistent messages for general information and pre-disaster preparedness. This covers household emergency plans; emergency survival kits and getaway kits; first aid kits and first aid kits for pets; and evacuation, sheltering in place and post-disaster safety (NEMA 2023). Part B provides hazard-specific consistent messages.

Landslides are one of the hazards covered by these consistent messages (NEMA 2023). While this resource does not provide guidance for specific landslide warning messages, it offers a basis for providing general information about landslide hazards that can be used to inform warning messages and any public engagement campaigns to raise education and awareness of a LEWS if one is implemented.

3.3.2.3 *Alert Levels*

Alert levels can be used to communicate risk levels based on the likelihood and severity of the landslide hazard in a standardised way; however, they may not be appropriate or needed in all situations. Guzzetti et al. (2020) found that most regional and national LEWSs adopt an escalating approach where the information is first used internally to analyse the situation and make decisions such as to perform further analyses, change the monitoring frequency, consult with experts, or call additional personnel. When the pre-defined monitoring thresholds (Section 2.2) are reached or exceeded, or based on consultation, the information is then passed to the authorities, who may take actions, including disseminating the forecast information to the public.

The number of alert levels can be determined based on the audience(s) of the EWS, scale of the EWS, uncertainty associated with the forecast and capability to make decisions based on uncertain forecasts (Guzzetti et al. 2020). In a global literature review of regional and national scale LEWS, 26 were found to use between two and five alert levels to address three main audiences: (1) an internal audience; (2) the authorities, such as Civil Defence and emergency management groups, elected officials, critical infrastructure asset managers; and (3) the public (Guzzetti et al. 2020). As summarised in Table 3.4, most local-scale LEWS use two to three alert levels (Pecoraro et al. 2019), and most national- and regional-scale LEWS use three or four alert levels (Guzzetti et al. 2020). Furthermore, most national- and regional-scale LEWS use two levels for internal audiences or authorities, while public-facing regional- and national-scale LEWS use four or three alert levels (Guzzetti et al. 2020).

Research suggests that three to four alert levels for national and regional LEWS are a reasonable compromise between the complexity and uncertainty of operational landslide forecasting and the need to provide effective information to authorities and the public, who typically are not landslide experts (Guzzetti et al. 2020). Recognising that the number of alert levels may be dictated by organisational or legal constraints, landslide forecasters and LEWS managers are encouraged to decide the number and characteristics of landslide alert levels based on optimisation procedures where possible (e.g. Guzzetti et al. 2020; Piciullo et al. 2017a, 2017b).

Alert levels are often communicated using the international traffic light colour scheme (e.g. green, amber, red), with the number of colours varying with the number of alert levels (Guzzetti et al. 2020). While these colours are generally recognised and understood worldwide, possible problems arise for colour-blind people (Guzzetti et al. 2020). Additionally, green is typically associated with being safe; however, if green represents the first alert level, where landslides are not likely but their occurrence cannot be ruled out, the green colour may create a false sense of security (Guzzetti et al. 2020). Therefore, careful consideration is needed to assign intuitive and appropriate colours to the alert levels (e.g. Potter et al. 2014). Other alert-level systems use words (such as Aotearoa New Zealand’s MetService Advisory, Watches and Warnings), symbols and numbered systems (including Aotearoa New Zealand’s Volcanic Alert Level System [Potter et al. 2014]). More research is needed on what is the most effective design of alert-level systems to achieve appropriate behavioural responses.

Selecting the appropriate language used in alert-level systems is important as well. Confusion can arise when the language is not standardised and terms are not defined (Guzzetti et al. 2020). LEWS managers should adopt standard vocabulary to define the advisory levels and the messages associated to each level to minimise confusion and ambiguity (Guzzetti et al. 2020). Providing the message(s) in languages that are relevant to the communities that are at risk is also critical to build response capacity (Cherry and Allred 2012; Nguyen and Salvesen 2014; Yong et al. 2017).

3.3.2.4 Uncertainty

Landslide forecasting and warning contains much uncertainty due to the pre-existing uncertainty present in forecasting the triggering hazards, such as rainfall and/or earthquakes (Guzzetti et al. 2020). The level of uncertainty in a landslide occurring, its severity and how that uncertainty is communicated to audiences can affect the warning performance. For example, uncertainty caused by errors in landslide-triggering instances were found to significantly impact the performance of a LEWS by potentially increasing the occurrence of false positives (Peres et al. 2018).

Technology has made it possible to reduce uncertainty but not eliminate it altogether. Improving the communication of likelihood, forecasts or warning messages in uncertain contexts such that the information can be used effectively is critical to improve perceptions and understanding of warnings (Losee et al. 2017). Landslide forecasters are encouraged “to incorporate and propagate model uncertainties in their forecasts” (Guzzetti et al. 2020). Communicating uncertainty in a way that reduces cognitive load can improve warning recipients’ trust and expectations and, ultimately, compliance and decision quality (Joslyn and LeClerc 2013; LeClerc and Joslyn 2015). For example, research has found that that the provision of probabilistic forecasts resulted in meteorological forecasters issuing wind advisories when the probability of strong winds was high, whereas, before the forecasters received the probabilistic information, they tended to issue too many advisories with low probabilities and too few advisories with high probabilities (Joslyn et al. 2007).

3.3.3 Train Personnel to Implement System

Implementation of a LEWS must include training activities. Experience is invaluable for forecasters and scientists to aid their decision-making under uncertainty (Doswell 2004; Fearnley 2013; Morss et al. 2015; Potter et al. 2014). Education and training activities help to develop this experience to increase the confidence of the forecasters and scientists who have to make critical decisions for issuing warnings at the proper time and location (Doswell 2004; Doyle 2011; Fearnley 2013; Roebber and Bosart 1996). Examples of training activities that have proven to be useful for building experience and important skillsets for EWS and emergency response are listed in Table 3.7.

Table 3.7 Training activities for forecasters, scientists and other personnel involved in the landslide early warning system decision-making process.

Training Activity	Description	Source
Role-play games	Role-playing games and simulations with researchers, developers, forecasters and other stakeholders involved in the decision-making process for warnings provides a fun and interactive learning tool to enhance participants' understanding of the complexities and challenges for various actors in the decision-making process, to identify opportunities or solutions to overcome those challenges in a low-risk environment and to increase collaborative capacity.	Dohaney et al. (2018), Terti et al. (2019); Weyrich et al. (2021)
Cross-training	Cross-training involves specific activities to enhances an individual's awareness and knowledge of their team members' tasks, duties and responsibilities. These activities are: (1) providing specific information about other roles and responsibilities in the team, (2) discussing and observing team members' behaviours in their given role(s) and (3) allowing team members to spend significant periods of time performing other team members' jobs and roles. These activities facilitate the holistic understanding of team functioning and the interdependent role of a given agency within a multi-agency team.	Doyle et al. (2015)
Scenario planning	Scenario planning involves creating multiple scenarios of 'different futures' in ways that specifically accommodate the perspectives of multiple agencies. This activity enables the integration and awareness of social, political, economic, cultural and other environmental forces that underpin the expectation of the different agencies involved in the response.	Doyle et al. (2015)

Various resources are available from NEMA[6] to design training exercises and build capabilities for emergency management, including the Director's Guideline that provides a general approach to writing and managing exercises (MCDEM 2019a). The three critical steps to running exercises as outlined by NEMA are: (1) design the exercise, (2) conduct the exercise and (3) evaluate the exercise. These resources may be useful for designing exercises for training and capability development for a LEWS.

3.3.4 Evaluation

Evaluation of communication strategies is necessary to ensure that messages are reaching the population and ascertain whether the communication equipment is able to withstand an extreme event (WMO 2018). Evaluation activities can involve:

- Testing the functionality of the communication networks (e.g. testing sirens, hazard lights, emergency mobile alerts).
- Ascertaining the reach of the warning communication and dissemination systems to the population (including seasonal populations and remote locations [WMO 2018]).
- Evaluating the warning messages and other associated content, for example, through public surveys, interviews and other social science research methods (Potter et al. 2018a; Taylor et al. 2019; NWS 2011).

6 https://www.civildefence.govt.nz/cdem-sector/exercises/resources/

Communication should be two-way to ensure that messages are received, appropriate and useful. Two-way communication can allow forecasters and warning services to determine how messages are being received and understood and thus update these accordingly. Social media can facilitate this two-way communication, whereby forecasters and warning services can monitor how their messages are being shared and discussed and engage in the conversation to ensure that messaging is being received and understood (Demuth et al. 2018; McBride and Ball 2022).

3.4 Preparedness and Early Response Capacity

Building preparedness and response capacity is key to developing community resilience and is thus the fourth component of an EWS. The key activities in this component are co-developing preparedness and response plans and carrying out education and awareness campaigns to ensure uptake and understanding of the EWS and its various components.

3.4.1 Preparedness and Response Plans

Reducing impacts and saving lives is not just dependent on the delivery of a warning message – understanding the warning; knowing what to do; and having the physical, psychological and/or financial capacity to take appropriate action are also critical factors as to whether and how people respond to a warning message (Spahn et al. 2010; Perera et al. 2020). Establishing relevant and clear preparedness and response plans can build the early response capacity and help to identify opportunities for building or enhancing individuals' or communities' response capacities. For example, the process of developing preparedness and response plans can reveal a lack of shelters or safe zones that must be built or established, or it can highlight individuals in the community who are unable to evacuate on their own due to mobility barriers, thus creating an opportunity to develop community-based solutions that are targeted at the most vulnerable people.

Emergency management plans must be developed and updated based on the risk assessment. The ISO guidelines for implementing a community-based LEWS also recommend a disaster preparedness team that consists of a chair and others with expertise in data and information management, early warning and mass evacuation systems, first aid, logistics and security (ISO 2018a). CDEM Groups throughout Aotearoa New Zealand have much of this knowledge and capability, thus it will be important to involve the appropriate CDEM Group in this process. Community groups and leaders, including iwi/hapū, may also be involved to ensure representation of the various needs in the community. Preparedness and response plans are essential for increasing individuals' and communities' readiness to respond to the landslide hazard(s) and the respective warnings and messages (Johnston et al. 2016; Vinnell et al. 2020).

3.4.1.1 Co-Development of Preparedness and Response Plans

Preparedness and response plans should be co-developed and targeted at vulnerable members of the community (ISO 2018a; WMO 2018). The co-development process should involve locals and experts who, together, identify evacuation zones, routes, safe areas and assembly points and develop and design evacuation maps (ISO 2018a; WMO 2018). In Mexico, community-based mapping workshops with children in peri-urban mountain areas enabled the co-production of disaster risk knowledge and landslide exposure (Ruiz-Cortés and Alcántara-Ayala 2020). The community-based mapping activities produced useful maps that inform disaster risk management, represent how the local children view their geographic space, and transform these views to personal and communal awareness of disaster risk (Ruiz-Cortés and Alcántara-Ayala 2020).

3.4.1.2 Evacuation

In Aotearoa New Zealand, the NEMA website provides guidance for evacuation planning and management (NEMA [2023b]). The guidance refers to Sections 73–78 of the Civil Defence Emergency Management (CDEM) Act 2002, Section 23 in *The Guide to the National Civil Defence Emergency Management Plan* and the Mass Evacuation Planning Director's Guideline (MCDEM 2008), all of which details the guiding principles, objectives and decision requirements for evacuations. More specifically, the Mass Evacuation Planning Director's Guideline was prepared to help CDEM Groups, local authorities and other emergency management agencies with designing, implementing and promoting evacuation plans. While the guidelines are focused on planning for large-scale evacuations, the principles can be applied to planning evacuations of any size (NEMA [2023b]).

In line with the ISO Guidelines (2018a) the Mass Evacuation Planning Guideline states that engaging with stakeholders in the evacuation planning process is necessary to ensure that:

- All aspects of planning are considered.
- There is 'buy-in' from the community and key stakeholders.
- The community and stakeholders understand the evacuation plan in detail (through participation).
- All key organisations have their own procedures in place for evacuations.
- All key organisations' plans are integrated.
- Any deficiencies in resources are identified and addressed accordingly (MCDEM 2008).

The roles and responsibilities for evacuation management are set out in the National CDEM Plan (MCDEM 2015) as:

> ***141 Management of evacuation***
>
> *(1) Evacuations are managed at the local level in the affected area and are supported, and may be co-ordinated, by the [Emergency Coordination Centre].*
>
> *(2) Co-ordination and support at the national level for evacuations will be provided when CDEM Group capability is overwhelmed.*
>
> *(3) Further information on the management of evacuation is provided in The Guide.*

According to the ISO (2018a) guidelines, evacuation maps and routes should be developed as operational guidelines for the disaster preparedness team and the community to leave the risk zone, follow a pre-determined route and gather at a pre-determined assembly point. The identification of landslide risk zones should be identified from a risk assessment (as described in Sections 2.0 and 3.1) and should inform the evacuation map (ISO 2018a).

The evacuation map should provide the following information (MCDEM 2008; ISO 2018a):

- High-risk, impact or evacuation zones
- Low-risk (safe) zones
- Evacuation route(s) and the direction of travel along the evacuation routes
- Assembly point(s)
- Location of shelters and welfare centres

- Warning signals and sources of information
- Locations of EWS installation points
- Alert posts
- Residences, including the estimation of the number of residents in each
- Community facilities: schools, places of worship, community health centres, offices, markets and landmarks
- Streets and alleys.

Engaging with local communities and community groups during mapping activities should be done to collect data based on local knowledge around which roads are likely to be flooded and who is likely to need special assistance during an evacuation (MCDEM 2008). Furthermore, local authorities within a region, and the CDEM Group, should consider co-ordinating their GIS mapping activities due to the cross-boundary issues likely to arise during a hazardous event (MCDEM 2008).

3.4.1.3 Evacuation Drills

After developing the evacuation plan, education and evacuation drills are necessary to ensure that the individuals understand the evacuation plan and maps and know the evacuation routes. Key activities for this are described in the next section (3.4.2). The maps should be designed such that they are intuitive and easily understood, with all critical cartographic elements provided and organised to ensure readability (Thompson et al. 2018).

It is also important to evaluate the effectiveness of the preparedness, response and evacuation plans. Evacuation drills provide an opportunity to analyse responses and measure the effectiveness of both the maps and drills and improve either product or activity as required. For example, social scientists in Aotearoa New Zealand continue to evaluate awareness of and participation in tsunami evacuation dills (tsunami hīkoi [Johnston et al. 2016]) and ‘drop, cover, hold’ earthquake drills (Vinnell et al. 2020). These studies help to inform the design of education and awareness campaigns to increase individuals’ and communities’ readiness to these hazards.

Post-event analyses should also be undertaken to identify lessons and update procedures. An example of a post-event analysis and the lessons learned is that of the organisational response to the 2007 Ruapehu Crater Lake dam-break lahar to assess the effectiveness of planning for and responding to the lahar (Becker et al. 2018). The results of the analysis highlighted how good communication contributed to an effective emergency response and that planning and exercising developed effective internal communications and engendered relationships (Becker et al. 2018). The study also found that more effort could have been given to develop and integrate public information about the lahar, which would have eased understanding about the event and integration of information across agencies (Becker et al. 2018).

3.4.2 Education and Awareness

The purpose of education and awareness campaigns is to disseminate knowledge and improve the communities’ or individuals’ comprehension and understanding about landslide hazards and their risks, as well as to build an understanding of the communities’ aspirations (ISO 2018a; WMO 2018). Improving people’s understanding of disaster management, reinforcing risk governance and investing in programmes that foster adaptation and resilience can reduce vulnerabilities to landslide impacts (Antronico et al. 2020). Knowledge dissemination methods and materials should be developed based on the disaster risk assessments (ISO 2018a).

The community should be provided with information on (ISO 2018a):

- Types of landslide disasters.
- How and why these occur.
- Factors that control and trigger the event(s).
- Structural and non-structural strategies to mitigate the consequences of landslides, including an EWS, the warning levels and associated signage.

The dissemination of knowledge should use clear language, provide useful information, identify the authoritative agency and provide multiple communications methods to ensure that the maximum number of people is reached (see Section 3.3) (ISO 2018a). The education and awareness campaigns may also lead to the identification of the key people who are interested in participating in a disaster preparedness team (ISO 2018a).

Key activities for education and awareness campaigns named in the ISO guidelines and tested in research for landslides, earthquakes and tsunami are summarised in Table 3.8. The activities designed for non-landslide hazards can provide a template to design landslide-specific activities. Mātauranga Māori in Aotearoa New Zealand is important to ensure that the EWS and accompanying education and awareness resources and campaigns are appropriate and relevant to the values of the local iwi/hapū. This is shown through work by Kaiser and Boersen (2020) with kura kaupapa Māori for tsunami preparedness and additional work by Kaiser et al. (2020) to co-design a bilingual pukapuka (book) based on Ngāti Kahungunu iwi pūrākau that relate to natural earthquake warnings and preparedness within their region. Each of these activities can empower individuals, communities and organisations to participate in the EWS.

Table 3.8 Summary of education and awareness activities to engage with, inform and empower individuals and communities about landslides hazards and landslide early warning system.

Activity	Examples	Source(s)
Prepare and make accessible background information on landslides (types, historical events), impacts, mitigation options, ‘what to do’ messages, warning levels, false alarms, local information	The consistent messaging resources provided by NEMA offer a starting point for developing these materials. Providing information in different languages to ensure that the message reaches the diverse groups across the country is another strategy to make the information more accessible.	Cherry and Allred (2012), NEMA (2023), Nguyen and Salvesen (2014), Yong et al. (2017)
Community-based landslide mapping	Community-based mapping activities can raise education and awareness of local landslide hazards and risks and produce resources that have been developed by the community, thus empowering the community through a sense of ownership.	Ruiz-Cortés and Alcántara-Ayala (2020)
Train communities on the natural warning signs and appropriate actions	The ‘long or strong, get gone’ campaign educates individuals on natural warning signs of tsunami.	Dhellemmes et al. (2021), NEMA ([2023a]); Vinnell et al. (2022a)
Inform communities about the LEWS	Educate the public about the thresholds and alert criteria, different alert levels and associated colours, prescribed actions, alerting mechanisms (e.g. sirens, lights, emergency mobile alert) such that they know, for example, what a siren, hazard light or the alert level colours mean, and what protective actions to take in response to each alerting mechanism.	Tan et al. (2021), Taylor et al. (2019)
Target campaigns to specific audiences and needs (e.g. schools, farms, emergency managers, media, infrastructure companies)	A Māori-led, bi-cultural approach was taken to create culturally and locally relevant materials for ākonga (students) and kura kaupapa Māori and give ākonga a pro-active role in making their communities better prepared for a tsunami event. Simulation tools and scenarios offer engaging training tools for emergency managers.	Chaturvedi et al. (2018); Kaiser and Boersen (2020)
Practice evacuation drills	Drills such as ‘drop, cover, hold’ and tsunami evacuation hīkoi with school children develop the procedural knowledge to perform appropriate protective actions in response to earthquakes and tsunami, respectively.	ISO (2018a), Johnston et al. (2016); McBride et al. (2019); Vinnell et al. (2020)
Develop interactive simulations	Simulations that provide experiential feedback to participants can improve their decision-making around landslide mitigation and preparedness.	Chaturvedi et al. (2018)
Evaluate and update strategies/programmes regularly	The ‘drop, cover, hold’ drill and tsunami evacuation hīkoi in Aotearoa New Zealand are regularly evaluated to identify barriers to people acting on them, such that solutions and alternatives can be developed to increase accessibility.	Johnston et al. (2016), McBride et al. (2019), Vinnell et al. (2020)

4.0 DECISION SUPPORT TOOLS FOR LANDSLIDE EARLY WARNING SYSTEMS

Landslides are highly complex due to their multiple triggers (e.g. rainfall and earthquake), contributing factors (e.g. deforestation, slope stability, soil and soil moisture) and variability in spatial and temporal scales (e.g. slope scale, regional scale, rapid or slow mass movement). This makes it difficult to design a 'one size fits all' LEWS. As such, a number of tools have been developed both within Aotearoa New Zealand and overseas to support the decision-making process for designing and implementing a LEWS. These tools are summarised in Table 4.1 and are described next within the context of the EWS component(s) that they could inform.

Populating hazard inventories and databases is critical action for developing risk knowledge for a LEWS. The 2016 Kaikōura Landslide Inventory Version 2 and accompanying webmap to view and access the inventory are two useful tools in this component that have been developed by the EILD team and provide the underpinning data to develop further understanding of landslide risk in Aotearoa New Zealand.

Risk modelling, such as RiskScape (an open source, Aotearoa New Zealand -based risk modelling software package) provides a quantitative approach to assess the risk of landslide for both short- and long-term planning and to rapidly assess the impact of a landslide event pre- or post-event. For example, scientists at GNS Science used RiskScape to estimate the likely economic and human losses due to landslides impacting households in Wellington, Aotearoa New Zealand (Massey et al. 2019). This work can inform decision-making around the need for a LEWS and other mitigative solutions.

Immediately after any earthquake, using the outputs of the earthquake-induced landslide forecast tool to indicate the intensity and likely location of landslides, risk models can be used to identify areas that could be susceptible to additional landslides and so in need of a temporary or long-term LEWS. By combining rainfall forecasts in real time with landslide forecast tools, and increasingly using RiskScape to calculate the potential impacts, impact forecasts for rainfall-induced landslides can be given ahead of the rainfall event occurring. This provides the opportunity for users to have situational awareness of areas likely to receive landslide-related impacts so that they can take anticipatory actions and mitigate the risk of landslides as best as possible. This approach was taken during ex-Tropical Cyclone Gabrielle in February 2023, where impact forecasts for the roading network and residential properties were delivered to emergency management, along with landslide forecasts.

Additional tools can also be used, in combination with risk models and other analytical tools and techniques, to further assess the needs of a LEWS. For example, the outputs of the F-angle and RoARS tools, combined with asset data such as building locations and structure (e.g. through RiskScape) can help to determine the vulnerability of buildings and their residents to the impacts of a landslide, thus informing a needs assessment for a LEWS.

Table 4.1 Summary of decision support tools for landslide early warning systems.

Decision Support Tool	Description	Source	EWS Component Informed by this Tool
Landslide inventories (e.g. 2016 Kaikōura Landslide Inventory Version 2[7] and the New Zealand Landslide Database[8])	The Kaikōura Version 2.0 inventory contains nearly 30,000 landslides. The data contains all landslides from Version 1.0, plus additional landslides mapped from the high-resolution aerial photographs. The Version 2.0 inventory is published as points that represent the centroids of the mapped landslide source area. Version 2.0 data is available in both CSV and GIS Shapefile format, projected in the NZGD 2000 New Zealand Transverse Mercator coordinate system.	Massey et al. (2007)	Disaster risk knowledge
Earthquake-Induced Landscape Dynamics (EILD) Webmap[9]	The EILD webmap displays spatial data captured or derived from the project as it becomes available. Some data can be downloaded. The webmap currently has earthquake-induced landslide points generated by the M7.8 2016 Kaikōura Earthquake, as well as earthquake-induced forecast maps for 100-, 250-, 500- and 1000-year return period earthquake shaking for Aotearoa New Zealand.	Massey et al. (2021a, 201b)	Disaster risk knowledge; detection, monitoring, and warning
Risk modelling, e.g. RiskScape[10]	A quantitative approach to (a) assess the risk of landslides and (b) rapidly assess the impacts of landslides.	Massey et al. (2019), Paulik et al. (2023)	Disaster risk knowledge; detection, monitoring and warning
Earthquake-induced landslide forecast tool[11]	To provide rapid advisory information about the 'intensity' and likely location of landslides following a major earthquake in Aotearoa New Zealand.	Massey et al. (2021a)	Disaster risk knowledge; detection, monitoring, and warning
Measuring landslide runout distance (e.g. F-angle tool[12]) and volume of rockfall (e.g. RoARS[13])	The F-angle tool calculates a Fahrböschung angle that can be used, with further analysis, to estimate the runout distance for a certain type of landslide from a slope. The RoARS tool provides indication/forecasts of the magnitude of rock/debris that could fall from a slope (of a given height, angle and area) at different levels of earthquake shaking.	Brideau et al. (2021a, 2021b); Massey et al. (2014, 2022)	Disaster risk knowledge; detection, monitoring and warning

7 https://slidenz.net/data-tools/2016-kaikoura-landslide-inventory-version-2/
8 https://data.gns.cri.nz/landslides/
9 https://slidenz.net/data-tools/webmap/
10 https://riskscape.org.nz/
11 https://slidenz.net/data-tools/earthquake-induced-landslide-forecast-tool/
12 https://slidenz.net/data-tools/empirical-landslide-runout-relationships-data-set-v1-0/
13 https://slidenz.net/data-tools/roars-tool/

Decision Support Tool	Description	Source	EWS Component Informed by this Tool
Instrumentation flowchart (Figure 4.1)	A decision-tree for choosing suitable instrumentation for slope-scale EWSs to facilitate monitoring and detection of land movement.	Intrieri et al. (2013)	Detection, monitoring and warning
Organisational flowchart (Figure 4.2)	To support decisions around the organisation and design of a LEWS, such as threshold levels and number of alert levels.	Intrieri et al. (2013)	Communication and dissemination mechanisms; preparedness and response capabilities
Public Alerting Options Assessment Tool[14]	To support agencies responsible for warnings with deciding on the most appropriate public alerting mechanism(s) in relation to their budget and target areas' hazards and demographics.	MCDEM (2009), Wright et al. (2014)	Communication and dissemination mechanisms; preparedness and response capabilities
Checklist for Aotearoa New Zealand agencies in writing effective short warning messages (Figure 4.3)	To provide best practise for writing short warning messages for the public to achieve a desired behavioural response.	Potter (2018)	Communication and dissemination mechanisms; preparedness and response capabilities

Two decision trees have also been developed in Italy to assist with the identification of instrumentation for slope-scale landslides (Figure 4.1) and for decisions relating to alerts, planning and response to a landslide (Figure 4.2) (Intrieri et al. 2013). The intention is for both decision trees to be used together to support decisions around the organisation of the LEWS. These tools could be useful for designing a LEWS in Aotearoa New Zealand.

14 https://www.civildefence.govt.nz/cdem-sector/guidelines/public-alerting-options-assessment

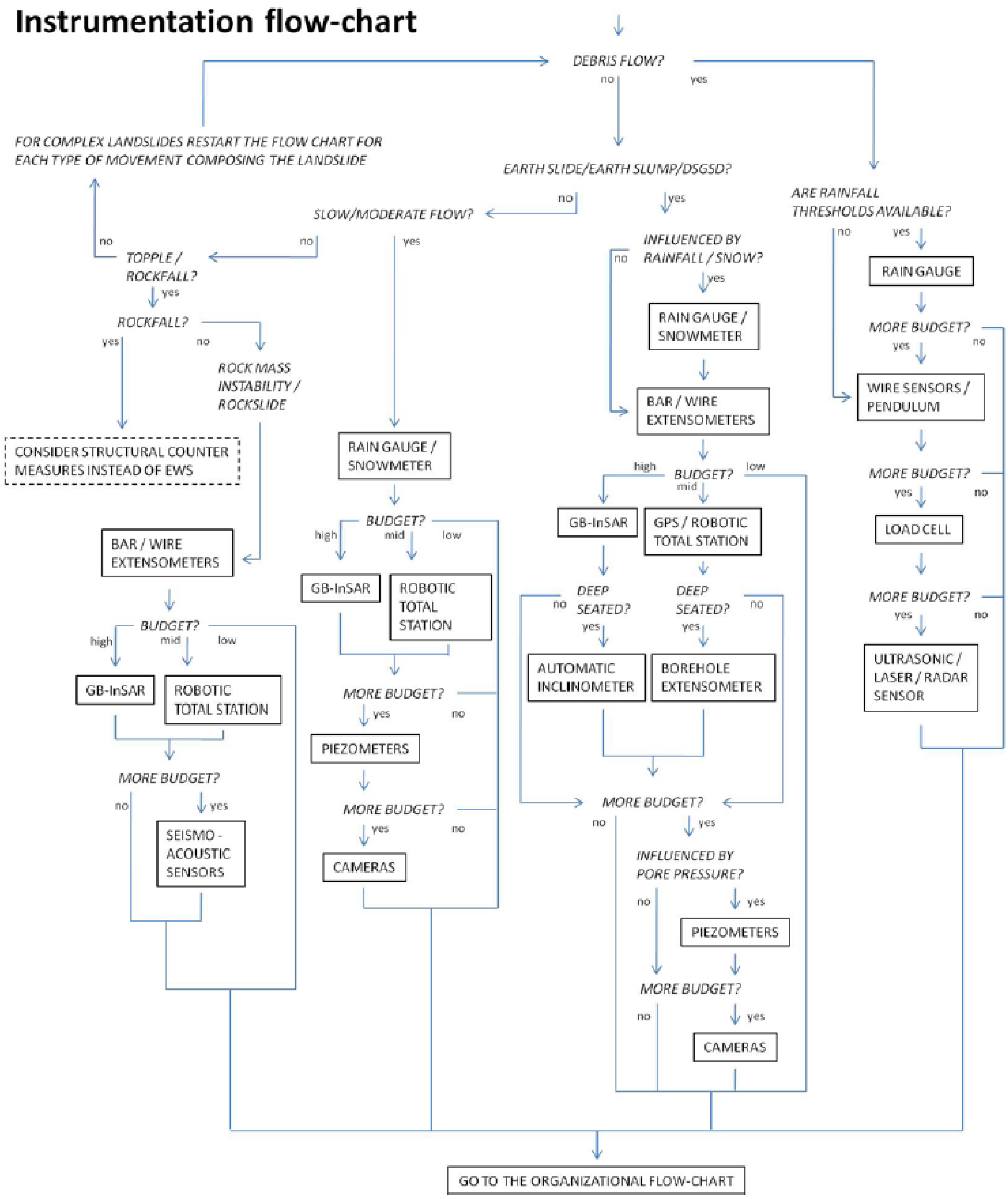

Figure 4.1 Flow-chart for the choice of instrumentation suitable for slope-scale landslide early warning systems, from Intrieri et al. (2013):

> *"The terms 'earth slide' and 'earth slump' follow the widely accepted classification of Cruden and Varnes (1996) and refers to rotational or translational landslides in granular or cohesive material. DSGSDs (Deep-Seated Gravitational Slope Deformations) are defined by Agliardi et al. (2001) as slope movements occurring on high relief slopes and with relatively small displacements before the final phase of collapse. GB-InSAR (Ground-Based Interferometric Synthetic Aperture Radar) is an advanced remote sensing monitoring apparatus recently used in LEWSs (Del Ventisette et al. 2011; Intrieri et al. 2012)."*

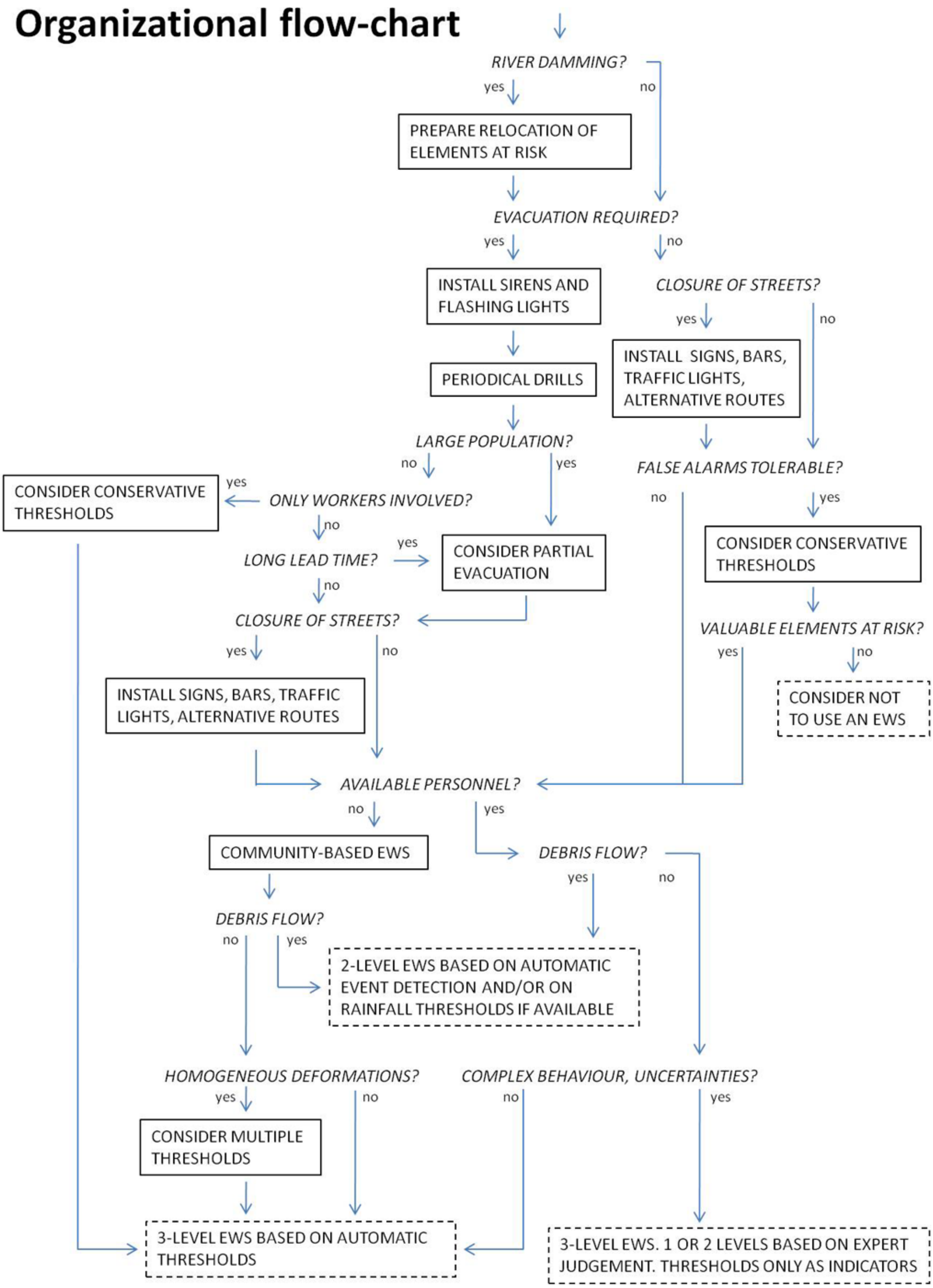

Figure 4.2 Flowchart for the choice of organisational features in a slope-scale landslide early warning system (Intrieri et al. 2013).

To help with communication and dissemination mechanisms and the preparedness and response capabilities, an interactive public-alerting options decision support tool was developed to assist Aotearoa New Zealand emergency managers with selecting the best suite of public-alerting systems for their local hazard priorities and community demographic make up. This tool helps decision-makers evaluate and compare the cost versus benefit and effectiveness of different public-alerting mechanisms against the demographical, geographical and hazard characteristics of a particular area[15] (MCDEM 2009; Wright et al. 2014).

A checklist is also available for warning issuers in Aotearoa New Zealand to follow to ensure that the messages contain all the recommended information (Figure 4.3) (Potter 2018).

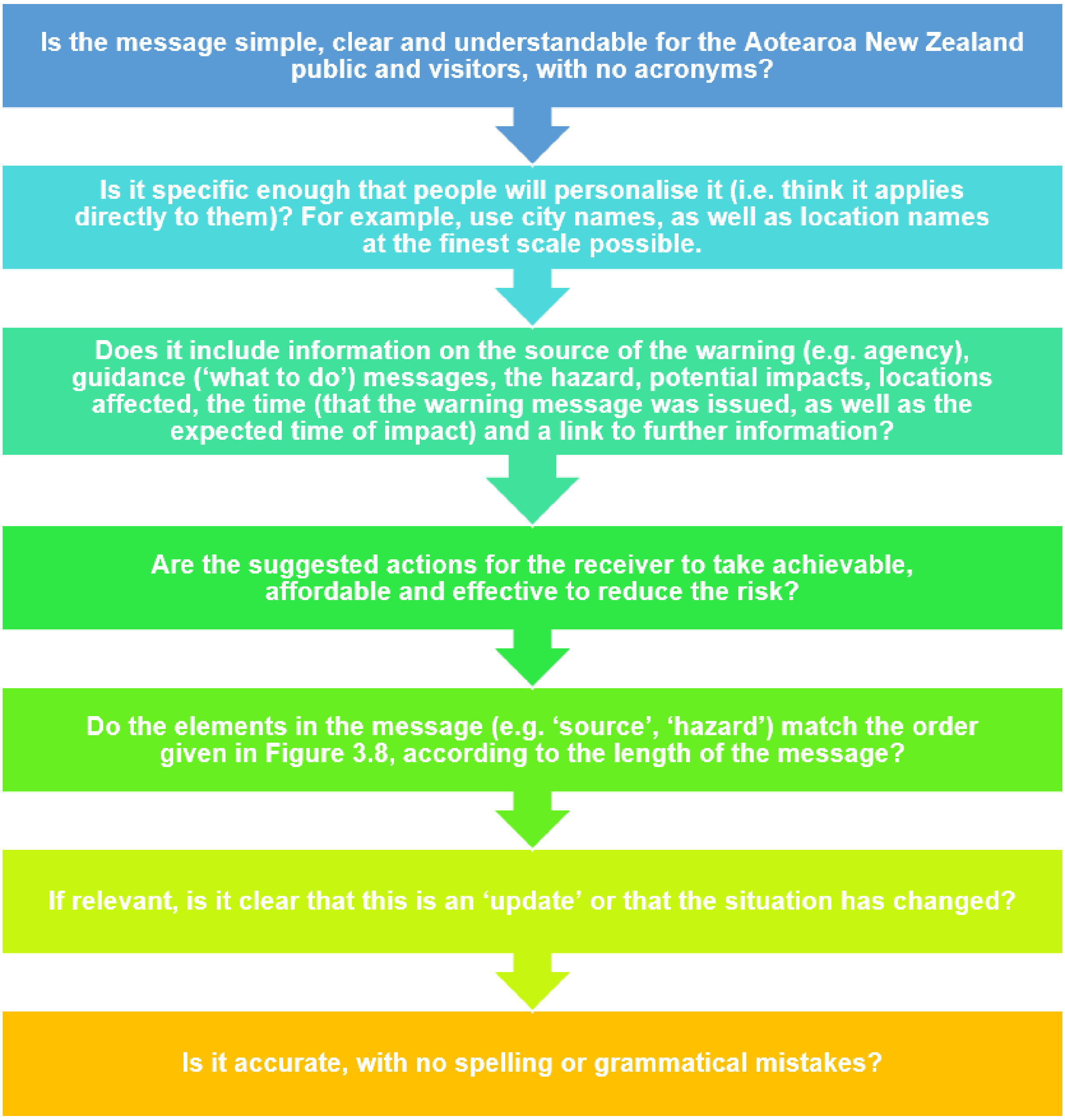

Figure 4.3 Warning message construction checklist for agencies involved in warning the Aotearoa New Zealand public (Potter 2018).

15 https://www.civildefence.govt.nz/cdem-sector/guidelines/public-alerting-options-assessment/

Including impact information together with prescribed actions can improve perception and understanding of the warning and intended behavioural responses (Potter et al. 2018a; Weyrich et al. 2018). Including impact information in the warnings requires involvement and co-ordination between all organisations that possess the required knowledge about the hazard(s), impacts, exposure and vulnerabilities (Harrison et al. 2022b). Thus, it is important to establish the strong linkages in the detection, monitoring and warning services component described in Section 3.2.4 and carry those linkages through to the warning messages to ensure consistency and relevancy (Potter et al. 2021).

5.0 CONCLUSION AND NEXT STEPS

Aotearoa New Zealand's geographic position, environment and tectonic setting promotes a dynamic hazard-scape, as demonstrated over the past decade through various earthquake, tsunami, volcanic, weather/flooding and landslide events. In some cases, where other risk mitigation options are ineffective or not possible, an EWS may act as the last line of defence to protecting lives and assets (see Section 2.0 for more).

In this guidance document, we described the key activities and decision-making considerations when developing a LEWS (Section 3.0). We described various practical tools that are available in Aotearoa New Zealand for landslide hazard and risk management (Section 4.0). These tools show that much work is being done nation-wide to support the development of LEWS in Aotearoa New Zealand. However, as shown through these examples and in the global literature, the complexity of landslides makes it difficult to design a 'one size fits all' LEWS. Furthermore, much work is still required to operationalise some of the tools described in Section 4.0 and ensure that these tools are useful, usable and used.

More work and research are needed in the following areas:

- Understand how people perceive landslide risk and whether and how people would respond to landslide forecasts and warnings in Aotearoa New Zealand.
- Characterise multi-hazard warnings and audience reach.
- Identify data sources and develop methodologies to integrate dynamic exposure and vulnerability into risk models and EWSs.
- Explore how people understand uncertainty in landslide forecasts and warnings, and how the uncertainty affects people's responses to landslide warnings.
- Determine the scale and standardisation of LEWS and appropriate audiences in Aotearoa New Zealand (e.g. whether warnings are for the public, key responding agencies, or both; having tailored systems for specific catchments or a nationwide system, etc.).
- Determine whether alert levels for LEWS are appropriate in Aotearoa New Zealand, design these, define the thresholds and automate the alert system.
- Improve geotechnical features, solutions and vulnerability functions.
- Design better triggering systems that are coupled with geotechnical knowledge.
- Identify the appropriate spatial resolution for LEWS.
- Set up the data streams (e.g. modelled rainfall and other real-time data products available from NASA and other agencies) necessary for implementing real-time multi-hazard impact forecasting and warning systems.
- Determine appropriate decision support tools for a Aotearoa New Zealand context, such as described in Section 4.0.

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APPENDICES

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APPENDIX 1 SUMMARY OF KEY DOCUMENTS AND LITERATURE

Topic	Documents and Examples	Key references
International Standards and Guidance	• ISO/DIS 22327:2017 *Security and resilience – emergency management – guidelines for implementation of a community-based landslide early warning system* and its adaption of ISO 31000 • AS/NZ ISO 31000:2018 *Risk management – principles and guidelines* • WMO (2018) checklist for developing multi-hazard early warning systems • WMO (2021) *Guidelines on multi-hazard impact-based forecast and warning services – Part II: putting multi-hazard IBFWS into practice*	ISO (2018a, 2018b), WMO (2018, 2021)
Aotearoa New Zealand governance documents	• Civil Defence Emergency Management Act 2002 • Resource Management Act 1991 • Local Government Amendment Act 2012 • The Guide to the National Civil Defence Emergency Management Plan 2015 (MCDEM 2015)	
Aotearoa New Zealand guidelines, good practise, other hazards	• NEMA resources (e.g. consistent messaging, public education, exercises) • Good-practise guidelines and resources for early warning messages and channels • Earthquake-Induced Landslide Dynamics tools and products • Case studies, good practise and learnings from other hazards in Aotearoa New Zealand (e.g. tsunami, earthquake, volcano, floods, severe weather) • Risk-based planning and landslide planning guidance	Allstadt et al. (2018), Brideau et al. (2021a), de Vilder et al. (forthcoming 2024), Massey et al. (2021a), Massey et al. (2020a), MCDEM (2010), Potter (2018), Saunders et al. (2013), Saunders and Glassey (2009), Wright et al. (2014)
International literature, good practise, case studies	• Global literature reviews of local-, regional- and/or slope-scale LEWS and landslide monitoring techniques • Case studies of LEWS design and implementation	Glade (2001, 2003), Guzzetti et al. (2020), Intrieri et al. (2013), Pecoraro et al. (2019), Scolobig et al. (2017), Thiebes and Glade (2016)

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