Chapter 3
Connecting Warning with Decision and Action: A Partnership of Communicators and Users

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Abstract In this chapter, we explore the challenges of achieving a level of awareness of disaster risk, by each person or organisation receiving a warning, which allows them to take actions to reduce potential impacts while being consistent with the warning producer's capabilities and cost-effectiveness considerations. Firstly we show how people respond to warnings and how the nature and delivery of the warning affects their response. We look at the aims of the person providing the warning, the constraints within which they must act and the judgement process behind the issue of a warning. Then we address the delivery of the warning, noting that warning messages need to be tailored to different groups of receivers, and see how a partnership between warner and warned can produce a more effective result. We include illustrative examples of co-design of warning systems in Argentina and Nepal, experience in communicating uncertainty in Germany and the Weather-Ready Nation initiative in the USA. We conclude with a summary of aspects of the warning that need to be considered between warner and decision-maker when designing or upgrading a warning system.

Keywords Decision-maker · Emergency responder · Response · Media · Vulnerability · Confidence · Behaviour

3.1 Introduction

In this chapter, we explore the challenges of achieving a level of awareness of disaster risk by each person or organisation receiving a warning, which allows them to take actions to reduce potential impacts while being consistent with the warning producer's capabilities and cost-effectiveness considerations. We show that:

- A successful warning provides the receiver with useful information in a usable form and is used effectively.
- Warnings are issued in a complex and challenging environment, in which needs are constantly changing.
- Success depends on the warner providing 'fit for purpose' information and on the response of the receiver as well as on the accuracy of the information and the technology to deliver it.
- Information sources, social and environmental cues, channel access and the receiver's characteristics influence behavioural response.
- Warnings are issued on uncertain information, and the level of confidence should be reflected in the warning.
- The 'warning to decision' process is not only about exchanging information but also about establishing relationships.
- A successful relationship requires assessment of the receiver's needs, beliefs, values, behaviours and decision-making processes.
- Warning messages should be tailored to different groups of receivers. The Common Alerting Protocol (CAP) can facilitate this while minimising the overheads of using multiple channels.

- Critical evaluation is the foundation for improvement. It allows receivers to feedback on warning effectiveness and reinforces communication.

3.2 Needs of the Receiver

3.2.1 *Who Receives Warnings?*

Warnings are produced for use by a variety of receivers in different situations. The job of a professional emergency manager is to be aware of the risks they are responsible for and to be prepared to respond to a warning and hazardous event. They may be highly knowledgeable about relevant hazards and familiar with technical language, though perhaps less familiar with the specific forecasting methods used by the warner. There is a much larger group of responders who are given an emergency response role as part of a wider job, but who nevertheless will generally have had some training in the risks and in the responses that are needed. Both of these groups will typically have some understanding of the relationship between the hazard and the impacts that they are concerned with, so will look to obtain supplementary information on the hazard. Whereas these groups have been given responsibility to respond primarily on behalf of others, the vast majority of receivers are responsible for their own safety and that of their families, friends, dependents and businesses (Lazo et al. 2020). They have a wide mix of understanding of hazard and risk, but in general are less interested in the hazard and are more interested in the specific impact on them and in understanding what they should do. Members of the public are increasingly able to prepare their personalised response and preparedness plans (e.g. multiple mobile phone applications now provide these decision support tools). However, levels of preparedness and guidance on the responses people should be undertaking can vary considerably.

Multi-hazard early warning systems are encouraged to be ‘people-centred’ (Basher 2006; UNISDR 2015), empowering ‘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, p. 3). In people-centred warning systems, the public is a central element and resource: ‘communities’ (…) inputs to warning system design, and their ability to respond ultimately determines the extent of risk associated with natural hazards’ (UNISDR 2013). For example, some individuals might act as local champions or peer educators to fellow residents to increase their level of preparedness and capacities to respond to warnings. A stronger involvement of the public and communities can also lead to stronger political and budgetary support for warning systems and reduction of conflicts related, for example, to decisions about warning system implementation (Kuhlicke et al. 2011). One of the main drivers for change towards people-centred systems is also the changing requirements of users, in response to increased information availability and growing threats (World Bank 2019). Some key characteristics of people-centred warning systems include a stronger focus on stakeholder engagement and responsibility sharing, enhanced communication supported by technological innovations and institutional capacity building, including stronger inter-agency collaboration (Scolobig et al. 2015).

In order to become people-centred, those implementing a warning system must know who their audience is and conduct meaningful engagement to understand their information requirements for an optimal response (Zhang et al. 2019). Thus, a critical question is: who are the receivers of weather warnings? Warnings are received by a wide range of sectors, including various publics (including tourists, business owners/operators, vulnerable communities, event organisers and attendees, the education sector, the horticulture and agriculture sectors, community groups, outdoor enthusiasts and motorists), agencies with emergency response and mitigation roles (including emergency services, emergency management from local to national levels and operations), the health sector, lifelines and infrastructure network agencies (including water, electricity, gas, telecommunications, road, rail), media, insurance, marine, aviation, science and monitoring agencies for cascading hazards, private weather services, global re-users (e.g. Google, IBM/The Weather Company) and non-governmental organisations.

This wide range of sectors demonstrates the immense challenge of issuing a severe weather warning that meets the needs of every receiver. Another challenge is to provide warnings that are co-designed between those implementing and those receiving them. An example of the co-design of a new warning product based on a receiver's needs assessment in Argentina is reported below.

Box 3.1 Users' Needs Assessment for the New Early Warning System in Argentina
Julia Chasco

In 2014, the National Meteorological Service of Argentina (NMS-AR) presented, as a result of cooperation with academic institutions, the Alert.Ar project. One objective was to better understand users' meteorological information needs for the management of severe weather events. Users were mainly emergency managers and operators. The needs assessment was carried out by triangulating different methods and tools that were conceptualised by a multidisciplinary team of social scientists: sociologists, anthropologists and geographers. Over approximately 2 years, multiple workshops, surveys and in-depth interviews were carried out, revealing to the NMS-AR that the information included in the meteorological warnings did not fit the needs of emergency managers.

Figure 3.1 shows the results of a simple exercise NMS-AR conducted with decision-makers who were all given the same weather warning in text format with the instruction, without interacting with each other, to draw their interpretation on a map of the country. As we can see, each decision-maker made a very different interpretation of the same warning.

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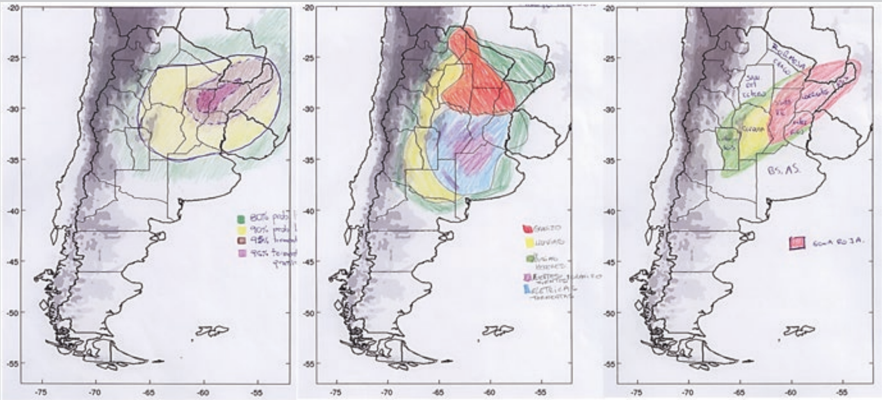

Fig. 3.1 Different interpretations of the same warning

This type of exercise allowed NMS-AR to identify weaknesses in the warnings: difficulties in understanding coverage areas and phenomena, little effectiveness in communicating spatial variations in severity and overly technical language in the message text.

Following this, the NMS-AR decided that this group of social scientists would become a permanent Department of Meteorology and Society with the mission of interacting with users to identify their needs and to use this information to improve services.

Between 2018 and 2020, the NMS-AR worked intensively on the implementation of a new early warning system oriented towards users' needs and decision-making. Some of the main changes in the new early warning system include:

1. Interoperable messages in traffic light formats and map displays.
2. Categorisations of phenomena with simple unified nomenclatures.
3. Publication of warning thresholds.

The Department of Meteorology and Society tested the nomenclatures, the iconography and definition of colours and the warning thresholds with different users. To meet the needs of emergency agencies, services were developed to facilitate monitoring over large areas, e.g. the NMS-AR has developed a graphic product, only for emergency agencies, which is sent by email twice a day at 6 am and 6 pm with alerts of the day for each province. Most emergency organisations communicate in large groups on WhatsApp, so the product was designed to be shared easily on that platform. NMS-AR developed systems for requesting special forecasts for specific operations or events as well as a special access platform in case there are problems with the website, so they can independently access alerts, nowcasting and radar and satellite images.

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The system also provides alert messages for persistent phenomena not covered by weather warnings, such as reduced visibility due to smoke, dust, ash and high or low temperatures. This information is in addition to the already established heat wave warning system, co-designed with the Ministry of Health and based on mortality data.

As part of any implementation made by NMS-AR since the creation of the social scientists' work unit, any system change is accompanied by training options for decision-makers, which implies an investment of several months. The Department of Meteorology and Society concluded that for improved warning understanding, co-production processes should be developed and tested at multiple levels of implementation, although they may be time-consuming.

3.2.2 The Nature of the Decision

The need to take protective action can arise at any time and in any place, not just when an emergency manager is at their desk, or a member of the public is at home. When a warning is received, the actions will be different for someone at home, at the office, working outdoors, engaged in sport or at a public gathering such as a festival. Those at risk need to be reached on a back-country hike or a sailing trip, woken in the middle of the night, interrupted in a business meeting, with information relevant to their situation. Once alerted, they need to confirm that a response is needed, perhaps requiring access to additional information, regardless of when, where and how they received the warning. A warning informs situational awareness and decision-making in a variety of ways, depending on factors such as the role and responsibilities of the receiver, their familiarity with the location and the hazard, costs and benefits of the decision, emotions and confidence in the information. While confidence is low, it may still be worth taking low cost, 'no regrets', protective actions that will either reduce the need for later action or prepare for more disruptive and costly actions when confidence becomes higher.

Responding agencies use warning information to plan their response and allocation of resources and may generate further communications to the public and other responding organisations such as infrastructure companies (Kox et al. 2015). Their tasks and duties are strongly influenced by national legislation and vary between countries. Responders have pressures inherent to their decision-making, including acceptable risk thresholds, time pressure and constantly changing conditions (Doyle & Johnston 2011). Weighing up the costs and benefits of the decision, while also taking into account the level of uncertainty associated with the warning, is a difficult challenge for receivers. For responding agencies, the decision to act on the warning can have very high stakes, such as the lives of exposed populations. However, the cost of reacting to a warning, such as by ordering an evacuation, is also high. Responding agencies must determine acceptable risk thresholds, which incorporate likelihood and potential consequences. Members of the public use weather warnings as one source of information to determine their behavioural response. Lindell and Perry (2012) describe how the decision-making process follows a series of ideal stages:

- Risk identification (assessing perceptions of level of threat).
- Risk assessment (expected level of personal impact).
- Protective action search (retrieving information about what to do to reduce the impact).
- Protective action assessment (determining which of the options is most suitable).
- Protective action implementation (when does the determined action need to occur).

Often the decision will be to look for further information to increase understanding of any of these factors (Wood et al. 2017). More generally, a number of factors related to the hazard, the situation and other respondents' characteristics (see Sect. 3.2.4) determine whether respondents are able to assess all of the decision-making steps described above.

Responding agencies may conduct risk assessments as part of their decision. Risk assessments can be quantitative (e.g. dollar losses or fatalities), or qualitative (e.g. low, medium, high), and use various tools. The result may fall into the categories of 'acceptable risks', where the risk is seen to be minimal and no mitigation measures are required; 'tolerable risks', where it is determined that the benefits of living with the risk outweigh the potential cost, and some mitigation may be required; and 'intolerable risks', where the risk is seen as being high and mitigation actions are required (e.g. Standards New Zealand 2009).

3.2.3 Which Information Sources Do Receivers Use?

Identifying the information sources receivers use is important for understanding the relative value of each source, and the contributions of those sources to the provided information and messages (Lazo et al. 2009). Information sources vary between users, according to their needs. They may include official sources, private weather services, environmental cues (such as seeing storm clouds), social cues and/or culturally indigenous cues. The information often travels through multiple channels, including the traditional and social media (such as tabloid newspapers), social connections (such as from friends, family, neighbours, colleagues and education facilities) and/or response agencies (including emergency services, local government, infrastructure companies and emergency management). Each of these channels, and the way the information travels through secondary sources, can have its own challenges.

Official sources of weather information tend to be National Meteorological and Hydrological Services (NMHS). Depending on national legislation, many NMHS are entitled alerting authorities, listed in the WMO Register of Alerting Authorities (https://alertingauthority.wmo.int/). Some receivers of information (e.g. airline companies) pay for a subscription service to receive more detailed or specific data to meet their needs.

Official information can be disseminated and often altered through other channels (such as TV stations/media or emergency managers) to provide additional information. In fact, most people access weather forecasts from the media and via the private sector, rather than directly from official information sources (Lazo et al. 2009, Hayes et al. 2014). As a result, most people use multiple sources of information when making response decisions, such as evacuating from a hurricane (e.g. Dow & Cutter 1998), to meet their individual needs. The majority of private sector weather forecasts are directly or indirectly based on official weather services (Lazo et al. 2009), including using public-sector global observations and models, and atmospheric research (Thorpe & Rogers 2018). The private sector is often highly interested in incorporating the 'authoritative voice', such as issued warnings, into their products and services (e.g. Google Crisis Response/Public Alerts – https://crisisresponse.google/products/public-alerts/) (Kaltenberger et al. 2020), for consistency, and to add further information or features to make their products more user-oriented. An increasing interest in impact-based forecasts and warnings by the private sector is expected due to the focus on user needs (WMO 2015; Thorpe & Rogers 2018).

Environmental and social cues are key sources of information that can influence the receiver's perceptions and actions (Lindell & Perry 2012). Environmental cues, such as a gathering storm, a funnel cloud, a roaring sound or heavy rain, are often considered when determining a response, such as during the Joplin, Missouri and US tornado warnings (Kuligowski et al. 2014). However, environmental cues can be hidden by low light (at night) and muffled by other noise (e.g. flash flooding muffled by heavy rain). Some cues are subtle or ambiguous, whereas others are much more obvious. Perceptions of environmental cues can also be altered depending on the time of day and other activities that are prioritised by the recipient (Ruin et al. 2014). Social cues stem from observing what other people are doing (e.g. packing a car to evacuate) and receiving information from community networks, such as family/friends and neighbours. This can be via a range of channels, including social media, phone calls, text messages and face-to-face. The availability of assistance, including the provision of transport and shelters, also provides cues (Lindell & Perry 2012).

In addition to the above sources, responding agencies sometimes have their own information sources. These can include trained storm spotters, staff members collecting impact or hazard data, crowdsourced reports, video cameras in public areas (e.g. traffic cameras) and their own monitoring equipment.

Finally, personal experience and cultural knowledge including, for many people, indigenous knowledge are used as information sources or a lens through which to interpret cues, prepare and respond. In many areas of the world, such knowledge is drawn upon to interpret environmental cues, such as the behaviour of wildlife, to help forecast future weather and seasonal events (e.g. Pareek & Trivedi 2011). Traditional knowledge is also a source of information to inform mitigation plans, and preparedness and response activities, such as terracing hillsides to prevent runoff and erosion and building sturdy houses that can withstand strong wind. The relevance of such knowledge is often lost when people migrate, especially into urban environments, but can be replaced if communities make efforts to build a new shared experience, e.g. by marking the heights of historic floods or the limit of inundation by tsunamis, by acknowledging anniversaries of disasters and by ensuring that schools teach their children about the hazards and responses appropriate to where they live and go to school.

3.2.4 Behavioural Influences on Decision-Making

Why do some people not respond in the way that they were directed to by a weather warning? There are many things that influence people's behavioural response to a warning. Several theoretical models describe these influences, such as the Protective Action Decision Model (PADM; Lindell & Perry 2012). Other theories and models are described in the best practice guidelines for risk communication and behaviour by the NOAA Social Science Committee (2016).

Lindell and Perry (2012) describe the factors influencing the 'pre-decisional processes' of the receiver (Fig. 3.2). They include the receiver's characteristics, such as their age, gender, primary language, mental models (general understandings and misconceptions), economic resources, social resources and physical abilities. As discussed in Sect. 3.2.3, behavioural responses to warnings may also be influenced

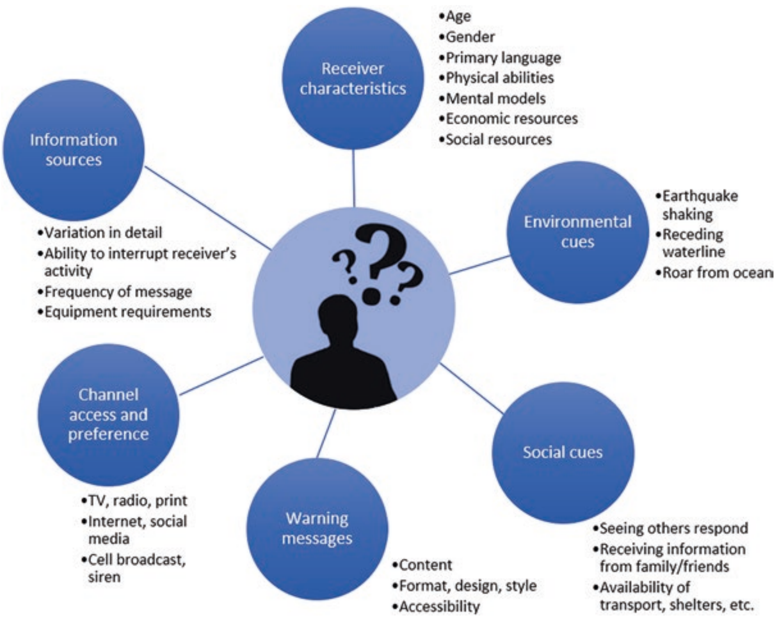

Fig. 3.2 Factors influencing pre-decisional processes towards protective actions. (From Potter (2018), based on the Protective Action Decision Model (Lindell & Perry 2012))

by indigenous knowledge and cultural norms, environmental and social cues and information sources (Shaw 2009). Message characteristics (particularly content and format, e.g. Wood et al. 2015; Potter 2018) and channel access and preference (see Sect. 3.3.3) are further influences, with relevant channel characteristics including the level of detailed information, precision of the message, the frequency that the message is sent out, the equipment requirements and how much it interrupts the receiver's activities.

The pre-decisional processes inform the decision that is being made according to the level of exposure the receiver had to the cues or warnings, the attention they paid (including intrusiveness of the alert) and their level of understanding of the message – including weather literacy (Fleischhut et al. 2020) and understanding of forecast uncertainty (Joslyn & Savelli 2010; Morss et al. 2010).

This demonstrates how using simple language, avoiding jargon and using a range of languages, when possible, influence the response. The influences mentioned here can take place very quickly and without much conscious thought. Theory from cognitive science suggests that in situations of high stress, people may make decisions using a faster decision pathway that is rather emotion-driven, while in less stressful situations, they are more likely to base their decisions on information (Weyrich et al. 2020b). In such cases, more information is not necessarily better. Moreover, which decision-making pathway people utilise may depend on the context. At the same time, cognitive theory has been hard to test in the field, because of the ethical challenges of submitting people to actually dangerous conditions.

A high level of preparedness can reduce the shock and facilitate an informed response to a warning. This may be achieved through education, drills and exercises and early alerts. Once a likely future hazardous event has been identified in forecasts, a range of communication formats can be used to build a general expectation that action will need to be taken.

Once the pre-decisional process is complete, the receiver's core perceptions provide another filter through which the information is assessed. The receiver's perception of the threat (or risk) has a large influence on their decision to respond (e.g. Kox & Thieken 2017). Risk perception refers to the judgments people make when they are asked to characterize and evaluate hazardous situations. This is influenced by numerous factors such as a respondent's prior experience, familiarity with the hazard, expected/perceived severity of consequences, perception of benefits and control over the risk source, etc. (for a review of risk perception literature, see Slovic et al. 2004, 2007). Cultural and social factors also strongly affect how people live with and perceive risks (for a review of cultural theories of risk, see Thompson et al. 1990). Yet, research shows mixed results as to whether a higher risk perception relates to a higher level of preparedness or response behaviour (e.g. Mileti & Sorensen 1990, Potter et al. 2018, Wachinger et al. 2013).

The receiver's perceptions of the source of the information (such as the agency issuing the warning) also influence their response. In particular, the perceived trustworthiness, expertise and protection responsibility of the source are taken into account (Arlikatti et al. 2007). On the one hand, institutional trust, for example, in NMHS issuing weather warnings, and credibility of the source, increases the likelihood for protective action (Potter et al. 2018, Ripberger et al. 2015). On the other hand, self-efficacy, including the belief in their own ability to inform and protect themselves against severe weather, is also an important driver for protective action (Kox & Thieken 2017).

A receiver's perception of protective actions can influence their decision to respond (e.g. Demuth et al. 2016; Johnston et al. 2005). An action perceived as effective in reducing the risk has a higher likelihood of being acted on, as do actions that are considered to be affordable and achievable and take little time and effort and that don't require coordination with other people. However, much of the research that has been conducted requires more testing in a warning context, rather than a general preparedness context, and in a 'real event' context, as opposed to a hypothetical context.

Following the pre-decisional processes and the triggering of the core perceptions, the decision to respond is undertaken (Lindell & Perry 2012). Once the risk has been identified, people look for information about the risk, involving thinking about personal impacts and length of time until the impacts are likely to occur. Options to increase their safety include drawing on their memory and past personal experiences as well as those they have seen in the media or read about, and education initiatives (Demuth et al. 2016; Sutton & Woods 2016). The receiver may seek further information, observe social cues and/or use guidance messages from warnings. Alternative actions are compared with continued normal activities. If it is determined that multiple actions need to be taken, the order of these needs to be assessed. A response plan may be determined only if there is time and a good-enough knowledge to do so. The plan may indeed range from vague to detailed, potentially including factors such as evacuation route, destination and means of travel. These decision-making processes can cause delays to taking action as further information is sought, which is referred to as 'milling' (Wood et al. 2017). This highlights the importance of including 'what to do' guidance messaging in the warning message, and hyperlinks to detailed information to help people determine their actions. Once an action plan has been developed, the situation may hinder its implementation. For example, roads could be blocked, children and pets need to be found, or there may be a lack of access to transport, prompting alternative actions to be assessed, decided on and implemented.

3.3 Capabilities of the Warner

3.3.1 Who Issues Warnings?

While many countries have legal limitations on who can issue a public warning, in reality, both professional responders and the public have access to a variety of sources of warnings. Government agencies dominate as sources of information, while police and/or fire and rescue often have the final authority to order people out of an area of immediate danger. For infrastructure operators, however, while the advice may come from a government agency, it will often be an in-house emergency manager who will issue the emergency response order to the operations department. More generally it is a variety of public, private and non-governmental organisations that issue warnings to the public, in a wide range of formats and through a variety of media. Some of these organisations may simply repeat the message issued by the originator, but more often than not, there will be some degree of translation and reformatting. Indeed, a compelling presenter, even if they have minimal knowledge of how the warning was created, can have a huge influence on the level of response – and may become, in themselves, the basis for the trust of the audience.

Underlying observations and model predictions are generally provided by NMHS. This information is then used by themselves and private sector meteorologists to produce forecasts and warnings (Thorpe 2016; Pettifer 2015). These different – public and private – sources do not always provide consistent warning information: through the use of different colour-coding and warning thresholds, by interpreting model outputs differently, or by conveying different overall messages, they create perceived or real inconsistencies in the warning information received by the public (Weyrich 2019). National weather services and emergency managers have suspected that these conflicting cues exist and negatively influence public behaviour; however, more research is needed. Existing empirical evidence clearly shows that contradictory visual and textual information have negative effects on public behaviours (Lindell & Brooks 2013; Williams & Eosco 2021).

The challenge of consistent warning information grows with the number of agencies involved in the warning decision process. Inter-agency coordination is needed to ensure the delivery of consistent messages by multiple agencies within impact-based forecasting and warning systems (Potter et al. 2021). On a regional scale, cross-border high-impact weather situations have a greater potential for conflicting warning information from multiple-channel sourcing information from different NMHSs. This is not just because of differently designed warning systems but also because of a lack of standard operating procedures (SOPs) in exchanging information among neighbouring NMHSs (Kaltenberger et al. 2020). Regional programmes, such as Meteoalarm in Europe (https://meteoalarm.eu) and WMO GMAS-Asia (https://gmas.asia), aim to foster regional cooperation and information exchange that improves cross-border warning information consistency. Such consistency is of fundamental importance both to global re-users and to global responders such as the UN and international NGOs.

3.3.2 Types of Warnings

Warnings may be classified in many ways, including how they are produced, their message structure or the mode of delivery. For speed of response, automated warning is optimal, e.g. a fire alarm based on a smoke sensor or a flood siren that sounds when an upstream river gauge registers above a critical threshold. Such systems depend on recipients being familiar with what the alert means and what they should do to respond. In the past, warnings were often produced using bespoke templates and with highly compressed language to minimise the number of characters or words to be transmitted. Warnings of this type remain in use, such as in maritime and aviation safety. They typically use fixed hazard thresholds related to impacts that are meaningful to a specific audience. Free-form warnings give more options for the warner to include information specific to an event or for multiple audiences, but also increase the risk of misunderstanding or lack of clarity.

In order for everyone to have a common understanding of the severity of the hazards that are forecast, are observable or have occurred in the recent or distant past, they are often given a label. This understanding can have many uses, one of which is to help raise awareness in the public about an impending event so as to prompt preparedness actions. Some systems are numerical and continuous (e.g. earthquake magnitudes), some are divided into categories (such as the Saffir-Simpson hurricane wind scale), others have a small number of levels (such as meteorological 'outlook, watch, warning' systems), and some are binary (e.g. fire alarms). When designing a warning or category system for a hazard, one of the many decisions that needs to be made is what it will be based on (the 'foundation'; Potter et al. 2014). This determines the trigger for issuing a warning. Options range from hazard through to guidance on response, i.e. what people should do. Each has its own benefits and challenges.

At one end of the spectrum is basing the foundation on the hazard. This means that warnings are triggered by the severity, extent, duration or magnitude of the peril, regardless of whether people will be exposed to it. Examples include expected wind speed, rainfall intensity and earthquake magnitudes (such as the Richter scale, moment magnitude and local magnitude), where the scales have fixed thresholds based only on their intensity. Volcanic alert-level systems primarily use the magnitude or severity of volcanic activity as a foundation for warnings (e.g. New Zealand's, Potter et al. 2014; and the US system, Gardner & Guffanti 2006). The benefits of these systems are that scientists can issue information quickly, based on their understanding and data; little coordination is needed with agencies who hold information on impacts, vulnerability, exposure and mitigation procedures. The main challenge is that phenomena-based systems may not initiate the most appropriate or timely responses by members of the public. Including impact information and guidance on response can improve effectiveness (e.g. WMO 2015).

Further along the spectrum, the severity thresholds chosen for each warning or category level may be fixed according to the severity of damage it would cause to people or property if they were exposed to the hazard. These systems assume someone or something could always be exposed; i.e. the thresholds do not vary over space or time. Examples of this type of system include the enhanced Fujita scale, Saffir-Simpson hurricane wind scale and the modified Mercalli intensity (earthquake shaking intensity) scale. Once the thresholds vary over space and/or time (e.g. climatology-based thresholds), the system is heading towards being an impact-based warning system. This can take account of the dynamic situation, including antecedent ground conditions (e.g. prior rainfall causing wet catchments and therefore accelerated flooding), variable populations (such as rush hour) and specific impacts such as airport closures (WMO 2015). These systems require collaboration between agencies who hold the information about meteorology, society and impacts, which has the potential to cause delays in issuing warnings (Potter et al. 2021). Impact-based forecasts and warnings are thought to increase the level of understanding about the situation by the public, and raise risk perceptions, but there are mixed results as to their effectiveness in prompting a behavioural response (e.g. Weyrich et al. 2018; Potter et al. 2018). Determining which impacts or consequences to base the warning on becomes important, whether it is for safety of life, injuries and well-being, damage, disruption, or economic or environmental impacts. Risk modelling can help with mitigation and hazard management (Crawford et al. 2018) and may become increasingly utilised in real-time situations.

Personalised warning messages that include information about local disruptions and impacts may help to prompt effective responses and would generally be issued by partner agencies who hold the roles and responsibilities to issue them (WMO 2015). These 'impact-oriented' warnings require substantial improvements in impact data collection and storage (Kaltenberger et al. 2020). Finally, some warning systems are based on the action required by the population at risk. Higher levels may include evacuations of large areas, and lower levels may promote increased awareness. Examples include New Zealand's COVID-19 pandemic alert-level system, Japan's volcanic alert-level system, fire alarms or tsunami sirens requiring an evacuation and the seatbelt sign in aircraft. These systems tend to promote compliance and require receivers to understand the actions relating to the levels or alerts. Further investigation into these types of systems would be beneficial to identify how underlying observational data support the decision-making to trigger a warning.

3.3.3 Communication Channels

Getting the warning to the receiver is essential if it is to have any value. The diverse types of dissemination channels – print, mechanical, electronic and face-to-face – have very different characteristics, for instance with respect to the dissemination rate or precision (Lindell & Perry 2012). A wide range of channels should be used according to the needs of receivers, including local or national TV (including cable), radio (including specific weather radio channels), newspapers, friends/family, co-workers, neighbours and smart/cell phones. Increasingly, web pages and mobile applications are important sources of weather information, including cell broadcast alerts and social media (Hayes et al. 2014). A siren can make people instantly aware of a threat but has a limited reach and provides no further information. Mobile phone applications can provide instant messaging with greater information content, but the recipient needs to have a (functioning) mobile phone and to consult it to receive the message. Newspapers are slow, but can provide detailed information and context, and are ideal for early alerts. Television can strongly engage the viewer, but with limited airtime, and may miss out important information. A trusted neighbour or official is a compelling source in an emergency but is very resource intensive and time-consuming.

Different channels support a different range of warning formats. For instance, some channels are restricted to text (SMS on cell phone), audio (radio) or video (regular TV), while others can contain a variety (websites, smartphone apps, weather TV). A mixture of formats can reinforce the message if consistent and if they are quickly and easily accessible. For instance, the Met Office weather app provides colour-coded warnings identifying the type of hazard on a map of the UK. Each warning can be expanded to a higher-resolution map, identifying affected towns and cities, supported by a brief explanation of the hazard and its source, what the likely impacts will be and the status of the warning (including when it was last updated and why). Links are provided to guidance on how to respond, and to additional information including a more detailed context and a list of the administrative authorities covered. Supporting material is also provided in the form of the TV weather forecast video, which includes the same information communicated verbally and visually by a presenter. Care must be taken when using visual formats as many people have difficulty reading maps, colours should be distinguishable by those who are colour blind, and colour scales and icons are not universally recognised (but see Guemil (2021) for an initiative towards an internationally accepted set of emergency icons). Consideration needs to be given to how many and which languages will be used, and to reaching the visually impaired and those with severely limited language skills.

Channels differ in the extent that they reproduce the authoritative warning or add or provide their own or other independent warning information, but it is essential to acknowledge that only in an ideal world should they all tell the same story, but in reality inconsistencies persist. Thus it is essential for agencies to recognise and to live with inconsistencies. Where the information source is known and trusted, the dissemination channel should provide source attribution and branding, as these will speed up recognition by the user, and help to distinguish the message from other potentially conflicting or misleading messages. Indeed, as the information landscape becomes more crowded, an increasingly important role of the information provider must be to monitor these multiple sources and try -to the extent possible- to issue corrective statements to counteract false information before it spreads.

New technologies, based on smartphones, are not only a channel to disseminate information. They can also be used to test the effectiveness of different communication strategies, such as by disseminating different types of messages (e.g. impact and non-impact based) to the receivers and by enabling verification – including via surveys – of which types of messages lead to adaptive behaviours (Weyrich et al. 2020a). They can also open a window for two-way communication through social media and for collecting data through crowdsourcing, for example.

Sights and sounds that indicate hazard onset are important inputs for people's emergency response (Lindell & Perry, 2012), but may come too late. For example, the presence or absence of thunder and lightning during a storm may influence responses by providing evidence supporting the imminent threat. Where the threat is not yet sufficiently close, CCTV, webcams and social media videos can provide equivalent cues at a distance. Using two-way communication such as this can be a valuable component of a warning service. Not only can the local information provided through social media be used to reinforce the warning in places not yet reached by the storm, but it can also help the forecaster to keep abreast of an evolving situation and to fine-tune their forecast for use in updated warnings.

Many challenges currently hinder the incorporation of social media and crowdsourced data in warning practices. For example, agencies are afraid that social media will produce harmful and inaccurate information and that it can be difficult to evaluate the credibility and validity of user-generated content (Weyrich et al. 2020a,b, Goolsby 2009, Kaplan & Haenlein 2010). Also, the enormous amount of information can be overwhelming, and ethical concerns can further discourage agencies from fully exploring their potential. These issues include the potential for breaches of privacy, even from anonymised datasets, the lack of consent involved and the possibility of misuse by commercial entities interested in surveillance (Maxmen 2019). Other problems arise from unequal access to social media. For example, in 2016–2017 nearly 1.3 million households had no Internet connection in Australia, and lower digital inclusion was observed in already vulnerable groups, including the unemployed, migrants and the elderly (Howarth 2018). As a result, gaps between privileged and marginalised people may grow wider. It must also be acknowledged that the private weather sector may view these social dilemmas and challenges differently, because of their interest in the commercial aspects of warning dissemination.

Opportunities for warning agencies to use these newer channels include a better understanding of public debates about warning-related issues, monitoring dangerous situations and interacting with receivers, promoting crowdsourcing and other collaborations as well as extending the reach of organisational information and improving transparency, visibility and reputation. In the future, artificial intelligence may increasingly be used to monitor these channels and to sift out the critical pieces of information that indicate a change to a warning is needed.

This plethora of media and formats can seem daunting when designing a warning system to a restricted budget. The international standard Common Alerting Protocol (CAP) provides an increasingly valuable tool for minimising the overheads of using multiple channels (FEMA 2020). Provided a warning is produced in the XML-based CAP format (OASIS-Open 2010), standard software is available to convert it for delivery through a wide and increasingly varied set of channels, including a degree of automatic tailoring to the needs of specific user communities. As an internationally supported standard, training, support and implementation guidelines are available to facilitate the use of CAP in new and existing warning systems (e.g. WMO 2013).

The following points highlight where CAP-enabled alerting can provide benefit:

- Enables effective dissemination through new media, using smartphones and the Internet of Things, as well as existing mass media such as radio and television.
- People with special needs or a language barrier can be served.
- Alerting areas can be precise, reducing receipt of alerts outside the area at risk.
- Simplifies issuing of alerts to a single message.
- Facilitates sharing of situational awareness between emergency managers and across boundaries to create a ‘common operating picture’.
- Enables links to immediate response alarms and automated controls.

3.3.4 Influences on the Warner

People who issue warnings are influenced by many factors, both individually as a person and corporately as a member of an organisation. These range from the quality and quantity of available information to their role and responsibility in providing science advice (legislative), to managing perceived risks from over-warning and warning fatigue by the public, through to personal and group psychological biases. Warners should be familiar with the nature of their audiences, including the way in which warnings will reach them. While helpful in general, this can easily lead to biased warnings and ultimately to a degraded response. Many procedures (e.g. tick boxes, thresholds and templates) are in place to help overcome biases and other influencing factors, and to retain consistency over time and between different warners and agencies (Fig. 3.3).

The legal, institutional and political context can also influence the warner and his/her behaviours and attitudes (see Chap. 2). For instance, in some countries there may be an increase in legal conflicts related to the dissemination, use and interpretation of risk, forecasts and warning information (Altamura et al. 2011) and, more generally, in disaster risk management (Lauta 2014). This can lead to defensive, self-protective behaviours of warners to avoid personal blame and liability. For example, following the trial and prosecution of scientists and officials in Italy following the communication of risk information and a subsequent impactful earthquake in the town of L'Aquila, the number of false alarms was observed to increase in Italy (Altamura et al. 2011), with consequent impacts on weather-related decision-making. On the other hand, a US National Weather Service policy decision to reduce false alarms for tornadoes by switching from county-based to storm-based warning areas resulted in a dramatic reduction in the size of warning areas (Sutter & Erickson 2010). The institutional framework can also weaken the warning process, for

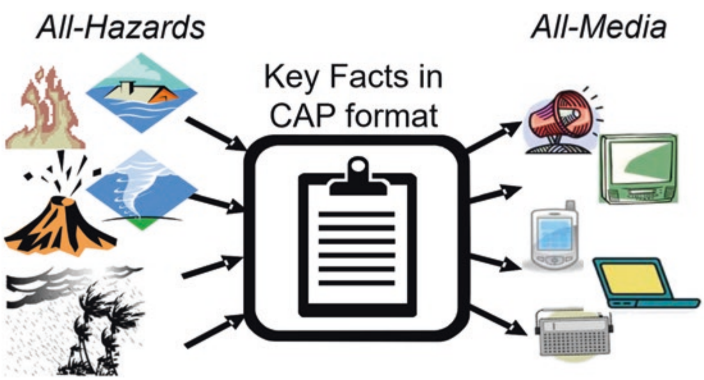

Fig. 3.3 Reaching a plethora of receivers with different needs from a single information source through multiple channels using the Common Alerting Protocol. (Source: Eliot Christian, based on ITU 2019)

instance by failing to define stakeholders' distinct roles and responsibilities (Thorpe 2016). This can impede collaboration and cooperation between the actors involved in the warning chain. Institutional priorities may also determine whether warnings are primarily aimed at reducing impacts on individuals or on society as a whole (Potter et al. 2021).

Technical and financial constraints mean that a warner is almost certainly working under time pressure and with access to information limited by the speed of a desktop computer. They usually have access to only a subset of the observational data used in the forecast, and to a limited range of forecast products, especially if the forecast has come from a global forecasting centre. They may be trying to provide direct information by phone to key individual responders while preparing their warning for the public and a script for a live broadcast. They should also be monitoring the current state of the hazard and information circulating in the media, including social media. Under these pressures, the warner's attitudes and behaviours will be influenced by a lack of resources, inadequate communication protocols and ineffective engagement with the media and the private sector (UNISDR 2013, NOAA 2016, Handmer & Dovers 2007).

Timeliness is of particular importance to the user since response actions take time and must be completed ahead of the arrival of the hazard. When forecast information is produced across several organisations, such as a weather service, a flood agency and an emergency response agency, there may be a substantial time delay before the warner even receives the information. This can be exacerbated with impact-based forecasts and warnings, which may require information from several agencies to be collated (Potter et al. 2021).

Behaviour may also be affected by organisational competitiveness, whether for profit, funding, prestige or power (such as with other ministries, businesses or nations), by inappropriate organisational or individual target setting (e.g. concentrating on volume or accuracy over user value) or by excessive protectionism (including requiring that everything is produced in-house) or outsourcing (so that internal roles are devalued). Misinformation on external media can be particularly challenging; interventions to correct false information carry the risk that both the false information and the correction distort the original message.

Warners, and experts in general, tend to perceive risk differently from each other, and from lay people (Bostrom 1997). While experts tend to use formal definitions of risk and emphasise the magnitude of the hazard and its likelihood, members of the public may include other factors, such as the familiarity of the threat and dread (Fischhoff et al. 1978). The social and institutional contexts of risk are important, such as motives and values. Experts also translate verbal probabilities (such as 'likely') to numerical probabilities (such as 70%) differently from non-experts, highlighting the importance of using probability translation tables (Doyle et al. 2011) as encouraged by the WMO (WMO 2008). Interpretations of probabilities also differ between experts and non-experts, and even within expert groups (Kox et al. 2015). The decision-making that goes into assessing risk inevitably requires a series of judgements to be made, to refine the circumstances or scope of the situation.

Many psychological biases can influence judgements at an individual or group level. In a setting of scientists/warners making decisions, these can include the desire to conform to the group (Asch 1952), the influence of a minority (Crano & Chen 1998), the groupthink phenomenon (Janis 1982), obedience to authority (Milgram 1974) and potentially the presence of an audience affecting performance (Dashiell 1930). The ways in which questions requiring judgement are asked can influence the outcome, with care needing to be taken to not bias the result (Potter 2014). Another influence on warner decision-making is avoidance of potential false alarms. While warners are often very concerned about the 'cry wolf' effect of false alarms, several studies have shown that their effect can be minimised by careful messaging before, during and after events. For example, Kox and Lüder et al. (2018) show that emergency managers state their discomfort about warning fatigue and high false alarm rates but indicate that they would respond to the warning as common practice. In general, policymakers are much more concerned about misses than false alarms. Various alternatives exist to support decision-making, such as a structured approach (e.g. Bayesian), or a more naturalistic approach (Doyle & Johnston 2011).

3.4 The Bridge Between Warner and Receiver

3.4.1 Building a Relationship

Those issuing warnings must understand the information needs of the receivers. This is achieved by building a relationship between the receiver, the warner and any other stakeholders involved in the process. This relationship can take many forms, depending on the laws and culture of the country, the governance structure of the warning organisation and the nature of the receiver – whether an individual, an organisation or a whole community. Relationships take time to build, require active management to thrive, depend on flexibility and compromise on all sides and ultimately need to commit to solutions that are beneficial to all parties. Relationships are equally necessary whether the warner is in a public or private sector organisation, and whether the receiver is a member of the public, a global business or a non-governmental relief organisation. However, the nature of the relationship will be different in each case. Sustaining the relationship requires continued and regular two-way interaction, as personnel change and technical capabilities evolve, including periodic training and exercising.

The level of engagement underpinning these relationships ranges from one-way informing (e.g. a radio announcement about a hazard/event) to 'empowering' the end users to make the decision (as described by the International Association for Public Participation; https://cdn.ymaws.com/www.iap2.org/resource/resmgr/pillars/Spectrum_8.5x11_Print.pdf). There is a vast literature maintaining that effective warning communication is achieved through a two-way exchange of information between parties and that involving stakeholders in the communication, planning and discussion stages can increase their commitment, and ultimately foster the adoption of effective behaviours (for a review, see Macintyre et al. 2019). Indeed, this relationship and, in general, the whole warning communication process are circular and two-way as it also depends very much on the environmental, social and technical context, as well as the degree of partnership among the involved stakeholders. Two-way exchange of information also includes co-design and co-production of information, in which the receiver's role shifts from pure user to collaborator and partner (Kox, Kempf et al. 2018).

There are multiple successful examples of co-design of people-centred early warning systems and citizen science engagement processes (Preuner et al. 2017, Scolobig et al. 2016). These show how it is essential to adopt a warning value chain approach to engage with multiple stakeholders and to co-design warning system options. They also provide evidence that the inclusion of different stakeholder perspectives on the technical, social, economic, legal and institutional characteristics of a warning system helps to address decision stalemates and conflicts, e.g. about funding allocation or priorities.

Yet, despite many authors highlighting that communication should be a two-way exchange of information, there is an operationalisation gap in many countries. The current literature and established practices suggest that most warning communication with the public remains unidirectional, from decision-maker to an uninvolved public, rather than a dialogue. Without doubt, there are multiple barriers to true two-way communication (see also Sect. 3.3.3). For example, given the large number of sectors and groups receiving warnings (as described in Sect. 3.2.1), it is difficult for agencies issuing warnings to build relationships and establish multidirectional engagement with all of them. Where stakeholder engagement is used in the co-design process, it can be difficult to involve some vulnerable groups such as women with young children, housebound elderly or those with chronic illness, and even when present, for these groups to feel equally engaged, especially if they lack good language skills. A combination of group meetings and individual interviews is needed, but community acceptance of such distributed inputs requires a high level of transparency in presenting and interpreting the evidence. It especially requires dedication of time and resources to develop successful processes. Co-production is also not suited for all kinds of warning communication. While it has proven successful for planning and evaluation, e.g. co-design of warning system options and evaluation of warning communication effectiveness, it is more challenging for fast two-way communication. This is currently the preserve of a small but rapidly growing group of receivers, such as storm spotters and organised groups of amateur observers (see, e.g. Elmore et al. 2014). Combining the concept of trained storm spotters or 'trusted spotters' with quality management of the data received was rated best practice by the European Meteorological Society (Krennert et al. 2018). Where funding is available for a tailored service to a specific business or sector, the opportunities for building a relationship are much greater than for a general public service. Yet, they are often missed, with available resources focused on technical capability at the expense of achieving a mutual understanding of the problem and its solution. With the growth of web-based warning services, tailoring has begun to be feasible for a much wider range of receivers. Tailoring by location has been in use in the USA for many years, firstly on NOAA Weather Radio and more recently on cell phones (Wireless Emergency Alerts), targeting messages to individual cities or counties (NOAA 2021). The ability to set locations of interest is also well established, for instance in the Red Cross warnings app (e.g. British Red Cross 2021). However, the potential for much greater use of targeting is shown by its increasingly sophisticated use in online advertising, for instance by Google and Facebook. Such targeting lies not only in selecting the information of interest but also in presenting it according to the selected or revealed preferences of the receiver. Ethical issues surround the use of this technology, but as it gains wide acceptance through online platforms like Google, there will undoubtedly be increasing application in the communication of tailored forecasts and warnings.

An effective long-term partnership provides an environment within which to build up many of the conditions for successful use of warnings, including education and training between events, shared experience and interpretation of historical events, mutual understanding of forecast capability and trust in the reliability of the warning system, all of which influence the way a warning is both produced and received (Parker et al. 2009).

Two examples follow that exemplify current good practices, via the establishment of strategic partnerships aimed at strengthening the relationships between the warner and the receiver.

Box 3.2 The Global Weather Enterprise
Sally Potter

The Global Weather Enterprise (GWE) 'is an enabling environment fostering global engagement between public, private, and academic sectors that share the common goal of providing accurate and reliable weather information and services that save lives, protect infrastructure, and enhance economic output' (World Bank 2019: 3) and is described by Thorpe and Rogers (2018). It focuses on increasing value through the full chain from scientific research and observations to models, forecasts, products and services. It is an initiative aiming to acknowledge and address obstacles in the collaboration of these three sectors (particularly public and private), including funding pressures on the public sector, growth of the private sector capabilities and international financing structures. It encourages a fair market for weather forecasts and services, and clear governance of taxpayer-funded open-access data in relation to commercialisation.

Indeed, business can derive economic value from weather knowledge – estimated at $US13 billion in a report by the US National Weather Service (NOAA/NWS 2017). Increasing the recognition of the value of underpinning publicly funded weather services in leveraging the private sector may help ease the funding pressures on the NMHSs (Thorpe & Rogers 2018).

(continued)

Additionally, it has been suggested that the public sector could make more use of private sector data, with the recognition that open-access data and long-term reliability of data be considered (Hayes et al. 2014). This includes exploring potential business relations with the private sector as part of pilot projects (World Bank 2019). The GWE also calls for clear roles and responsibilities, particularly around data ownership, as the private sector moves towards the provision of data services and away from infrastructure (Thorpe & Rogers 2018). At the same time, there are also opportunities and good practices related to the role played by the private sector that can be exemplary to improve warning communication. For a public audience, the ability to respond online to social media posts and media stories, and provide information through crowdsourcing mobile applications, enables a higher level of engagement than the traditional one-way communication of hazard information.

Box 3.3 NOAA's National Weather Service Strategic Goal: Building a Weather-Ready Nation
Douglas Hilderbrand

In 2011, a series of extreme events across the USA, including tornadoes, floods, hurricanes and wildfires that killed over 1000 people, became the driving force behind a profound movement to improve the country's 'weather services'. The National Oceanic and Atmospheric Administration (NOAA) and its daughter agency, the National Weather Service, started a long-term, strategic goal to improve forecast accuracy, communication and delivery of information to the public. The strategic goal to build a 'Weather-Ready Nation' (WRN) galvanised the operational and research arms of NOAA to improve not only forecasts and warnings but also their value through better societal responses (Hilderbrand, 2014). Internally, WRN became the impetus to measure value not just from a forecast accuracy perspective but also by a societal outcome perspective. This change in mindset has resulted in four focus areas:

- Delivery of Impact-Based Decision Support Services (IDSS).
- More effective communication of preparedness and protective 'call-to-action' statements.
- Integration of physical and social science in products and services.
- Better ways to deliver information in a timely and relevant manner.

Some WRN successes include:

- Creation of storm surge inundation maps that better communicate where and how much storm surge can be expected.

(continued)

Fig. 3.4 Components of the NWS Weather-Ready Nation initiative © NOAA 2021

- Use of social media such as Facebook and Twitter for two-way interactions (e.g. posting safety messaging and forecast information and receiving storm reports by followers).
- Emergency alerting on cell phones sent via the nearest cellular tower.
- NWS personnel on location at emergency management operations centres to deliver forecast advice within the broader decision environment.

Beyond the changes made internally, mentioned above, WRN also became a commitment to collaborate at the community level (Fig. 3.4). Government could not achieve a Weather-Ready Nation alone, but rather needed to embrace external partnerships at the federal, state and local levels, and across industry, non-profits and other community organisations. To show its commitment to partnership and give others 'partial ownership' of WRN, NOAA launched the Weather-Ready Nation Ambassador programme in 2014. As of August 2020, NOAA has recognised over 11,000 organisations as ambassadors, sharing the goal of making communities ready, responsive and resilient to extreme weather, water and climate events. WRN Ambassadors are as diverse as community needs – from global corporations to small non-profits. With these WRN Ambassadors acting as force multipliers, weather safety and life-saving forecast/warning information can reach many more people in communities across the USA. The wide range of skill sets collectively across these ambassador organisations allow for innovative collaborations with NOAA and even other ambassadors.

(continued)

Looking ahead, WRN continues to build momentum on tough challenges such as quantifying and communicating forecast certainty, folding probabilistic forecasting into the decision-making process and finding new ways to inspire the public to take appropriate actions so that when extreme weather threatens, communities will be ready.

3.4.2 What Works?

The content and format of a message differs depending on varying user needs, as does the channel through which they would like to receive it, and the timing and frequency of updates. As described in Sect. 3.1.1., extensive user engagement is required to understand these needs in advance, to ensure the information is received in a useful and usable way (e.g. Becker et al. 2019, Kox, Kempf et al. 2018).

The warning message directly influences people's warning response. Message content and style are thus important factors in determining whether people take self-protective behaviour or not. In order to be effective at inducing such behaviour, a message should contain the information elements of hazard (nature and magnitude), location (area affected by the hazard), time (occurrence time or time to impact), guidance (action recommendations) and source (Mileti & Sorensen 1990). Previous research also shows that, to be effective, warnings should describe the exact nature of the threat (including potential impacts), provide a source of confirmation and be personally relevant (Weyrich et al. 2018, Lindell & Perry 2012, Mileti 1999). Technology developments are increasingly allowing the inclusion of links to further information, facilitating faster information seeking and response decision-making. The order of these elements and the length of the message can themselves influence responses, with social science research showing that relative to shorter messages, longer messages can reduce people's inclination to search for further information, which then shortens the delay before responding (Wood et al. 2017). In addition, each of the information elements should be addressed by the five stylistic dimensions of a warning message, which are specificity, consistency, accuracy, certainty and clarity (Mileti & Sorensen 1990).

Familiarity and education have a key role to play. When a response is practised frequently, it becomes an almost automatic reaction. Fire alarms are a good example. Practising fire evacuations is mandatory for organisations in many countries, to ensure that employees not only recognise the warning but know what to do without thinking about it. Most hazard warnings are more complex than that but achieving an initial reaction through familiarity is still important. Beyond that, the response will be informed by knowledge, which requires education. The best time to learn is at school, but education about hazards and their impacts, warnings and their capabilities should be continuous and focused especially on those lacking familiarity with the area they live or work in. Education may take many forms, ranging from talks and workshops, through paper exercises and online games, to drills and full-scale exercises (ITU 2019). These build on one another and can be targeted at different stakeholders. Opportunities for knowledge reinforcement ahead of periods of increased risk should be taken, whether provided by changes in the seasons or by long-range weather forecasts. A critical issue is to mainstream warning-related learning units designed for different age groups in different subjects in order to guarantee that risk education is part of the curriculum.

Weather forecasts and warnings are inherently uncertain. Yet, reducing uncertainty is not the same as managing the effects of scientific uncertainty and communicating it (Brashers 2001). Notably, reducing and communicating uncertainty require completely different types of knowledge and expertise, ranging from natural to social sciences. Research shows that people understand that there is uncertainty inherent in weather forecasts, as well as that different scientific factors shape this uncertainty (Joslyn & Savelli 2010). With respect to communication, some researchers argue that communicating scientific uncertainty (e.g. in probabilistic forecasts) leads to better outcomes (Fischhoff & Davis 2014), as it will increase understanding (Stirling 2010). LeClerc and Joslyn (2012) found that providing weather forecasts (of high consequences but low probability) with uncertainty information enhances the chances that users take precautionary action. However, conclusions about how scientific uncertainties should be communicated (quantitative vs. qualitative, graphs/maps vs. text, etc.) are not yet clear and depend on the user, the context and the type of information.

Technological improvements continually reduce the level of scientific uncertainty in weather forecasts and warnings. Over the last decades, messages have been improved as warnings are made with greater accuracy, geographic precision and lead time. However, the information is not always clear, specific or consistent. Information may be more or less available, information from different sources may be inconsistent or contradictory, and information can increase or decrease the perception of uncertainty (Brashers 2001). For example, many people do not understand the standard phenomenon-based warnings and have difficulties translating a ‘heavy’ rainfall warning (e.g. indicating 100 mm of rain) into effective impacts. Communicating specific impacts, for instance on road and rail transport, and possibilities of delays, could improve warning effectiveness (Weyrich et al. 2018). Moreover, it is important that a warning message is consistent within itself and across different messages (Mileti & Fitzpatrick 1992). This means that the underlying meaning of a message and potentially the colours and terminology used are similar or uniform, including from different providers at a given point in time (Williams & Eosco 2021).

Unlike in some weather forecasts, including probability of rain forecasts, there is almost no room for the communication of uncertainties within most current public warning systems. Warnings are issued by a forecaster when expected weather events reach a subjective level of certainty. The inclusion of probabilistic information could enable the forecaster to better communicate the varying degrees of certainty associated with each warning situation. However, the price of this type of probabilistic information can be the risk of misinterpretation or lack of understanding within the target audience (Kox, Kempf et al. 2018). One means of dealing with these complications that has gained credibility in climate forecasting is to develop storylines based on forecast scenarios (Shepherd 2019). For instance, during December 2011, an extratropical cyclone was forecast to move up the English Channel, producing extensive snow in central England (Mylne 2012). However, within the range of ensemble predictions, there was a low probability that the cyclone would turn north, moving the area affected by snow and allowing damaging winds to affect the extreme south-east of England. Rather than limit his presentation to the most likely forecast, or attempt to present probabilities, the TV forecaster chose to convey the uncertainty by presenting these two scenarios as alternative storylines of likelihood and impact.

Communication of uncertainty is further complicated because it is multifaceted: not just scientific but also social, legal, institutional and political uncertainties affect how a warning is perceived and acted upon. Moreover, perceptions of uncertainty vary between people and social groups: one person may have an amount of information that other people would deem sufficient to make a decision, yet she/he may still feel uncertain on what to do (Brashers 2001).

While the general inclusion of probabilistic information in public warnings remains challenging and contentious, there is no doubt that it is an important component of the communication with many professional responders. In some cases, they have sufficient evidence to calibrate their actions directly on the probability of a specific threshold being crossed. In these cases, a role of the relationship is to identify these thresholds and the nature of the uncertainties, so that the warner can ensure that the information reaching the receiver contains the required level of probabilistic detail, and that it is unbiased.

Box 3.4 Probabilistic Weather Information for Emergency Managers in Germany
Nadine Fleischhut

Although probabilistic forecasts are key to informing decisions under uncertainty, probabilistic weather forecasts are still rarely communicated to lay audiences due to fears that they are difficult to communicate clearly and that lay people may be reluctant to use them. Yet there is growing evidence that people understand probabilistic information if it is presented transparently (Hoffrage et al. 2000), that it can improve decisions (e.g. Joslyn & LeClerc 2013) and that it is preferred by the public (Morss et al. 2008). In contrast, deterministic warnings can hinder informed decisions, since forecasters must issue warnings without knowing the needs of their users, who are left to guess the uncertainty of the forecasts (e.g. Fleischhut et al. 2020, Joslyn & Savelli 2010). Probabilistic forecasts, however, enable everyone to apply the decision thresholds that fit their needs.

(continued)

In Fundel et al. (2019), we described how we evaluated the usefulness of probabilistic forecasts for emergency managers' decisions in Germany. As a large and diverse group, their required lead times and probability thresholds differ considerably (Kox et al. 2015), likely reflecting varying institutional constraints and capacities (Demeritt et al. 2010).

Using a new approach, we designed FeWIS Pro: five uncertainty representations implemented in parallel within the fire brigade weather information system (FeWIS) of Germany's national meteorological service. The representations display forecasts for wind, rain and thunderstorms (48-hour lead time) as probabilities for binary events (exceeding warning thresholds) or as probability thresholds for continuous variables (e.g. for wind or precipitation). All representations were designed based on evidence from risk communication research in a range of fields, including medicine. The approach made it possible to observe and quantify emergency managers' preferences under real operational constraints and over a longer period of time.

We analysed which representations emergency managers preferred for two severe storms (Xavier and Herwart) in Germany in October 2017 (see Fig. 3.5). In general, emergency managers used probabilistic forecasts frequently, indicating that they found the forecasts informative and useful. During both storms, the most frequently consulted representation was a map displaying probabilities for exceeding warning thresholds. The map, which provides a clear overview of the areas most likely to be affected by the storms, may be useful for emergency managers coordinating emergency services, vehicles and personnel.

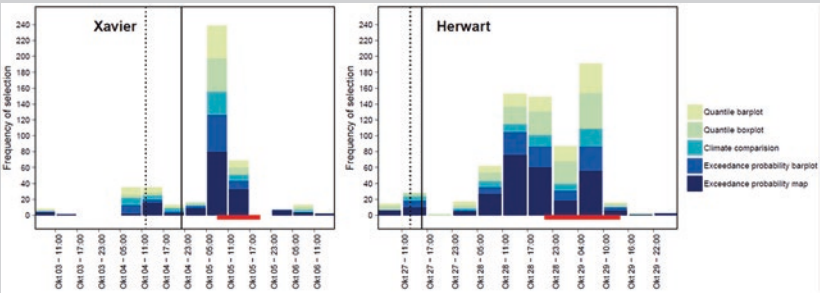

Fig. 3.5 Search for information before, during and after storms Xavier and Herwart. Plots show how often each representation was selected by time, from 48 hours before to 24 hours after the storm. Dotted lines mark when the first weather watch was issued; solid lines mark the first weather warning. Red lines along the x-axis indicate when the storms passed through Germany. For each storm, the analysis includes the behaviour of emergency managers who should expect to be affected first by the storm, defined here as all users for which the 90 percentile of the forecast was ≥110 km/h during the first third of the storm ($N = 93$ collective users for Xavier; $N = 114$ for Herwart). Overall, they selected representations 439 times during Xavier and 722 times during Herwart. For details, see Fundel et al. (2019)

(continued)

The other four representations presented timelines for a selected area. Of these, the representation of probabilities of exceeding warning thresholds was used most frequently during Xavier. Box plots showing the likely range of wind speeds were used most frequently during Herwart; they were only slightly less popular during Xavier. Quantile information (e.g. box plots) was consulted frequently shortly before – and even more so during – a storm.

Emergency managers' focus on warning thresholds may reflect that their main duties are reactive and that warnings trigger a range of decisions, such as the declaration of an emergency. Representations displaying probabilities of exceeding warning thresholds may thus be particularly useful during an early weather watch. In contrast, quantile plots such as box plots make it easier to evaluate how wind speeds might develop; they may therefore help emergency managers maintain the ability to respond during an event and prepare for daily operations afterwards (see also Kox, Lüder et al. 2018).

FeWIS Pro was developed as part of the interdisciplinary research project WEXICOM, funded by the Hans Ertel Centre for Weather Research. WEXICOM aims to improve the communication, understanding and use of uncertainty in weather and impact forecasts. The work and results reported here have previously been published in more detail in Fundel et al. (2019).

3.4.3 Measuring Success

The question of what makes a warning successful is one of the key aspects identified in the HIWeather context (Zhang et al. 2019). Agreeing how this will be assessed is critical to the relationship between warner and receiver. Transparent sharing of evidence and its interpretation is essential. Yet often the producer assumes that it is sufficient to verify the observable components of the information content, using statistically correct methods, and is then surprised if the receiver has a quite different perception of the value of the warning service. While the roots of successful warnings lie in having accurate meteorological information, its value depends on applications of the social, behavioural and economic sciences (Zhang et al. 2019), thus becoming an interdisciplinary matter.

To be successful, the warning must enable its recipients to make the right decisions to protect themselves and their communities (Golding et al. 2019; Taylor et al. 2018). In order to achieve an effect in the sense of risk-reducing behaviour through warning communication, warnings must generate attention (wake-up signal), indicate potential impact and give guidance for adequate response.

Recipients may differ in their needs and requirements for weather information and warnings, subject to their responsibilities and competencies. Thus, what constitutes useful or 'good' information varies according to the areas of activity an end user represents. In an essay on the goodness of weather forecasts, Murphy (1993) mentions three general types of forecast goodness: consistency, quality and value.

In order to be consistent, the forecast (oral or written) should be the best possible estimate or assessment of the weather situation by the forecaster. The forecast may be inconsistent if it contains (more or less) spatial or temporal specificity, or if the uncertainty in the judgement of the forecaster is not accurately reflected in the corresponding forecast, either in words or numbers. Quality refers to the degree of agreement (or similarity) between the forecast and observed events, expressed in terms of distortion, accuracy or skill. Finally, the value refers to an increase in benefit to a forecast user as a result of using the forecast. End users of forecasts and warnings place particular emphasis on the value aspect of a forecast's goodness (Kox, Kempf et al. 2018). Economic perspectives are most commonly used to define the value of weather forecasts and warnings (e.g. Lazo et al. 2009), but weather forecasts do not have an intrinsic value in an economic sense, they rather have a specific value for a user when he/she takes measures, and these measures avoid or reduce damage costs (Murphy 1993, 1994, Mylne 2002). Kox and Thieken (2017) add that a purely economic perspective does not apply to situations where monetary damage costs are difficult to allocate, such as loss of life or social or political prestige. In other situations, people may want to act, but may not be able to do so due to professional constraints or limited resources.

Fire brigades are a good example of such an end-user group operating outside of a simple cost-loss analysis, while road maintenance services responsible for salting roads have clearer cost calculations (Kox, Kempf et al. 2018). Accordingly, the end-user perspective may vary on what is understood as the goodness of a forecast or the success of a warning. A warning message that is of high value to one user may be useless to another. In this context, the ability to tailor warnings to individual needs (Joslyn & Savelli 2010) and to provide access to additional meteorological information is of importance to achieve high value for all end users.

Keeping all that in mind, the measurement of success is a difficult task. It gets further complicated by the possibility of 'grades of success' (Golding et al. 2019), for instance in near-miss situations, when the spatial or temporal extent is only slightly in error (Sharpe 2016), or in situations where no damage occurs due to successful warning. For example, in the case of road icing, observations of road state will not show that the road is covered in ice if it has been treated in advance, though the temperature may still show the road surface to be below freezing. In this instance the meteorological trigger for the hazard (sub-zero temperature) is verifiable, but the hazard itself (slippery road) is not. Here, the absence of such impacts might be an indicator of success especially if other impacts of the hazard are observed.

Continuous evaluation of warnings is essential if the benefits of improvement are to be identified and any degradation is to be arrested quickly. Changes in technology and external conditions can otherwise lead to a warning system rapidly losing its impact. Regular surveys of a range of users, especially following the issue of warnings, should be followed up with one-to-one interviews to identify negative issues before they lead to a loss of trust, and to reinforce positive changes.

To improve weather warnings in all three dimensions of forecast goodness, a broad range of challenges need to be addressed. A strong collaboration between the main users and the national weather services in the form of an ongoing dialogue and discussion of critical needs is important for the success of weather warnings (Kox, Kempf et al. 2018). This dialogue should be particularly active following any unsuccessful or only partially successful warning, to bring together the perceptions of the two sides and to conclude a joint evaluation. In parallel, it is also important to explore new options (e.g. for warning communication) from the perspectives of different stakeholders and to test these options theoretically and sometimes practically, to determine what is critical to improve the process from warning to decision (World Bank 2019).

Relationships are not static, and it is essential that the success of a particular relationship is reviewed frequently. With rapid population growth and urbanisation occurring in much of the world, vulnerabilities are changing, while in a warming climate, the hazards to which audiences are exposed are changing, too. And with new technical capabilities, both the forecast quality and the ability to communicate them are shifting. Among all these external changes, the lifestyles and expectations of warners and receivers, and the structures and personnel of the partner organisations, are also evolving. For a relationship to survive and thrive in this dynamic environment, it requires active management – including an open channel for feedback on any aspect of the warning service. However, it is also important to periodically review the health of the partnership: is the relationship still the right one? Does it have the right membership? Are the outcomes improving? Is the cost affordable? All of these questions should be addressed periodically – perhaps every 5 years – and if the answers are 'no', the relationship needs overhauling. Below is an example of rapid changes in the development of an early warning system.

3.5 Example

Box 3.5 Community-Based Early Warning System in Nepal
Dharam Uprety and Bikram Rana

Based on work undertaken in 2018.

Extreme and regular flooding in Nepal results in significant loss of life, property and livelihoods (Practical Action 2009, 2020; Bhandari et al. 2018). In response, several flood early warning systems (EWSs) have been established, in an attempt to reduce the number of people affected and killed by floods. However, there are still challenges in these systems, especially in communicating flood warning to the most vulnerable and ensuring they have the skills and resources to be able to respond:

> "If we can get information before the floods come, it will save our lives. We may not be able to rescue everything, but our children and families will be saved."

The roll-out of flood EWSs began about 20 years ago and was initially focussed on manual observation towers. These towers provided peace of mind

(continued)

for people in their immediate vicinity but had numerous limitations such as maintaining observers 24 hours each day as well as communicating warnings during heavy rainfall events. Their success created the momentum to work with the national Department of Hydrology and Meteorology (DHM) to explore more comprehensive systems, with expansion into real-time river level monitoring, automation of gauge stations and subsequently the adoption of technologies including forecasting and SMS messaging. The evolution of the system is indicated in Fig. 3.6.

The evolution of the EWS has been marked by parallel improvements in the local area. For example, social capital has been enhanced between the upstream and downstream communities, with a substantial number of households informing their neighbours immediately after receiving flood warning, and this is the primary warning source for many households. The increased warning time gives people more time to respond; human capital has been built as individuals have adapted from 'fright and flight' to learning what to do, including moving vulnerable assets to high ground or stored on upper floors prior to evacuating, with these responses reinforced by annual drills. This additional time has enhanced learning, and community members have constructed simple mitigation measures, such as waterproof storage facilities in their houses for grains and less movable assets, improving their physical

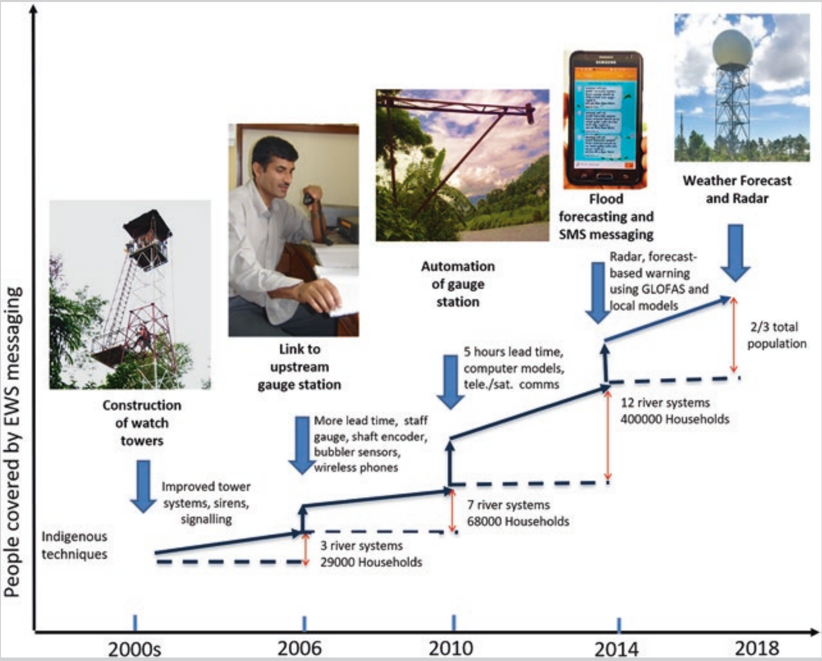

Fig. 3.6 Development and use of technology for flood early warning systems in Nepal

(continued)

capital. As local communities have experienced the positive benefits of the EWS, some people have started to express a willingness to pay for the EWS services, offering a boost in financial capital and perhaps a long-term and sustainable mechanism to cover the EWS operational costs long term. This has been further enhanced with the two major telecommunication companies in Nepal (NTC and NCELL) joining hands with DHM to send free mass SMS warnings to all mobile users living in the flood plains of major river basins during the monsoon:

> "If we can make early warning effective and efficient, the necessity for rescue can be reduced – if we can manage better with what we have I don't think we need 'big' technologies, we don't need more resources and we don't need extra personnel."

However, the EWS is far from comprehensive and many challenges remain. Firstly, climate change is a huge uncertainty in the Himalayas with implications for the appropriateness and robustness of the evolving system. Secondly, while progress has clearly been made in the monitoring and forecasting, integration of sociocultural aspects needs to be strengthened that can make early warning information accessible to the most vulnerable. Thirdly, engagement and ownership with local communities must be maintained to ensure the system is co-designed to deliver information tailored to meet their diverse needs for rapid dissemination and timely protective action. Finally, for flood risk communication to bridge 'the last mile' in terms of reaching the most vulnerable in the community, it must take account of their distinct social, economic and political experiences in both the content and the delivery of the information.

3.6 Summary

We conclude the chapter with a checklist of aspects of the warning that need to be considered to improve the relationship between warner and decision-maker/receiver when designing or upgrading a warning system:

- The 'warning to decision' process is not only about exchanging information but also about establishing relationships. Effectiveness depends on attention to both.
- A strong collaboration between the warner and receiver in the form of an ongoing dialogue and discussion of critical needs is the starting point for the success of warning communication. Only by understanding the decisions that individuals face can the warner produce the information that they need. The process is further characterised by continuous, flexible interactions between warner and receiver, including support in personalised preparedness planning, warning evaluation, co-design of warning system options and co-production of information, e.g. through citizen science. In these cases, the receiver's role shifts from pure user to collaborator and partner.

- To be effective, a warning message should contain the information elements of hazard, impact, location, time, guidance, source and a link to further information. In addition, each of the information elements should be addressed – to the extent possible – by the five stylistic dimensions of specificity, consistency, accuracy, certainty and clarity. Besides these general characteristics, a warning message should be tailored to different audiences. The international standard Common Alerting Protocol (CAP) minimises the overheads of using multiple channels and increases interoperability of systems.
- Not only addressing needs but also personalising the message by including information about local disruptions and impacts through impact-based forecasts and warnings may help to prompt effective responses. These warnings require substantial improvements in impact data collection and storage.
- Information sources, social and environmental cues, channel access and preferences and receiver's characteristics are key factors influencing a behavioural response after a warning is received.
- Reducing uncertainty is not the same as managing the effects of uncertainty and communicating it. There is no 'one fits for all solution' for managing and communicating uncertainty. Not only scientific but also legal, social, institutional and political uncertainties need to be taken into account for effective warning communication, together with the complete range of behavioural and psychological responses to uncertainty.
- Working with trusted sources and the public, testing different message options and evaluating the results of communication and cooperation efforts are critical. New technologies increasingly allow evaluation of communication effectiveness, sometimes even in real time using smartphone applications. The evaluation of warning communication as standard practice is also critical to guarantee that lessons are learnt and needed reforms are implemented. Evaluation also allows the public to provide robust feedback on warning message effectiveness and the warner to establish a permanent communication channel.

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