**Chapter 23: Should I stay, or should I go? Evacuation vs. shelter-in-place under imminent natural hazard threat**

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**1. Introduction**

*1.1 Hazards and protective actions*

Evacuation has a long history as the hazard protective action advocated by authorities: “For emergency managers, evacuation may be seen as a generic protective mechanism. It is effective across a variety of disaster agents: floods, hurricanes, volcanic eruptions, hazardous materials incidents and nuclear power plant accidents, to name only a few” (Lindell & Perry, 1991, p. 133). Table 23.1 summarises the protective actions recommended generally by authorities for what have been notably deadly types of hazard events globally (Abbott, 2017). Of the eight hazards listed, evacuation is the protective action recommended by authorities for all but two —tornadoes and earthquakes. However, for floods and wildfires sheltering in place has been proposed as a viable option. In addition, researchers have concluded that mobile and manufactured[[1]](#footnote-1) homes do not provide adequate shelter protection to residents in the path severe tornadoes, and the recommended protective action for these residents is to evacuate and shelter in nearby community tornado shelters or other sturdy structures.

Table 23.1 Natural hazards and protective actions recommended

by authorities

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| **Hazard** | **Recommended protective action** |
| *Weather-related hazards* |  |
| Floods | Evacuate, avoiding floodwaters |
| Tornadoes | Shelter underground or in a sturdy structure |
| Tropical cyclones (hurricanes, typhoons) | Evacuate inland |
| Wildfires | Evacuate to a safe location |
| *Geophysical hazards* |  |
| Earthquakes | Shelter using ‘drop, cover & hold on’ for most countries. |
| Landslides | Evacuate from steep slopes  |
| Tsunamis | Evacuate to high ground |
| Volcanic eruptions | Evacuate the area |

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Note: heat waves, droughts, famines, and pandemics were not considered

Before discussing evacuation versus shelter-in-place issues, terminology needs to be clarified. In ordinary conversation, ‘evacuation’ is what happens when people are removed from, or leave, a hazardous place. However, in the field of disaster management several distinctions are often made. *Preventive* evacuations occur prior to the impact of hazards in order to prevent injuries and loss of life, but post-impact evacuations may be initiated to reduce subsequent threats to life such as exposure to extreme weather and the spread of disease. Preventive evacuation is also distinguished from so-called *vertical* evacuation[[2]](#footnote-2) (also called evacuation to shelter, see below). In the former, people leave the area predicted to be impacted by the hazard. In the latter, people remain within the threatened area but relocate pre-emptively to nearby places deemed to be less vulnerable to the hazard. Evacuation may be *voluntary*—when people make the decision to leave the area based on their own appraisal of the likely threat posed by the predicted hazard; or *advisory*—when people choose to heed the advice from the relevant authority that they should leave; or *mandatory*—when authorities order people in the threatened area to leave, often reinforced by the threat of forcible removal. Evacuations may be *organised*—with authorities determining the timing and providing the means of egress, for example using aircraft, or *individual*—when individuals and households make their own travel arrangements, mostly using private vehicles or on foot.

In everyday conversation, ‘sheltering’ usually means taking refuge from some source of danger, as distinct from evacuating from the danger area. However, as Cova et al. (2011) noted, there is a lack of standardisation in terminology describing protective actions. They proposed that shelter-in-place protective action can take the form of either *refuge shelter* or *in-home shelter*. Refuge shelter typically refers to sheltering passively after a short trip to the chosen place of refuge in a vehicle or on foot—sometimes described as *evacuation to shelter*. The refuge may be a facility designated by authorities as an official place of refuge such as a community wildfire refuge, or it may be an informal place of last resort survival such as nearby high ground in the event of a tsunami threat. In-home shelter may involve sheltering passively in the home relying on the inherent protective nature of the house structure, or taking refuge in a purpose-built shelter which is part of the house (such as a cellar tornado shelter), or on the property close to the house (such as a household wildfire ‘bunker’). Alternatively, in-home shelter may involve actively defending the property against threatening aspects of hazard, usually described as a *stay and defend* protective action, notably in relation to defending a home against wildfire attack or rising floodwaters. However, as Cova et al. (2011) observed, ‘shelter-in-place’ may be used to refer to all forms of sheltering within a threatened area, or it may refer solely to the situation where no travel is involved—usually in-home shelter. Except where otherwise stated, we use shelter-in-place to refer to protective actions involving passive sheltering associated with no or minimal travel.

*1.2 Evacuation versus shelter-in-place: issues*

It seems that the respective merits of recommending residents evacuate or shelter-in-place when threatened became an issue of concern for authorities following several accidental toxic chemical plant releases and nuclear power plant emergencies in the 1970s and 1980s. In a frequently cited paper Sorenson et al. (2004, p. 2) encapsulated the critical issues as follows: “Conceptually, the evacuation/in-place protection decision is simple and revolves around two questions:

1. Will shelter in place provide adequate protection?
2. Is there enough time to evacuate?”

The authors noted that in, relation to a specific threat, if the answers were ‘yes’ to one question and ‘no’ to the other, then the issue was resolved; if the answers were ‘yes’ to both then considerations other than residents’ safety, such as the amount of community disruption or cost, should be the deciding factors; if the answers to both were ‘no’, then other options, such as rescues, should be explored. In reality however, the answers to these questions will often by shades of ‘maybe.’

In principle, seven somewhat inter-related factors determine appropriate answers to the questions proposed by Sorenson et al. (2004) about a specific hazard threat to a particular location.

1. The physical nature of the hazard and the sources of its danger to life: the forces and energies involved. Hazards vary greatly in the mechanisms by which they threaten life: wildfires can kill at a distance through radiant heat causing fatal hyperthermia (need to insert reference), most tsunami deaths result from drowning (Keim, 2006) (Table 23.3).

2. The properties of the available shelter options: their ability to protect people from the life-threatening aspects of the hazard. Viable shelter options can vary considerably according to the nature of the hazard. They can include fire-resistant defendable homes for wildfires; and tall, solidly built structures for floods.

3. The amount of time available from detection of the threat to the predicted impact of the hazard on the community, and the amount of time required for the threatened community to evacuate. In their typology of hazards in relation to community warnings Mileti and Sorenson (1990) noted several features of different hazards which determine whether or not there will be time for residents to evacuate safely, including (a) predictability, authorities’ ability to forecast the location and timing of impact of a hazard; (b) lead time, the amount of time between detection of the hazard and impact on threatened communities; and (c) visibility, the degree to which a hazard manifests itself so that residents are directly aware of the developing threat.

4. The evacuation options: whether evacuation is mandatory or advisory; and the available egress routes and safe(r) destinations. Mandatory evacuations appear to result in higher levels of compliance and lower levels of delayed evacuations (Thompson et al., 2017). However, when a mandatory evacuation is ordered by authorities egress roads can become congested due to the sudden high traffic volume. Destinations can range from large well-equipped and staffed community evacuation centres established some distance away from threatened locations, to nearby places of last-resort survival in the face of fast-moving wildfires, such as in vehicles parked on sports fields (Blanchi et al., 2018).

5. Levels of preparedness of threatened residents to take appropriate protective actions. There is a body of evidence indicating that readiness of members of the public to evacuate is related to their level of preparedness for the hazard (Thompson et al., 2017). Research has indicated that levels of household preparedness to take protective actions in the face of natural hazard threats are generally lower than desirable (Thompson et al., 2017; Wachinger et al., 2013).

6. The level of risk associated with the evacuation. There have been disaster events where the number of casualties among evacuees has exceeded that among those who sheltered-in-place (Cova et al., 2011; Haynes et al., 2018). The stress of an evacuation may have serious adverse consequences for vulnerable populations such as elderly resident of aged care facilities, including elevated mortality rates (Willoughby et al., 2017). The economic and social costs of a large-scale evacuation are likely to be considerable (Kolen & Helsloot, 2014).

7. The national, cultural, and socioeconomc context of the threat to at-risk communities. In contrast to OECD countries, most developing countries are characterised by relatively weak economies and limited communications, transport, and emergency response systems. Location and construction of dwellings and structures outside major cities are largely unregulated by development and building codes. When a hazard strikes a developing country protective action options for residents are likely to be limited resulting in appreciable numbers of dead and injured. Historically, this has been especially so for meteorological hazards such as tropical cyclones (*2.3*). Hurricane Sandywas the deadliest [hurricane](https://en.wikipedia.org/wiki/Tropical_cyclone) of the [2012 Atlantic hurricane season](https://en.wikipedia.org/wiki/2012_Atlantic_hurricane_season). In the US, Hurricane Sandy affected the entire eastern seaboard from [Florida](https://en.wikipedia.org/wiki/Florida) to [Maine](https://en.wikipedia.org/wiki/Maine). Its [storm surge](https://en.wikipedia.org/wiki/Storm_surge) hit [New York City](https://en.wikipedia.org/wiki/New_York_City) on October 29, flooding streets, tunnels and subway lines. Across all the affected areas in the United States (US) there were 106 fatalities. In late April 2008 Cyclone Nargis formed in the north east Indian Ocean and made [landfall](https://en.wikipedia.org/wiki/Landfall_%28meteorology%29) in Myanmar on 2 May 2008, sending a [storm surge](https://en.wikipedia.org/wiki/Storm_surge) 40 kilometres up the densely populated [Irrawaddy](https://en.wikipedia.org/wiki/Irrawaddy_River) [delta](https://en.wikipedia.org/wiki/River_delta), causing catastrophic destruction and at least 138,370 fatalities.

*1.3 Warnings*

Natural hazard warning messages provided by authorities play a crucial role determining residents’ protective actions. However, the process by which residents make decisions and take action following a hazard warning is complex and warning messages may fail their purpose at many points: warnings may be missed, ignored, misunderstood, or rejected. Mileti and Sorenson (1990) described the warning-protective action process as involving six stages.

1. Registering. Both official and unofficial warning messages must be heard (radio, TV, siren, phone) or viewed (TV, SMS); environmental cues must be seen or heard or felt (e.g., smoke, heavy rain, earth tremor).

2. Understanding. Once registered, the threat and protective action implications of the messages or cues must be understood. Such understanding may result from one or more of prior experience of the hazard, previous community education endeavours by authorities, social memory (Reid et al., 2018), or cultural tradition (Rahman et al., 2017). For some, such as newcomers to the community, understanding may be lacking.

3. Believing. Once understood, people make judgements about the believability of the warning. Perceived trustworthiness of the sources of warning messages is a key aspect of message credibility. Belief is enhanced by warnings from multiple sources communicating consistent message content. Inconsistencies between warning messages and environmental cues may generate doubt and uncertainty (Dootson et al., 2019). ‘Milling’ occurs often in the Understanding and Believing phases as people seek to reduce uncertainty by searching for corroborating information—often from trusted informal sources such family, friends and neighbours. Such information searching may unnecessarily delay taking appropriate protective action.

4. Personalising. Realisation of likely adverse effects of the hazard on self and household is a critical development. It generates awareness of a need to take some form of protective action.

5. Deciding and acting. Decisions about taking protective action—including that of taking no action—are made based on the information at hand about the threat, including that contained in warning messages, and the person’s understanding of the household’s circumstances. An initial decision to evacuate may be set aside in favour of taking shelter (in one form or another) following re-evaluating and concluding that safe egress is doubtful. An initial decision to shelter in place or to stay and defend may be rejected in favour of evacuating upon realisation of the likely severity of the hazard. A delayed evacuation attempt may have to be aborted and last-resort survival attempted.

6. Confirming. This is activity—endeavouring to update the information about the hazard threat—may be undertaken during all the preceding stages. It allows people to reconsider risks and alter decisions. It may also serve to delay decision making in order to avoid committing to an action. Information searching is most likely in an information void, when authorities are not providing regular updates about a developing threat situation.

**2. Weather-related hazards**

*2.1 Floods*

Most flooding occurs following extended periods of heavy rainfall[[3]](#footnote-3) and this results in a significant number of deaths annually world-wide. Researchers have reported generally low levels of preparation by residents to mitigate their risk from floods, in the form of both minimising damage to homes and contents, and readiness to evacuate. Evacuation is the protective action recommended by authorities because of four major dangers. First, the large lateral forces involved in the flow of floodwaters can destroy or sweep away homes and other structures. Second, rising flood waters can submerge homes. Third, threats may be posed to health by contaminants in the water (especially human and animal waste). Finally, the likelihood of long-term isolation of people in the flooded areas with lack of power, potable water, food, communications and medical help. However, several reports have demonstrated that “…other than those who were rescued or evacuated late, many people have sheltered, either through choice or necessity in a large number of floods worldwide” (Haynes et al., 2018, p. 781).

Several studies across OECD countries found that few flood related deaths have occurred while people were sheltering: most fatalities have resulted from people drowning after entering floodwaters, either in a vehicle or on foot (Haynes et al., 2017; Petrucci et al., 2019). Haynes et al. (2009) noted the importance of distinguishing between flash flooding (in which very rapid water level rises occur within about six hours of intense local rain) from riverine flooding, which occurs more slowly, is more widespread and develops over a longer time span. Haynes et al. concluded that sheltering in place was likely to be a safer option than evacuating during a flash flood event, provided suitable shelter was available: adjacent higher ground or a suitably tall and sturdy structure.

Haynes et al. (2018) noted that there were very few published studies examining reasons for sheltering in place during flooding and experiences of those who sheltered. They reported findings from interviews and questionnaire responses from more than 400 residents in flood-prone areas of Australia’s east coast about their most recent flood event. About one quarter reported that they remained on their property because they had no choice: it was deemed too unsafe to leave. Three-quarters of these residents stayed on their properties because they felt safe to do so, and about one-third of them also wished to protect property or animals. The experiences of staying varied greatly. For many, it was a very stressful experience due to uncertainty about how high the water would rise and how long they would remain isolated. Haynes et al. concluded that authorities needed to recognise that safe evacuation was not always possible, and instead of simply emphasising evacuation to engage with at-risk communities to better educate residents about preparation for sheltering in place if this was their choice or in case evacuation was not possible.

Recent research indicates that the channels for flood warnings preferred by residents are television, radio and text (SMS) messages sent by agencies (O’Sullivan et al., 2012), while the channels through which residents receive flood warnings most often are phone or text messages from family, friends and neighbours, and television and radio news items (Ryan, 2018). There is some evidence that impact-based (severity) warnings (IBW) are more useful to residents for making protective action decisions than conventional hazard warnings (HW) which make geographic predictions using probabilistic language (Melendez-Landeverde et al., 2019).

Overall, the lessons from the literature seem to be (a) that early and accurate warnings of flooding are crucial to allow safe evacuations by those who do not plan and prepare to shelter in place during a flood event; (b) those who intend to shelter in place need to be well-informed about what this will involve and the preparations needed; and (c) official warnings which emphasise likely severity of flooding are more likely to lead to considered protective actions by residents compared with warnings of probable flooding locations.

2.2 Tornadoes

A tornado is a rapidly rotating vertical column of air descending from a thunderstorm and making contact with the ground. They occur in many countries but are a notable hazard in central regions of the US, where they form as a result of a lower-level warm, moist air mass encountering an upper-level cold air mass moving in the opposite direction while being perturbed by a high-altitude jet stream (Abbott, 2017). Their destructive power results from the high wind speeds of the rotating air column. Tornadoes are most commonly classified according to their destructive capability based on wind speed using the Enhanced Fujita (EF) scale as shown in Table 23.2.

Table 23.2: Enhanced Fujita Wind Damage Scale

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| Enhanced Fujita Scale | Wind speeds kph**a** | Damage level |
| EF-0 | 105 – 137 | Minor damage. Some damage to roof gutters or awnings; branches broken off trees; shallow-rooted trees pushed over. |
| EF-1 | 138 - 177 | Moderate damage. Roofs damaged; loss of exterior doors; and windows, mobile homes overturned or badly damaged. |
| EF-2 | 178 - 217 | Considerable damage. Roofs torn off; homes shifted off foundations; mobile/manufactured homes destroyed; large trees snapped or uprooted. |
| EF-3 | 218 - 266 | Severe damage. Houses destroyed; severe damage to large buildings such as shopping malls; trains overturned; heavy cars lifted off the ground and overturned. |
| EF-4 | 267 - 322 | Devastating damage. Well-constructed houses completely levelled; cars and other large objects thrown through the air. |
| EF-5 |  > 322 | Extreme damage. Well-built houses blown away; steel-reinforced concrete structures severely damaged; tall buildings collapsed or have severe structural deformations; cars, trucks, and trains can be thrown a kilometre or more. |

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**a** The EF scale was developed based on wind speeds in mph.

The major causes of death during tornadoes are traumatic injuries resulting from persons being thrown into the air or being struck by high velocity wind-blown objects. In addition to wind speed, the other dangerous aspect of a tornado is its ‘track’: the area of ground contacted by the vortex, or vortices. This depends principally on the tornado’s time period of ground contact and its forward rate of travel. In the US since the 1980s, long-track EF-5 tornadoes have been associated with the greatest number of deaths (Abbot, 2017).

Recommended protective actions are to evacuate the predicted impact area, in a vehicle, but only if there is ample warning; otherwise to shelter immediately in a community tornado shelter or other solidly built public access structure; or in a home cellar shelter or purpose-built ‘safe room’, or in an interior room in a permanent dwelling. Following the disastrous 2011 tornado season in the US, Simmons and Sutter (2012, p. 959) noted that “Permanent homes offer adequate protection for weak and even strong (EF-2 or EF-3) tornadoes, provided residents receive a warning and take shelter in an interior closet or bathroom prior to impact…(however) these rooms often fail to protect residents from an EF-4 or EF-5 tornado”. While the wind speed and track of a tornado are the principal sources of danger, three other issues are central to residents’ evacuate versus shelter decisions: accuracy of predictions, lead times of warnings, and shelter options. Despite advances in predictive capability it remains well-nigh impossible to predict precisely when and where a tornado will form and touch ground, Trainor et al. (2015) reported a 74 percent false alarm warning rate for all tornadoes in the US over a 5-year period. Historically, homes in at-risk US communities were constructed with cellar storm shelters. However, new homes are often constructed without these to save costs. In their place some homes are now built with tornado-resistant ‘safe rooms’, but these add to cost (Simmonds & Shutter, 2012) and since the 2011 tornado season (with 553 fatalities) community shelters have been increasingly provided by local authorities.

In summary, the dangers of being outside or in a vehicle or in a flimsy structure when a tornado strikes are so great, and the impact site and track so unpredictable, that sheltering is most likely to be the safer choice—provided that the available shelter facility is adequate to withstand the predicted intensity of the tornado.

2.3 Tropical cyclones (hurricanes, typhoons)

A tropical cyclone is a large-area, rapidly rotating, severe thunderstorm system characterized by a [low-pressure](https://en.wikipedia.org/wiki/Low-pressure_area) centre (or ‘eye’), very [strong winds](https://en.wikipedia.org/wiki/Beaufort_scale) (> 118kph) and heavy rainfall. A tropical cyclone that develops over the [Atlantic Ocean](https://en.wikipedia.org/wiki/Atlantic_Ocean) or north-eastern [Pacific Ocean](https://en.wikipedia.org/wiki/Pacific_Ocean) is called a hurricane, and is called a [typhoon](https://en.wikipedia.org/wiki/Typhoon) if it develops over the north-western Pacific Ocean. They are referred to as cyclones in the south Pacific or [Indian Ocean](https://en.wikipedia.org/wiki/Indian_Ocean)s. Tropical cyclones form over large bodies of relatively warm (tropical) water. They derive their energy from the evaporation of warm [water](https://en.wikipedia.org/wiki/Water) from the surface of an ocean, which ultimately [condenses](https://en.wikipedia.org/wiki/Condensation) into [clouds](https://en.wikipedia.org/wiki/Cloud) and then rain when the moist air rises and cools to [saturation](https://en.wikipedia.org/wiki/Saturated_fluid). The diameter of the rotating wind system can range from 100 to 2,000 kilometres. Similar to tornadoes, tropical cyclones can be categorised according to severity on the basis of wind speed, but conventions differ across countries.

The main potential dangers to human life are the same as those posed by floods—drowning, and by tornadoes—traumatic injuries from the effects of high wind speeds and from flying objects, though the areas impacted by tropical cyclones are much larger than those for tornadoes. The evacuate or shelter in place decision for those threatened by a tropical cyclone can thus be more complex than for a flood or a tornado threat. A US emergency management maxim describes the hurricane evacuation/sheltering principle as “Run from water, hide from wind” (Wolshon et al., 2005, p.130). However, an analysis of US fatalities from Atlantic hurricanes over the period 1963-2012 showed that of the 2,544 fatalities, approximately 90 percent of the deaths occurred in water-related incidents, mostly by drowning, and ocean storm surges were responsible for 49 percent of these while rainfall-induced inland flooding and landslides accounted for 27 percent. Winds were responsible for between 8 and 13 percent of fatalities, with a significant number of these resulting from falling trees (Rappaport, 2014). These findings suggest that evacuation of residents from coastal areas and inland flood-prone areas predicted to be in the path of the storm system should be the protective action of choice, given advances in the capabilities of weather services globally to predict a system’s likely path. A meta-analysis of 38 hurricane evacuation studies found no evidence that warnings which proved to be false alarms effected subsequent hurricane evacuation decisions (Huang et al., 2016). However, Ahsan et al. (2016) found that for many Bangladeshi residents who did not respond to evacuation warnings during Cyclone Aila in 2009, prior false alarms was a factor—other factors were distance from evacuation centres and the needs of their livestock. Warning messages which give greater emphasis to the likely severity of the impact of storm surges and the likely damaging effects winds on structures are more likely to prompt residents to decide to evacuate (Morss et al., 2016).

While evacuation is clearly the preferable protective action, sheltering and evacuating-to shelter in structures built to withstand cyclonic winds located inland but not in flood-prone areas, may be viable protective actions. However, storm systems which advance slowly across the terrain can deposit large rainfalls resulting in severe inland flooding. Travelling during and immediately following the passage of the storm system is likely to be particularly dangerous.

2. 4 Wildfires (bushfires, forest fires)

A wildfire (also called a bushfire or a forest fire) is an uncontrolled [fire](https://en.wikipedia.org/wiki/Fire) burning in a large area of [vegetation](https://en.wikipedia.org/wiki/Vegetation) outside urban [areas](https://en.wikipedia.org/wiki/Rural_area). Wildfires owe their destructive capability to the enormous amounts of thermal energy released through the burning of large masses of combustible vegetation. Wildfire intensities are a joint function of the available mass of vegetation and its moisture content, and weather conditions--air temperature, relative humidity, and wind strength. Most civilian deaths during wildfires result from the effects of radiant or convective heat, or from burns resulting from flame impingement. Significant numbers of deaths also result from traumatic injuries sustained in motor vehicle accidents during late evacuation attempts. The majority of house and other structure losses result from wind-driven embers igniting some combustible feature of the building (McLennan et al., 2019; Syphard & Keeley, 2019). Authorities in most jurisdictions invoke mandatory evacuation as the protective action when a wildfire threatens communities. However, in Australia evacuations are mostly advisory. During the period 2005 to 2010 the official position of Australian fire and land management agencies was that residents should choose between two protective actions in the event of a bushfire threat: stay and defend a suitably prepared house, or evacuate early: the so-called ‘Prepare stay and defend, or leave early’ policy (McLennan et al., 2019). The policy attracted considerable attention among North American wildfire researchers and fire agency personnel because of deaths during some wildfire evacuations and concerns about the number of undefended homes being destroyed (Paveglio et al., 2008). However, in February 2009 Australia experienced its worst wildfire disaster to date with 172 civilian deaths in the State of Victoria’s ‘Black Saturday” bushfires. More than 110 deaths occurred in or near to homes. Following extensive investigations authorities concluded that the policy of giving undue emphasis to active property defence was unsound due to the inherent dangers posed to structures by intense wildfires, and that evacuation should be the recommended protective action for threatened residents (McLennan et al., 2019). Numerous fatalities resulted when people sheltered passively in homes (Blanchi et al., 2018). An investigation by McLennan et al. (2013) reported that 20 percent of houses defended by residents interviewed in the worst affected areas of the 2009 fires were lost regardless of householders’ levels of preparation for property defence. McLennan et al. concluded that (a) a wildfire of extreme intensity could defeat all defence endeavours, and (b) chance factors played a major role in the success or otherwise of staying and defending as a protective action.

Appraisal of the extensive literature on the wildfire evacuation versus sheltering in place issue indicates the following:

(a) despite the emphasis by authorities on the need for prompt evacuation in the face of a wildfire threat in order to preserve lives, and provision of timely and informative warnings, many residents are reluctant to leave their homes unless there is overwhelming evidence that danger is imminent. There is a widespread tendency for people to ‘wait and see’ if evacuation is necessary. In many instances this leads to dangerously late evacuations (sometimes with fatal consequences) or residents being forced to defend inadequately prepared houses or to seek last-resort survival shelter (McLennan et al. 2019).

(b) early evacuation before wildfire threat is imminent is the safest protective action, late evacuation is particularly dangerous;

(c) Sheltering passively in a house which has been purpose-built to with stand wildfire attack on a property with a large surround-zone cleared of vegetation and other combustible material may be a viable protective action, but the outcome is likely to depend largey on the intensity and duration of the wildfire attack.

(d) sheltering passively in an inadequately prepared house is very dangerous, especially if the place of shelter does not permit monitoring of possible house ignition and safe egress from the house;

(e) successful active defence of a house is very dependent on both the intensity of the fire and the wind speed, and the vulnerability of the house structure to ember attack;

(f) successful defence of a house is more likely if: (i) the house is more than 80 metres distant from the closest substantial stand of flammable vegetation, (ii) the house is constructed of ignition-resistant materials, (iii) there is an adequate supply of water independent of town source and there is a water pump which is powered independently of mains electricity, (iv) there are four or more physically fit and mentally prepared individuals to conduct the defence;

(g) there should be a viable last-resort shelter facility available very close to the structure in case defence fails.

**3. Geophysical hazards** (< 2,000 words)

3.1 Earthquakes

An earthquake can be literally defined as an episode where the earth shakes (or quakes). Severe earthquakes can cause considerable damage to the built environment and may lead to extensive human injuries and fatalities, particularly in developing countries (Kenny, 2009). Earthquakes can also lead to landslides and tsunamis which may compound the injuries and fatalities from the event (Budimir, Atkinson & Lewis, 2014) (see below for more information on landslides and tsunamis).

The primary causes of human injuries and fatalities in an earthquake are building collapse and striking or being struck by objects and debris (Kenny, 2009; Southern California Earthquake Centre, 2020). There are now few building collapses in developed countries but this is common in developing countries where earthquake building standards are either not in place or not adhered to (Kenny, 2009; Southern California Earthquake Centre, 2020).

Many countries that are prone to earthquakes have early warning systems that can determine the exact location and ultimate size of an earthquake before the rupture has finished (Li, Lu, Song, Ma & Zhao, 2019; Wyss, 2012). While these systems can be useful in shutting down potentially hazardous operations (e.g. nuclear power plants and railways) before severe shaking occurs in most cases they don’t allow people enough time to evacuate (Wyss, 2012). Running outside during an earthquake is not recommended because of the difficulties of moving around while the ground is shaking and the risk of being struck by falling objects (Southern California Earthquake Centre, 2020). Instead people are advised to shelter in place using the ‘drop, cover and hold on’ method. The ‘drop, cover and hold on’ method recommends that people drop to the floor, cover their heads, take refuge under a solid object (e.g. a table) and hold on (Southern California Earthquake Centre, 2020). A number of other sheltering methods, such as taking refuge in a doorway and the ‘triangle of life’ (where people take shelter next to a solid vertical object) are widely known but offer little genuine protection during an earthquake (Arlikatti et al., 2019; Southern California Earthquake Centre, 2020). In developing countries where buildings are unreinforced and the risk of building collapse is reasonably high the best protective action may be to try to move outside to an open space (Southern California Earthquake Centre, 2020).

3.2 Landslides

Landslides are downhill mass movements of slope-forming earth materials under the influence of gravity (Kennedy et al., 2015). They are commonly caused by heavy rainfall on steep slopes, which may have been destabilised by removal of vegetation. Landslides, mud slides and debris flows often occur when heavy rain falls following an intense wildfire (*2.4*). Earthquakes (*3.1*) also trigger landslides. Pettly (2012) concluded that between 2004 and 2010, a total of 2,620 non-earthquake related landslides resulted in 32,322 recorded deaths, most in developing countries. The most common cause of death from landslides is asphyxiation due to burial and consequent immobilisation of respiratory and diaphragmatic functions Other fatalities result from traumatic injury (Petly et al. 2010).

Because of the powerful forces of gravity and momentum involved in mass earth movements, evacuating from the slope and the area below is the only viable protective action—survival in a landslide seems mostly a matter of fortune (Sanchez et al., 2009). However, there is typically very little warning of an impending landslide—especially those triggered by earthquakes. A period of heavy rainfall, or signs of increased seepage from nearby upslope bodies of water such as dams (Petly et al., 2010) may signal an increased likelihood of a landslide and thus allow evacuation of residents to be considered. However, in developing countries in particular, those residing on or below steep slopes mostly do so because they have no alternative. Mitigating risk from landslides in developing countries is thus often a formidable challenge because of the complex and powerful socioeconomic, financial and political factors which force vulnerable people to live in high-risk areas (Tierney, 2019). However, Coles and Quintero-Angel (2018) described an encouraging Colombian program in which local female heads of households were trained to recognise the physical signs of imminent landslide and to warn threatened residents to evacuate.

3.3 Tsunamis

A tsunami is a series of large waves of water that inundate a coastal area. Up until the mid 1980s these events were referred to as tidal waves but since then the Japanese word ‘tsunami’ has been preferred (Sutton et al., 2020). A tsunami generally occurs as a series of waves that can be 3-15 meters high and can reach speeds of 500-1000 kilometres per hour (Keim, 2006). Tsunamis are generally caused by earthquakes, volcanos, underwater land slippages and in very rare cases, meteorites (Keim, 2006). Large tsunamis can cause widespread death and destruction because of the strong forces of multiple large waves and high levels of flooding.

The sudden onset of the water means that people may drown, be struck by objects carried along by the water or impaled on/by sharp objects (Keim, 2006; Taylor, Emonson and Schlimmer, 1998). Like large flash floods, the water can possess large lateral forces that may dislodge buildings, quickly submerge dwellings, and may contain contaminants that are hazardous to health. The widespread devastation often caused by tsunamis also means that like floods people may be isolated in affected areas without essential services for an extended period of time.

Because of these factors the protective action recommended for tsunami is for people in boats is to move out to sea and for people on land to evacuate inland and to higher ground where possible (c.f. Ready.gov, 2020). Many areas that are prone to tsunami (such as areas of the Pacific and Indian Oceans) have systems that are able to detect and provide early warning of a tsunami to allow people time to evacuate (Igarashi, Kong, Yamamoto & McCreery, 2011). However, the time between the initiating event and the tsunami may be very short if the initiating event is close to the shore (Igarashi et al., 2011; Lindell et al., 2015). If people are unable to evacuate, it is possible to shelter in tall buildings but this may be problematic because of the unknown height of the flood waters, the repeated force of the large waves damaging the integrity of the structure and the risk of being isolated in a disaster area for an extended period of time without essential services.

3.4 volcanic eruptions

Volcanos come in all shapes and sizes but often they are an obvious feature of the landscape and people are normally aware of their presence. However, volcanos may be quiet for many decades or centuries and even during heightened activity and eruptive episodes there may be long periods of time where there seems to be little or no threat (Perry & Godchaux, 2005; Siebert, Cottrel, Venzke & Andrews, 2015). In consequence human settlements may be established quite close to active volcanos and the volcano itself may attract large numbers of tourists (Erfurt-Cooper et al., 2015; Siebert et al., 2015).

A volcanic eruption may contain a number of different hazards to people who are in the local area of the volcano. The most common hazards include the release of: lava, poisonous gases, pyroclastic flows and surges (super-heated mixtures of gasses and rock fragments); lahars (flows of water and rock fragments), and tephra (fragments of rock of various sizes ejected by the volcano) (Simkin, Siebert & Blong, 2001; Whitam, 2005; Wilson, Cole, Johnston, Stewart & Dantas, 2012). Small tephra (such as ash) can be carried a large distance from the volcano (in some case up to a 1000km) causing building collapse, health problems and disruption to essential services (Wilson et al., 2012). For volcanic eruptions that occurred in the 20th Century, pyroclastic flows were the main cause of death, followed by lahars (Whitam, 2005).

Because of the high lethal potential of erupting volcanos the only effective protective action for the local area around a volcano is the establishment of exclusion zones or the evacuation of people prior to an eruption (Perry & Godchaux, 2005; Wilson et al., 2012). Many volcanos close to human settlements around the world are monitored and while it is still very difficult to predict exactly when a volcano will erupt this has led to successful evacuation prior to eruptions (Palister & McNutt, 2015; Tilling, 2008). For more distant areas that may be exposed to ash fall, shelter in place may be appropriate for lighter falls, but for heavier falls evacuation is recommended because the build-up of ash can cause buildings to collapse, public health issues and significant disruption to essential services (Simkin, Siebert & Blong, 2001; Wilson et al., 2012).

**4. Conclusions, implications for research and risk mitigation endeavours**. (300 words).

Obstacles to evacuation urged by an official warning are many - but include optimism bias (that is, it hasn’t happened here before, so we will be OK), previous experience with a similar hazard that turned out not to be so serious, cost of evacuation, uncertainty about the location of facilities offered at an evacuation centre, lack of transport, lack of family consensus on evacuation, being unable to take pets to an evacuation site, evacuation fatigue (in which a hazard threatens multiple times in short space of time), concern about traffic during evacuation, and lack of trust in the sender of the warning or the evacuation process.

Table 23.3: Issues for evacuating versus sheltering-in-place as protective action responses to natural hazards threats

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| --- | --- | --- | --- | --- | --- | --- | --- |
| **Hazard** | **Major Causes of Death** | **Threats to shelter** | **Predictability** | **Lead time (detection to impact)** | **Visibility** | **Evacuation advisability** | **Shelter advisability** |
| *Weather-related hazards* |  |  |  |  |  |  |  |
| Floods - riverine | Drowning. | Destruction or submergence of the shelter. | High. | Long. | High. | Advised, avoid entering floodwaters. | Not advised due to uncertainty of water height and likely long period of isolation. |
| Floods - flash | Drowning. | Absence or destruction or submergence of the shelter. | Likely weather conditions: High. Impact location: Low. | Short. | Low. | Not advised. | Advised, unless there is no viable short-term shelter option such as high ground or a solid structure. |
| Tornadoes | Traumatic injury due to flying debris. | Destruction or submergence of the shelter. | Likely weather conditions: High. Point of impact: Low. | Short. | High. | Only advised if there is ample time to leave the predicted impact area. | Advised in underground shelters, ‘safe rooms’, or inner rooms in solid structures resistant to damage from extreme winds. |
| Tropical cyclones (Hurricanes, Typhoons) | Drowning. Traumatic injury. | Destruction or submergence of the shelter. | High. | Long. | High. | Advised. | Not advised due uncertain storm surge heights, flooding, and vulnerability of homes to high wind velocities.  |
| Wildfires | Hyperthermia due to radiant heat. Damage to airways due to convective heat. Burns. Trauma due to motor vehicle accident. | Ignition of the structure. | Likely weather conditions: High. Point of ignition: Low. | Depending on (a) proximity to the point of ignition, (b) wind speed, and (c) ground slope. Spot fires may be ignited by wind-blown embers great distances ahead of the main fire front. | High. | Advised only if the lead time is sufficient to allow safe egress from the threatened area. | Advised only if evacuation is very likely to be hazardous. Potentially viable shelter options include: ember-attack resistant defendable structures; purpose-built bunkers or shelters; in stationary vehicles or other low-ignitability shelter options more than 40 metres from flames; on large open areas with non-ignitable surfaces more than 200 metres from flames—such as beaches, parking lots, or ploughed fields. |
| *Geophysical hazards* |  |  |  | . |  |  |  |
| Earthquakes | Traumatic injury due to impacts of collapsing structures and striking or being struck by objects and debris. | Collapse of the structure. | Low. | Short. | High. | In developing countries people on the ground floor of a dwelling may be safer moving to open space areas to avoid injury from collapsing structures. | In developed countries if inside a building shelter using the ‘drop, cover and hold’ on method to avoid striking or being struck by debris and objects. |
| Landslides | Asphyxiation. Traumatic injury. | Destruction of the shelter structure | Likely weather conditions: High. Impact: Low. | Short. | Low. | Advised. | Not advised due to the vulnerability of homes and other structures to mass earth movements. |
| Tsunamis | Drowning. Traumatic injury due to impact or impaling on objects and debris. | Destruction or submergence of the shelter structure. | Low. | Dependent on proximity to the initiating event. | Low. | Advised: to higher ground inland | Not advised unless unable to evacuate. |
| Volcanic eruptions | Burns, asphyxiation, drowning, poisoning & traumatic injury. | Destruction or burial of the structure | Low. | Short | High | Advised | Not advised |

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1. Manufactured homes are assembled on site from prefabricated components, or assembled elsewhere and transported to the site. [↑](#footnote-ref-1)
2. So-called because it was used initially in relation to floods when people relocated to nearby higher ground or moved to the upper floors of a building. [↑](#footnote-ref-2)
3. Some disastrous flood events have resulted from the collapse of dams. Flooding is often associated with tropical cyclones making landfall. [↑](#footnote-ref-3)