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Introduction

The problem with natural hazard risk assessments

There is a problem with many natural hazard risk assessments. They do not incorporate long-term and/or prehistoric records of extreme events; otherwise known as natural hazards when they affect humans physically, psychologically, socially or economically. Short historical records are frequently assumed to be a true reflection of the long-term behaviour of a hazard. Historical records may be appropriate, in this regard, where they extend for at least several centuries or even a millennium such as in China. However, in many countries, like the United States, United Kingdom and Australia, the historical record is often not much longer than 100 years. Many assessors of risks from natural hazards see these short records as appropriate for determining the natural variability of a hazard. From this they extrapolate to determine the magnitude of less frequent, higher magnitude events and construct probability distributions of the occurrence of a hazard at various return intervals. Inherent in this process is the assumption that natural hazards occur randomly over a variety of time scales and that the mean and variance of the hazard do not change. This may be true in certain circumstances, especially shorter time periods, but is often not the case for longer intervals. When we rely upon short historical records we run the real risk of not capturing the natural variability of the hazard. Here lies the crux of the problem – when we do not understand the true nature of the hazard in question we cannot hope to make realistic assessments of community vulnerability and exposure and we increase the chance of making an unreliable estimate of the risk of that hazard. Our ability to increase community safety and reduce economic loss is dependent upon our understanding of the behaviour of the hazard. Short historical records rarely display sufficient information for us

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to interpret this natural variability. Nature, however, effectively records its own extreme events, and often its not so extreme ones, providing us with a documented history in the form of natural records that can display the full range of variability of most hazards that confront society. Long-term records, therefore, are the only real source for uncovering the true nature of the behaviour of natural hazards over time.

Scientists who study the Quaternary – the most recent period of geological time (or approximately the last 2 million years) know that natural events including hazards often occur in clusters or at regular to quasi-periodicities. Over longer time intervals, the Quaternary record shows us that the periodicity of events, including climatic changes, is governed by many factors, some of which are external to the Earth. For example, climatic changes of various scales occur at intervals from 100 000 years to 11 years based upon regular variations in the orbit of the Earth around the Sun, along with the tilt of the Earth's axis and precession of the equinoxes, to sunspot activity. There are many other regular cycles of climate change that occur in between the 100 000 and 11 year cycles that have been uncovered from a variety of natural records. The clear message from Quaternary records is that many of the climatic changes that occur on Earth do not occur randomly and in this sense are not independent of time. The same could be expected of many extreme natural events.

While it is true that natural records do not document the event as accurately as the instrumented record, they are nonetheless of sufficient precision to show us the magnitude of the most extreme events and how often these events are likely to occur. Even more importantly, natural records provide us with a very effective means by which to test the assumptions of the stationarity of the mean and variance, and randomness of occurrence of a natural hazard. In the absence of these tests we cannot hope to realistically assess community vulnerability and exposure, and therefore risk. Social scientists, involved in that part of the risk evaluation process devoted to community and social parameters, also need to be aware of the assumptions made by scientists and engineers in determining the physical nature of the hazard. This is frequently not the case and planners are left with false impressions of which areas are safe for urban, industrial and tourism developments.

We can only really attempt to reduce risk from natural hazards when we factor the dependence on time of a hazard into our risk equations, or at least test for it, and then see where the historical record fits in the sequence. Unfortunately, this approach is rarely adopted. It is imperative that we examine each of the forms of evidence, being the instrumented, historical and prehistoric records when undertaking risk assessments. Many practitioners, however, are unfamiliar with prehistoric records and are hesitant to incorporate them into risk assessments. Through familiarity, though, comes awareness of the insights that the prehistoric record can provide into gaining a more realistic impression of the behaviour of natural hazards.

The risk assessment process

Risk from natural hazards is a function of the nature of the natural hazard (i.e. probability of its occurrence), community vulnerability and the elements at risk. Risk can have a variety of meanings and is sometimes used in the sense of the probability or chance that an event will happen within a specific period of time. Alternatively, risk can refer to the outcomes of an event occurring. In this latter sense, risk refers to the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular natural phenomenon. Risk is really the product of the specific risk and the elements at risk. The specific risk here means the expected degree of loss due to a particular natural phenomenon and is a function of both the natural hazard and vulnerability (Fournier d'Albe, 1986). The elements at risk, otherwise known as the level of exposure, refers to the population, buildings, economic activities, public services, utilities and infrastructure that may be directly impacted by the hazard.

Community vulnerability is determined by the social and demographic attributes that influence a person's perception of the risk to the hazard. It often concerns peoples' attitudes, preparedness and willingness to respond to warnings of an impending hazard. Anderson-Berry (2003) notes that community vulnerability is not a static state but a dynamic process. It is generated by the complex relationships and inter-relationships arising from the unique actions and interactions of the social and community attributes and characteristics of a particular population.

These attributes and characteristics include:

- societal structures, infrastructure and institutions including the integrity of physical structures;
- community processes and structures such as community organisation, mobility of the household population, and community cohesiveness and the social support this affords; and
- demographic and other characteristics of individuals within the community such as age, ethnicity, education and wealth (Keys, 1991; Fothergill, 1996; Buckle, 1999; Fothergill *et al.*, 1999; Cannon, 2000).

These factors, along with actual experiences of the hazard in question, help to shape the individual's and the community's perception of risk. Anderson-Berry

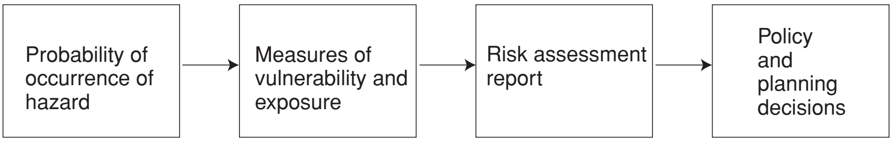

Figure 1.1. Generalised sequence of process occurring in a risk assessment. In reality there are many feedback loops between the steps outlined here.

(2003) notes that people individually and collectively decide what precautionary measures will be undertaken and how warnings will be complied with so as to ensure that the loss resulting from a hazard event is limited to an acceptable level. If the perceived risk is a true reflection of the actual risk associated with a particular hazard, then mitigation strategies, warning compliance and response preparedness are likely to be appropriate and vulnerability can be minimised. If risk perception is biased, the reverse is true and vulnerability may be increased. The perception of risk, therefore, can often be the precursor to determining the level of exposure to that risk, although it is true that perceptions can and do change over time. So increasing awareness with time, due to education about or experience with the hazard may result in the realisation that more elements are exposed than previously thought. The level of exposure, therefore, is a function of past and present perceptions of risk.

The total risk is often expressed as:

$$\text{risk (total)} = \text{hazard} \times \text{elements at risk} \times \text{vulnerability}$$

Often each of these components of the risk equation is determined separately and in isolation from the other components. When this occurs it is typically a function of the background and the training of those employed to undertake the task. For example, it is common to have a physical scientist or engineer determine the probability of occurrence of the natural hazard, whereas social scientists are usually best trained to deal with vulnerability and exposure. The two sometimes do not fully comprehend each other's assessments and will not question the veracity of the methods used or the results obtained. The social scientist, for example, may not feel comfortable reviewing the engineer's assessment of the hazard and will accept, at face value, the results as being correct or the best that can be obtained. The level of exposure is then assessed which in turn influences the assessment of vulnerability and vice versa. A report is often produced which becomes the basis for planning and policy decisions by various levels of government. Hence, the engineer's assessment is critical to and underpins all subsequent stages of the risk assessment process. Figure 1.1 outlines this process.

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Each of these stages is critical and no less valuable than the others in terms of reducing risk from natural hazards. However, any variation to the outcome of the first stage (i.e. the hazard probability) influences each of the other stages; hence, each of the latter are dependent on the former. For example, hundreds to thousands more homes may be deemed to be exposed to tsunami inundation depending upon whether the assessed probability of occurrence of tsunami run-up height is 1 or 2 m above a certain datum for a given time interval along a densely populated low-lying coast. Likewise, government policy decisions may set aside a considerably larger area of coastal land deemed to be unsuitable for permanent development depending upon the height of the tsunami run-up determined. Obtaining the most accurate and realistic estimate of the magnitude of a hazard at a given probability level, therefore, is usually in the best interests of all concerned in the risk assessment process, and likely even more so for those potentially subject to impact by the hazard. The perception of the most realistic estimate, however, can vary and is the essence of the earlier stated problem in the risk assessment process. There can be a difference between the mathematical and/or statistical certainty of a certain magnitude hazard occurring in a given time period and the so-called realistic estimate of the size of that hazard.

Mathematical and statistical certainties versus realistic estimates

The probability of occurrence of a given event is a statistical measure. Probability assessments are normally based upon the assumption that the event occurs randomly with respect to time, and that events occur randomly with respect to each other. Randomness in this sense is commonly likened to the probability of obtaining a head or tail in tossing a coin. We determine that there is always a 50% probability of obtaining a head or tail each time we toss the coin. Each toss occurs independently of the other and hence the outcome of the toss is random with respect to past tosses and therefore time. This does not mean of course that we will get a head, then tail, then head with each successive toss. Time is a dependent factor when we consider that with increasing time or number of tosses we increase the probability of obtaining two or more heads in a row. But if we take any specified period of time we can expect to get a certain outcome based upon the independence of tosses relative to each other and the outcome is a function of randomness. The same view is taken with respect to the occurrence of many, but not necessarily all, natural hazards. Each year in the time series, in a sense, represents a toss of the coin. For a given magnitude event we could expect a certain probability of occurrence of that hazard. With increasing periods of time this event will have a greater probability of occurrence (like obtaining two or more heads in a row) but its probability of occurrence in

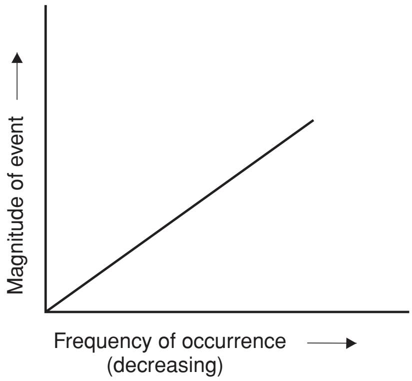

Figure 1.2. Typical relationship between event magnitude and frequency. Note that larger magnitude events occur less frequently than smaller magnitude events.

any one year always remains the same. In fact, its probability of occurrence is regarded as remaining the same for any period of time. This remains the case if the event occurs independently of prior events and therefore, like the toss of a coin, occurs randomly within any given period of time. If external factors influence the occurrence of that event then it will not be occurring independently of a specified period of time. To once again use the coin tossing analogy, if something influences the outcome of the tosses of a coin for some specific period of time then we can no longer say that the outcome is a random occurrence. We know that this is unlikely to be the case when tossing a coin, but it is a very real possibility with respect to the occurrence of natural hazards over time.

There are statistical measures, such as Bayesian analyses, which do assume that prior events influence the occurrence of subsequent events and these are sometimes used in risk assessments of some natural hazards such as earthquakes. Bayesian analysis is usually only used for hazards that have known build-up and relaxation times, as occurs for example when crustal stresses along a fault or tectonic plate boundary build to the point of release causing an earthquake. Following the earthquake, it takes some time for those stresses to once again build to a level to induce the next earthquake. So the time between earthquakes is not random and the probability of an earthquake occurring at that specific location is reduced for a period and hence varies over time. This can be called a conditional probability. Other hazards, such as many atmospheric hazards, however, where such processes are thought not to operate, are generally regarded as occurring randomly with respect to previous events and in this sense randomly with respect to time.

High-magnitude events usually occur less frequently than low-magnitude events. A typical distribution of events over time is shown in Figure 1.2. It is

Table 1.1 *Percentage probabilities of occurrence for given time intervals*

Return period (years)	Annual exceedence probability (AEP) (%)	Probability of occurrence (%) for the period (years)				
		25 years	50 years	100 years	200 years	500 years
50	2	39	63	87	98	99.9
100	1	22	39	63	87	99.3
200	0.5	12	22	39	63	92
500	0.2	5	9.5	18	33	63
1000	0.1	2.5	5	9.5	18	39
5000	0.02	0.5	1	2	4	9.5

more likely, therefore, that a place will experience a high-magnitude event with increasing time. So location X, for example, is unlikely to experience a high-magnitude event over 100 years but is reasonably likely to experience this event over a 1000 year period. But, as stated earlier, the likelihood of that high-magnitude event occurring in any 100 year period remains the same, even if it has been 900 years since the last high-magnitude event. The probability of that event occurring between year 900 and year 1000 is exactly the same as the probability of occurrence between year 100 and year 200. Probabilities, therefore, are determined according to the time interval to which they pertain. The probability of the 1 in 100 year event (1% annual exceedence probability, AEP) occurring is 1/100 in any given year. In other words, this event has a 1% chance of occurring in any given year. Likewise, it has a 39% chance of occurring in a 50 year period, 63% chance of occurring in a 100 year period and 99.3% chance of occurring in a 500 year period. Table 1.1 sets out the probabilities of events occurring over various time intervals. The determination of these probabilities is calculated according to the binomial distribution. The equation for the binomial distribution is

$$P(r) = {}^{n}C_{r}\, p^{r} q^{n-r} \tag{1.1}$$

where ${}^{n}C_{r}$ (the binomial coefficient) $= n!/r!(n-r)!$ and where $P(r)$ is the probability of occurrence, n is the number of events in the record, $r = 0$ and $q = 1 - p$.

The binomial distribution is based upon the randomness of occurrence of events over time. The same distribution is used to explain the chance of obtaining a head or tail in the toss of a coin which is most certainly a random event. By applying the same statistical probability distribution to the occurrence of natural hazards we make the assumption that these events occur randomly like the chance of obtaining a head or tail in the toss of a coin.

The application of this approach to determining the probability of occurrence of a natural hazard is shown in Figure 1.3. The majority of events in Figure 1.3

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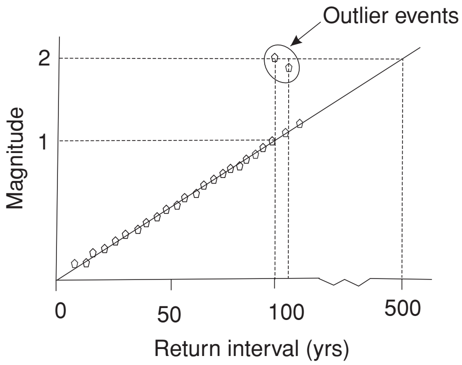

Figure 1.3. Magnitude–frequency curve and outlier points.

can be seen to fall roughly on a straight line; however, two events do not. These two events are referred to as 'outliers' and they are of higher magnitude than any other events to have occurred over the past 100 years. The probability distribution suggests that despite the fact that these outlier events have occurred within the last 110 years they do not belong to the normal range of events that could be expected to occur within this time frame. By extending the line representing the magnitude–frequency relationship for this particular hazard, these events appear more likely to correspond to the approximately 1 in 500 year event (0.2% AEP). Such a conclusion is firmly based upon the assumption that the slope of the line representing the magnitude–frequency relationship is applicable to any 100 year period. Therefore, this line, which only covers events from the last 100 years, is typical of any 100 year period. When we make this assumption we also deem it safe to extrapolate this line to determine an accurate estimate of the size of less frequent events. Whether this is a realistic interpretation of the nature of the natural hazard, however, is rarely ever tested during the risk assessment process. Nor is the possibility that non-stationarity may be evident when longer time series or records of events are examined. In the above situation stationarity has been assumed. Unfortunately though, nature rarely displays stationarity over the long term.

Stationarity in time series

Stationarity occurs when the relationship between the magnitude and the frequency of an event and/or its variance remains unchanged with time. Non-stationarity refers to a condition where the relationship between the magnitude and frequency and/or variance changes over time. In the former case this can be reflected as a change in the slope of the magnitude–frequency line. In these situations the magnitude of a certain frequency hazard changes. If the slope of

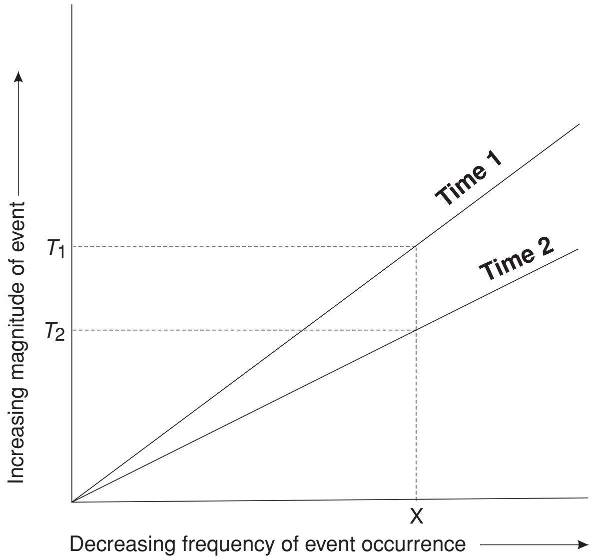

Figure 1.4. Non-homogeneity of magnitude–frequency relationship over time.

the line steepens, events of greater magnitude will occur more frequently. The converse is true when the slope of the line decreases. These changing relationships are shown in Figure 1.4. Two lines are presented here. Each line represents a different relationship between the frequency of occurrence of an event and its associated magnitude. An event with frequency X will have a magnitude of T_1 during a period named here as Time 1, and magnitude T_2 during the period Time 2. These periods may be years, decades, centuries or millennia in length. This is non-stationarity (see Fig. 1.5).

Stationarity, therefore, can only be assumed to occur for limited periods of time. The length of these periods is variable, and they will often dominate an entire short historical observational record. Hence, these records will not display non-stationarity even though this is the normal behaviour of a hazard over the longer term. Planners might say that the length of the period in question (i.e. the current period of stationarity) is longer than the proposed planning cycle so what is the use of attempting to test for non-stationarity. However, if we choose not to recognise that these changes occur we will not seek explanations for the cause of these changes and without knowing the causes we will not endeavour to understand the changes. Hence, we will not know when a change is likely to occur. If such changes do occur within the planning period, and because stationarity is assumed, the occurrence of a high-magnitude event will be regarded as an outlier, or an event of much lower frequency. This, of course, has implications for insurance premiums and claims, and future policy and planning. It also affects the way we perceive risk and, therefore, influences

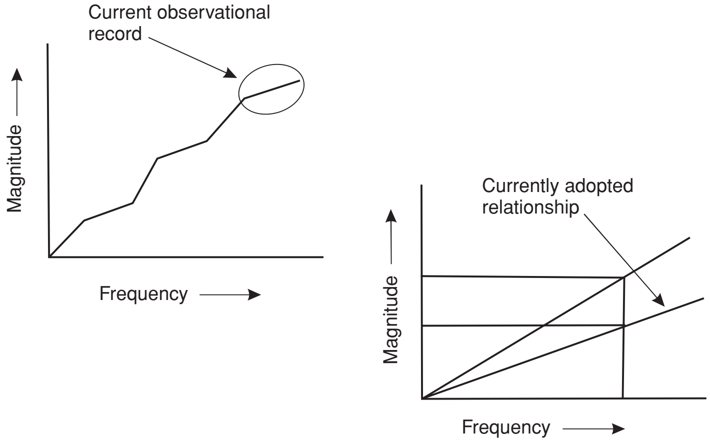

Figure 1.5. Non-stationarity in the time series.

community vulnerability and levels of exposure. If we believe that the high-magnitude event is an outlier then we will believe that the chances of an event of similar size occurring during the next planning cycle, or the near future, are low (i.e. as set out in Table 1.1). For example, if we perceive the outlier event to be a 1 in 500 year event (0.2% AEP) then we will draw the conclusion that its chances of occurring in the next 50 years are less than 10%. However, if we find from a longer-term record that this magnitude event is really more likely to be a 1 in 100 year event (and indeed it did occur only a little over 100 years ago in reality) then its chance of occurring in the next 50 years is about 39%. Alternatively, it could be an event that signals the onset of a change in hazard behaviour. Either way, when we assume it was a 1 in 500 year event, and ignore the possibility that it is part of a normal series of events for a regime that was not recognised due to the brevity of the observational record, then we will have placed potentially large numbers of people and property at higher than predicted levels of risk. Each change of phase in hazard behaviour, i.e. change of slope in the magnitude–frequency curve, can be referred to as a hazard regime (Nott, 2003). These regimes can be likened to alternating periods of variable stationarity. Recognising the possibility that these regimes may exist for a hazard at any location can only help us to gain a more realistic view of the nature of the hazard.

Reality versus reasonableness

Mathematics and statistics have dominated our approach to assessing risk from natural hazards. The strength of these methods is in their predictive