Chapter 7
A Paradigm for Applying Risk and Hazard Concepts in Proactive Planning

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Abstract The concepts of risk and hazard have been used with different meaning in a wide spectrum of disciplines. Even in the area of natural hazards such as the floods and droughts, the definitions used for all the related terms are still confusing the scientific community and the stakeholders. The objective of this chapter is to attempt to clarify some of these terms and propose a methodology for the risk assessment. Emphasis is given to the risk assessment of the affected areas due to the occurrence of droughts. Simplified examples are presented for illustrating the use of these terms. Particular attention is given to the concept of vulnerability, mainly in relation to proactive planning.

Introduction

Several concepts have been used over the past decades to describe the potential threats from natural phenomena and the capacity of the various structural and non-structural systems to protect people, properties and the environment from these threats.

Concepts such as hazard, risk and vulnerability are the most commonly used terms although they have different meanings for different people. In some cases there is also a lack of understanding between scientists and engineers who attempt to quantify these concepts, and the stakeholders who are asked to apply them in the real world.

Furthermore quantification is not an easy task. It is possible that some parameters affecting the above concepts are beyond quantification. However even so it is

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necessary to find a way for analyzing these parameters and assessing their importance in the final impact (Brauch, 2005, Thywissen, 2006).

From the above it is understood that a wide systematic effort should be undertaken in order to clarify all these concepts and propose a practical and easy to understand methodology for calculating them in the various disciplines and specialised applications (Klein, 2003).

Towards this initiative this chapter is attempting to address these concepts and propose practical algorithms for calculating them in the area of droughts, and their effect on agriculture (Tsakiris, 2006). The approach used however is to build a general framework in which several natural hazards could be incorporated and analyzed. For this purpose drought hazards are analyzed following the proposed general algorithm.

Hazard

According to Tsakiris (2007), the term "hazard" due to a natural phenomenon may be defined as:

1. a source of potential harm
2. a situation with the potential to cause damage
3. a threat or condition with the potential to create loss or damage to lives or to initiate any failure to the natural, modified or human systems.

The causes of hazard may be external (e.g. flooding) or internal (e.g. defective section of protection levees). Also under a different categorization hazards may be natural (meaning that the cause is natural (e.g. storm)) or human-induced (e.g. deforestation). Although this distinction may be unclear for certain cases it applies to the majority of applications.

Hazard according to the general definition above should be treated as a type of threat to lives, environment, cultural heritage and development. However this threat should be quantified somehow. This quantification may remain at a qualitative level by describing the number of people, the properties, the affected area etc being under threat or by estimating the frequency of a certain level of threat derived from the existing historical events. Therefore, although the numerical assessment is difficult and may be subjective, the hazard can be assessed in a softer way by characterizing it as small, moderate or high.

In a more structured form, hazard may be quantified in two ways:

1. The probability of occurrence of the hazardous phenomenon (e.g. discharge occurring once in twenty years with magnitude equal to or greater than the given value)
2. The sum of potential consequences of the affected area provided no protection system is in operation (e.g. in case of a catastrophic drought the damage to the rainfed agricultural area due to the loss in crop yield). The calculation of the potential consequences could be performed bearing in mind that a sort of basic

protection mainly for low severity events can be found in most of the systems. However this could be regarded as the reference level corresponding to the "totally unprotected" area.

Under certain conditions the first or the second way can be considered as more appropriate. In general it can be said that natural hazards caused mainly by external causes can be quantified by probabilistic approaches. On the contrary human-induced phenomena caused by mainly internal causes are better quantified through deterministic approaches by calculating the potential consequences from a very "critical" scenario of failure. Obviously the critical scenario selected represents the basis for designing any protection system.

Concentrating on the natural hazards in which the cause of initiating the failure mode is natural it can be argued that only the frequency is not sufficient to describe the level of hazard. In a more comprehensive way, natural phenomena may be described by their magnitude together with the frequency of their occurrence.

Since the magnitudes of the phenomenon (and therefore the anticipated consequences) follow, in most of the cases, a certain probability distribution, the following equations may be written:

$$F(x) = P(D \leq x) = \int_{-\infty}^{x} f_D(x)dx = \int_{0}^{x} f_D(x)dx \tag{7.1}$$

$$\text{or } 1 - F(x) = P(D > x) = 1 - \int_{-\infty}^{x} f_D(x)dx \cong 1 - \int_{0}^{x} f_D(x)dx \tag{7.2}$$

in which x is the sum of potential consequences of each hazard event of the phenomenon, $F(x)$ and $P(D \leq x)$ are the cumulative density functions (c.d.f.), $P(D > x)$ is the exceedance probability, and $f_D(x)$ is the probability density function (p.d.f.).

It should be noticed that for the calculation of $f_D(x)$, the relationship between $F(x)$ and x should be known. In general, this type of relationship may be any curve, not necessarily following a certain probability distribution. The *F-x* curve is produced from a table linking cumulative frequencies to magnitudes of the phenomenon and the estimated potential consequences (in case of a totally unprotected area).

The figure which gives a representative measure of hazard is the expected value *E(D)* which considers both the potential consequences and their probability of occurrence, provided that the area under threat is totally unprotected:

$$E(D) = \int_{0}^{\infty} x \cdot f_D(x)\,dx \tag{7.3}$$

Since *E(D)* is a measure of "average" (annualized) expected hazard it would be useful to calculate the variance *(Var(D))* as a complementary figure for estimating not only the most expected outcome but also the range of this outcome.

$$Var\,(D) = \int_0^\infty (x - \mu)^2 \cdot f_D\,(x)\,dx \tag{7.4}$$

in which μ is represented by *E(D)*.

$$\text{or } Var\,(D) = E\left(D^2\right) - (E\,(D))^2$$

$$Var\,(D) = \int_0^\infty x^2 \cdot f(x)\,dx - (E\,(D))^2 \tag{7.5}$$

When applying the above equations, an important assumption should be met. That is the function relating the potential consequences to the magnitudes of the phenomenon to be a 1 – 1 function. These functions are usually of geometric type and are called "loss functions".

In some cases return periods are associated with the magnitudes of the phenomenon without attempting to relate the phenomenon with the consequences.

A numerical example is provided for illustrating the procedure to estimate annualized hazard. Table 7.1 provides the data associating return periods of magnitudes of the hazardous phenomenon to the anticipated potential consequences.

Table 7.1 Return periods and anticipated potential consequences

Return period T (y)	Potential consequences D(M €)
2	0
10	400
50	800
100	1170
1000	3000
>1000	3000

Further from Table 7.1 another table (Table 7.2) is produced relating the frequency of each class of magnitude to the mean potential consequences of the class.

Based on Table 7.2 the (mean) expected value of potential consequences is calculated corresponding to the average hazard of the phenomenon.

Table 7.2 Frequency vs mean potential consequences of each class

Frequency $F\,(x_{i+1}) - F\,(x_i)$	Mean potential consequences $\dfrac{x_i + x_{i+1}}{2}$
0.40	200
0.08	600
0.01	985
0.009	2085
0.001	3000

$$E(D) = \sum_{i=1}^{n} \left(\frac{x_i + x_{i+1}}{2} \right) \cdot \left[F(x_{i+1}) - F(x_i) \right]$$
$$= 80 + 76.6 + 28.6 + 18.8 + 3 = 207\ M€/y$$
$$Var(D) = \sum_{i=1}^{n} \left(\frac{x_i + x_{i+1}}{2} \right)^2 \cdot \left[F(x_{i+1}) - F(x_i) \right] - (E(D))^2$$
$$= 37414.75 - 48849 = 24565.75$$

The standard deviation is then

$$SD = \hat{\sigma} = \sqrt{Var(D)} = 156.73\ M€/y$$

That is, the average rate of potential consequences is estimated as 207 M€/y with a standard deviation of 156.73 M€/y.

Vulnerability

Vulnerability of a certain system is generally defined as the degree of susceptibility to damage from a hazardous phenomenon or activity. In most of the cases quantification of vulnerability is a very difficult task. However some kind of assessment of vulnerability is required in order to estimate the real threat from an existing source of hazard. Therefore in most of the cases quantitative approaches could be implemented for assessing vulnerability.

A common characterisation of vulnerability is with the scale "low, moderate, high".

In a more detailed approach vulnerability may be characterised as related to the anticipated damages as follows:

1. Negligible or slight damage
2. Moderate damage
3. Substantial to heavy damage
4. Very heavy damage
5. Total destruction

As it can be easily understood, vulnerability of a system comprises of two components: the coping capacity of the system to withstand the hazardous event and the exposure of the system to this event. The assessment of vulnerability based mainly on the capacity of the system has no meaning, unless the system is exposed to the hazardous event.

In general, vulnerability of a system related to a hazardous phenomenon is dependent upon a large number of factors, most of which are listed below:

1. *Exposure*
2. *Capacity of the System*

- Infrastructure
- Condition of the system
- Institutional set up
- Quality of governance
- Motivation to react
- Skills and education of people
- Resources available
- Preparedness status
- Monitoring capabilities
- Existence of an emergency plan
- Development status
- Resilience / time of recovery
- Initial conditions of the system
- Interaction of interrelated components

3. *Characteristics of the hazardous event*

- Magnitude of the event
- Duration of the stress
- Timing of the event
- Conditions which may influence the destruction capacity

Under a different categorization the above factors may be grouped in four categories:

1. Exposure of the System (E)
2. Capacity of the System (S)
3. Social Factor (SF)
4. Severity and destructive capacity of the event (Qmax)
5. Conditions and interrelated factors (I)

It should be mentioned that in some formulations the Exposure is considered separate to vulnerability.

In mathematical terms

$$V = V(E, S, SF, Q_{\max}, I) \tag{7.6}$$

In more simplistic terms, vulnerability could be considered as a function ranging between 0 and 1.

In general terms, vulnerability may be related to the entire system or it may be necessary to disaggregate the system into a number of components and perform a detailed analysis on each of them. The aim of reclamation and protection works is to reach a lower level of the system's vulnerability. A comprehensive indicator of the improvement of a system is the ratio of anticipated consequences after the improvement divided by the initial potential consequences. A graphical representation of vulnerability and its reduction presented versus the magnitude of the hazardous phenomenon appears in Fig. 7.1. As can be seen the improvement of the capacity of the system is represented by a shift to the right of the vulnerability curve.

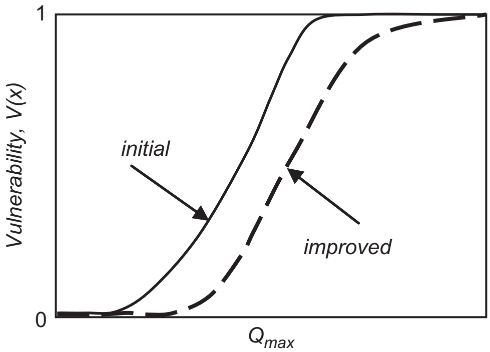

Fig. 7.1 Vulnerability vs magnitude of the phenomenon for the initial and the improved capacity of the system

The routes for reducing vulnerability may follow the main items upon which it is dependent. That is:

1. Improving the coping capacity of the system
2. Mitigating the magnitude of the phenomenon (and its potential consequences)
3. Improving social capacities to deal with the phenomenon (capacity building)
4. Controlling internal and external factors and their interrelations
5. Changing the exposure of the system

Risk

Risk may be defined as an existing threat to a system (life, health, properties, environment, cultural heritage) given its existing vulnerability. In a metaphor hazard could be viewed as a source with a beam of rays, vulnerability as the filter and risk as the beam of penetrating rays through the filter affecting the system.

Risk is similar to hazard but it is not a potential; it is a real threat. It is customary to express risk (R) as a functional relationship of hazard (H) and vulnerability (V).

$$\{R\} = \{H\} \Box \{V\} \tag{7.7}$$

in which the symbol $\Box$ represents a complex function incorporating the interaction of hazard and vulnerability. A simple example of such a function is the simple product of hazard and vulnerability.

$$\{R\} = \{H\} \times \{V\} \tag{7.8}$$

Since vulnerability is a dimensionless quantity, risk could be measured in the same quantities as hazard. That is, risk could represent the probability of harmful consequences or the expected damages resulting from interactions of hazard and vulnerable conditions.

Following the methodology for calculating the average (annualized) hazard, the average risk can be calculated as follows

$$R(D) = \int_{0}^{\infty} x \cdot V(x) \cdot f_D(x)\, dx \tag{7.9}$$

in which x is the potential consequence caused by the phenomenon of the corresponding magnitude, the p.d.f. of which is $f_D(x)$ and $V(x)$ is the vulnerability of the system towards the corresponding magnitude of the phenomenon.

Important issues when calculating the risk are the characteristics of the cause of initiating the failure mode and causing damage. These causes may be natural or due to human error or human involvement. If the triggering factor is due to human intervention or activity, then this process cannot be described probabilistically, but deterministic simulation is needed.

Therefore, to assess the risk threatening a certain area ("area at risk") or population ("population at risk") the worst conditions should be considered. For example, the breach of levees protecting an area can occur in the night under adverse conditions instead of midday on a sunny day. The assumption of the "critical" scenario could be the worst scenario in case lives or important properties or heritage are at risk.

If risk is calculated on the basis of probabilities of extreme events or processes care should be taken on the possibility of two or more causes of failure occurring at the same time. Then the total damage might be higher from the damage caused by the two causes occurring independently of each other.

The above analysis is based on the assumption that the system at risk is a uniform entity that is exposed to a certain hazard. If this system is considered as an element of a much wider and non-uniform system then the total risk could be calculated by integration over the sum of elements at risk.

Application of Drought Hazard to Rainfed Agriculture

An agricultural area is cultivated with cereal crops. No irrigation or other drought protection system is in operation. Analyzing a long historical record the frequency of a number of drought severity classes was associated with the crop production losses in monetary units. The severity of drought was calculated by a general drought index, the Reconnaissance Drought Index (RDI) on an annual basis (Tsakiris and Vangelis, 2005, Tsakiris et al., 2007). According to the thresholds adopted for this index four classes of severity were used. The results of this analysis are represented in Table 7.3.

Table 7.3 Drought frequency and crop yield losses from the agricultural area under study

Severity of annual drought	Probability of occurrence	Anticipated losses (k€)
$0 > \mathrm{RDI} > -1$	1 : 3	20
$-1 > \mathrm{RDI} > -1,5$	1 : 7	150
$-1,5 > \mathrm{RDI} > -2$	1 : 12	400
$\mathrm{RDI} < -2$	1 : 25	900

Based on Table 7.3, Table 7.4. is produced:

Table 7.4 Average losses from each class of drought severity vs frequency

$\bar{x}_{i,i+1}$ (k€)	$F(x_{i+1}) - F(x_i)$
20	0.333
150	0.142
400	0.083
900	0.040

The average (annualized) hazard due to drought occurrence can be calculated from the above table as follows:

$$E(D) = \sum \left(\frac{x_i + x_{i+1}}{2} \right) \cdot (F(x_{i+1}) - F(x_i)) \text{ or} \tag{7.10}$$

$$E(D) = 6.66 + 21.3 + 33.2 + 36 = 97.16\ k€/y$$

To protect the area from the above hazard several measures were taken. For example, the existing irrigation system was put into operation only during the most sensitive period of the growing season by using water conveyed from outside the affected area. The cost of the water transferred to the area in question is covered by the state as an aid to the farmers. By applying these measures, the following results concerning vulnerability are expected (Table 7.5).

Table 7.5 Average yield losses and expected vulnerability of the improved system for each class of drought severity

$\bar{x}_{i,i+1}$ (1) (1)	$F(x_{i+1}) - F(x_i)$ (2) (2)	$V(\bar{x}_{i,i+1})$ (3) (3)
0	0.333	0
100	0.142	0.667
300	0.083	0.750
700	0.040	0.778

The vulnerability of the system is therefore reduced, compared to the vulnerability of 1 of the initial system. The vulnerability is presented for each level of $\bar{x}_{i,i+1}$ (column 3 of Table 7.5). In Fig. 7.2 the vulnerability of the initial and the improved system is plotted against the severity of drought represented by RDI.

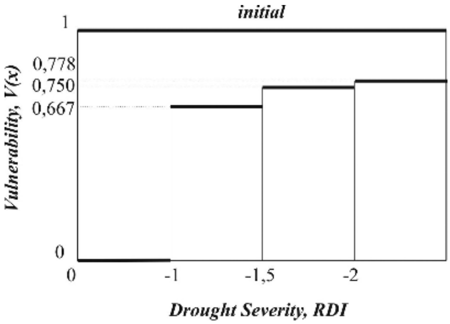

Fig. 7.2 Vulnerability of initial and improved system plotted against the drought index RDI

The average risk is therefore calculated for the improved system as:

$$R(D) = \sum \left\{ \bar{x}_{i,i+1} \cdot V\left(\bar{x}_{i,i+1}\right) \cdot f\left(\bar{x}_{i,i+1}\right) \right\} = 0 + 14.2 + 24.9 + 28 = 67.1\ k€/y$$

Similarly the standard deviation is calculated 152.14 k€/y.

Therefore due to the improvement of the system the average risk is reduced from 97.16 to 67.1 k€/y or about 31%.

Concluding Remarks

An attempt to clarify some of the parameters associated with the assessment of hazard and risk due to natural phenomena was made. Particular emphasis was given to droughts that affect rainfed agricultural areas.

It was concluded that the most difficult task in the process of calculating risk is the assessment of vulnerability of the affected system. With regard to drought risk, the average (annualized) risk is proposed incorporating both the frequency of each class of drought severity (expressed by drought indices) and the consequences measured as loss in crop yield.

Although rainfed agriculture was used as a simplified example for calculating the average risk, irrigated agriculture could be also studied in a similar manner assessing its vulnerability. Similar difficulties may be encountered in case the vulnerability of other systems affected by extreme natural phenomena is assessed. It is a challenge for researchers to investigate methodologies for assessing vulnerability of the various systems affected by droughts such as agricultural areas, municipalities, industry, tourism and environment.

Since natural phenomena may be of different magnitude and frequency for the future as compared with the events of the historical record some sort of modification in the proposed probabilistic methodology is required. That is climatic changes could be introduced so that the calculated average risk is more representative of the future than of the past.

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