European Water 19/20: 47-56, 2007.
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Practical Application of Risk and Hazard Concepts in Proactive Planning

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Abstract: The concepts of hazard and risk have been used in a wide spectrum of disciplines without having the same meaning. The objective of this paper is to present a paradigm of these terms in the scientific area of natural hazards. Particular reference is made to water-related hazards. By analysing the terms of hazard, vulnerability, exposure and risk, an attempt is made to devise a comprehensive framework for their study. For the purpose of proactive planning the concept of average (annualised) risk is proposed as the key factor for the prioritisation of the appropriate reclamation measures. Simplified examples are presented for illustrating the proposed methodology.

Key words: hazard, risk, vulnerability, exposure, proactive planning, floods, droughts

1. INTRODUCTION

Hazards may be characterised as natural or man-made, dependent on the type of cause. Although this work concentrates on the natural hazards there are a lot of cases in which man induced causes intensify or alter natural causes.

Natural hazards vary in magnitude and severity in time and space. Under certain circumstances they may cause loss of human and animal lives, destroy infrastructures and properties, influence economic and social activities, and cause destruction of the environment.

It should be stressed that during the last decades natural hazards have been the cause for loss of hundred thousands of human lives and billions of Euros damages in various places around the world.

The natural hazards may be classified into two major categories:

a) the *geological hazards* including earthquakes, volcanic eruptions and tsunamis. Also, landslides and avalanches belong to this category, which have also causes related to weather conditions.
b) the *climatic hazards* including windstorms, floods of various types, extreme sea levels and high waves, droughts and wild fires.

A particular sub-category of climatic hazards is the category of water-related climatic hazards including mostly the floods and droughts.

It is the objective of this paper to devise a comprehensive methodology for estimating hazard and risk for the potentially affected areas from floods and droughts. Also related concepts such as vulnerability, exposure and potential consequences are explained and analysed. Finally numerical examples are presented for illustrating the proposed methodology.

2. HAZARD

Hazard may be defined as:

- a source of potential harm

- a situation with the potential to cause damage
- a threat or condition with the potential to create loss of 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 leeves). Hazard, according to the above general definition, should be treated as a general term indicating a type of threat for life, environment, heritage and development. However, some sort of quantification of hazard is necessary. This quantification may remain at qualitative terms by describing the people, properties, land use etc that are under threat, or by estimating the frequency (from historical events) of this threat. Therefore, although it may be subjective, the hazard of an element exposed to a certain threat can be characterised as small, medium or high.

In a more structured way, hazard may be quantified numerically by two ways:

i) the probability or the frequency of occurrence of the hazardous phenomenon (e.g. the area is flooded with a probability 1 in 5 years)
ii) the sum of potential consequences that is in case of flooding the potential damage of the area. (e.g. loss of agricultural production, damage to the infrastructure etc).

Under certain conditions the first or the second way can be considered more appropriate. For example, the first way seems more meaningful in case of natural hazards whereas the second is more realistic in case man-made causes are also involved. Therefore an area which is flooded during 1 in 5 years, on average is characterised by a high flood hazard when compared to an area which is flooded during 1 year in a 50 year period, on average. On the other hand, the second definition seems more appropriate in the case of a storage dam located upstream of a community which will be flooded in case of dam break. This situation creates a high hazard to the area due to the anticipated loss of lives and other economic damages, but probabilities of the failure mode are not appropriate for estimation of hazard since this can happen due to a variety of reasons not necessarily described by probabilities.

The second quantification of hazard may be further explained through the presentation of an example. Let us consider the case of a forest fire hazard of a suburban forest. Due to the various human activities, the forest is under threat of a fire which may destroy the forest entirely in case of a warm sunny day with strong winds. In this example probabilities cannot be assigned to the causes of failure, because this may happen by a human accidental or planned activity. Therefore, the second definition of hazard is more appropriate based on the sum of potential consequences.

Concentrating on the natural hazards with entirely natural causes it can be supported 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 (and possibly therefore by their potential consequences) together with the frequency of these hazardous events. By the term potential consequences we mean all the people and elements which are under threat since in most of the cases no protection system exists. Since the magnitudes of the phenomenon follow a certain probability distribution, the following equations may be written:

$$F(x) = P(D \le x) = \int_{-\infty}^{x} f_D(x)dx = \int_{0}^{x} f_D(x)dx \tag{1}$$

or

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

in which x is the sum of potential consequences of the phenomenon, *F(x)* and *P(D≤x)* are the cumulative density functions (c.d.f.), *P(D>x)* is the exceedence 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.

The figure which gives a representative measure of hazards from a phenomenon described by a certain probability density function is the mean expected value *E(D)* which considers both the potential consequences and their probability of occurrence:

$$E(D) = \int_0^\infty x \cdot f_D(x) dx \tag{2}$$

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

$$Var(D) = \int_0^\infty (x - \mu)^2 \cdot f_D(x) dx \tag{3}$$

in which $\mu = E(D)$

or $Var(D) = E(D^2) - (E(D))^2$

$$Var(D) = \int_0^\infty x^2 \cdot f(x) dx - (E(D))^2 \tag{4}$$

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

A numerical example is now presented to illustrate the calculation of mean potential consequences related to a flood hazard. The maximum annual discharges at a river section follow a type of extreme value probability distribution. From the analysis of local conditions, the peak flood discharges are related to the anticipated economic loss as in Table I. The potential consequences are estimated by transforming the peak discharge to a hydrograph and then obtain the inundated area from each volume of flood. Finally, the potential consequences caused by the inundation of the area (Table 1).

Table 1 Return periods are associated with the peak discharges and the anticipated potential consequences.

Return Period T(y)	***Peak Discharge Q_{max} (m^3/s)***	***Potential consequences D(M€)***
2	*80*	*0*
10	*140*	*4*
50	*190*	*8*
100	*220*	*11.7*
1000	*360*	*30*
> 1000	*> 360*	*30*

Further from the above table, another table connecting the frequency of occurrence of each class with the mean potential consequences of the same class is produced (Table 2).

Table 2. Frequency vs mean potential consequences of each class

Frequency $\boldsymbol{F(x_{i+1})-F(x_i)}$	**Mean Potential Consequences** $\dfrac{x_i + x_{i+1}}{2}$
0.40	2
0.08	6
0.01	9.85
0.009	20.85
0.001	30

The (mean) expected value of potential consequences is then calculated as follows:

$$E(D)=\sum_{i=1}^{n}\left(\frac{x_i+x_{i+1}}{2}\right)\cdot\left[F(x_{i+1})-F(x_i)\right]=2\cdot 0.40+6\cdot 0.08+9.85\cdot 0.01+20.85\cdot 0.009+30\cdot 0.001$$

E(D)=1.596 M€/y

3. VULNERABILITY AND EXPOSURE

Vulnerability of due to a certain element at a certain hazard may be defined as the degree of susceptibility to damage from this hazardous phenomenon or activity. Vulnerability may be also calculated for an entire population or an area which is under threat.

An important term related to vulnerability is the exposure of an element or a system to a certain hazard. Exposure *(E)* may be represented by 1 or 0 corresponding to “exposed” or “not exposed” conditions. In case of a system (e.g. area or population), exposure can take values between 0 and 1 representing the part of the system under threat. Exposure may be treated within vulnerability or separately.

Needless to say that exposure is dependent on the magnitude of the phenomenon. Therefore each element of a potentially affected system may be exposed to the hazard above a certain magnitude of the hazardous phenomenon.

Vulnerability is dependent on various factors, the most important of which are related to:

1) the condition of the system *(S)*
2) the magnitude of the phenomenon Q_{max}
3) the so called “social factor” *(SF)*
4) the fuzzy interrelation of internal factors *(I)*

In mathematical terms vulnerability *(V)* is expressed as a function of the above variables including exposure:

$$V = V(E, S, Q_{\max}, SF, I) \tag{5}$$

The Vulnerability function takes values between 0 and 1. One means that the system is totally unprotected, whereas values near to zero correspond to a well protected system. A typical vulnerability function versus the magnitude of a hazardous phenomenon (eg. peak flood discharge) is presented in Fig. 1. As can be seen from Fig. 1, by improving the system, the vulnerability curve is moved to the right. This means that lower values of the vulnerability function are attained for the same magnitude of the phenomenon after the improvement of the system. In more detail, the system is totally unaffected at magnitude Q_o and totally destroyed at Q_c or above. After the improvement, the system remains unaffected at Q_o'($Q_o'>Q_o$) and totally destroyed at Q_c' ($Q_c'>Q_c$).

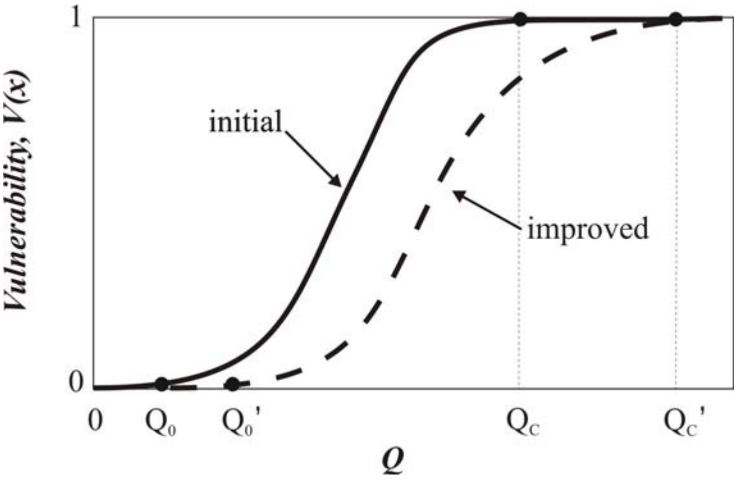

Figure 1. Vulnerability of a system vs the magnitude of the phenomenon

In general terms, vulnerability may be applied to the entire system. Alternatively it may be necessary to disaggregate the system into a number of components and perform a detailed analysis on each of them. It should be remembered that the aim of all reclamation and protection works is to reach a lower overall level of the system's vulnerability.

For improving the resistance of the system or decreasing its susceptibility to damage the following main strategies may be followed:

1) Mitigating the magnitude of the phenomenon
2) Improving the coping capacity of the system
   a) improving the internal conditions of the system
   b) improving the social capacities to deal with the phenomenon
   c) controlling internal factors and their interrelations
3) Decreasing the exposure of the system to the hazardous phenomenon.

The above strategies are further explained through the application example of river floods in a flood-prone area.

The three major categories of these strategies are discussed briefly below:

(i) *Mitigating the magnitude of the phenomenon*
Since large volumes of water are coming from the upper mountainous part of the river basin, there are several ways to control or retard the flood waters out of the threatened flat area. For example, small structures (e.g. small dams) may be constructed to decrease the gradient of the river and hold some quantities of flood water so that the flood velocity and volume are decreased and the river's erosive power is also decreased. As a result the peak discharge and the flood volume are smaller when the flood enters the flat area and therefore both the inundated area and the inundation depth are decreased mitigating damages.

(ii) *Improving the coping capacity of the system*
In this category of improvements there are a lot of measures and structures which may increase the resistance of the area under threat towards the flood of a certain magnitude. The most popular measures in this category are the reclamation works or flood defence structures (e.g. improving river flow conditions, or building levees and walls to protect the riverine areas). Important aspect in this category is the improvement of the institutional capacity and the enhanced conditions for public learning and participation to deal with the phenomenon. Early warning systems are also very important for an effective defence. Last but not least is the influence of all interrelated factors so that acceleration of extreme conditions is avoided.

(iii) *Decreasing the exposure*
Finally if the measures to combat flooding do not seem to be effective, an attempt can be

made to limit the exposure of the elements under threat. Such practical measures include transferring activities out of the area under threat or by avoiding living or working in basements or even in ground floor apartments or offices.

4. RISK

Different definitions of risk are adopted in various disciplines according to the objective or the type of extreme event under study. In some cases risk is defined as the probability of an adverse event and in others as the anticipated consequence of the adverse event. In the first case, risk *(R)* can be computed as:

$$R = 1 - P(X \leq x)^n \tag{6}$$

in which $P(X \leq x)$ is the cumulative probability and n the number of years, assuming stationarity and independence of the extreme events. Similarly, in reliability theory, risk is defined as the probability that an external forcing factor exceeds the capacity/resistance of the system leading to a failure (Hashimoto *et al.*, 1982; Nicolosi *et al.*, 2007).

In the second case, risk is defined as “the sum of expected losses due to a particular natural phenomenon as a function of natural hazard, vulnerability and the element at risk (UNDRO, 1991).

More specifically in the scientific area of natural hazards, risk may be defined as a real or existing threat to a system (life, health, property, infrastructure, economy and environment) given its existing exposure and vulnerability. In mathematical terms risk can be calculated as a functional relationship of hazard and vulnerability.

$$R = \{H\}\square\{V\} \tag{7}$$

According to the proposed methodology of this study the average (annualised) risk can be calculated as follows:

$$R(D) = \int_{o}^{\infty} x \cdot V(x) \cdot f_D(x) \cdot dx \tag{8}$$

in which x represents the potential consequence anticipated by the phenomenon of the corresponding magnitude the p.d.f. of which is $f_D(x)$. In the above equation $V(x)$ are the values of the vulnerability function of the system towards the corresponding magnitude of the phenomenon.

5. APPLICATION EXAMPLES

Typical examples for calculating average risk and assessment of vulnerability are now presented.

5.1 Flooding of a flood plain

Let us consider the example in paragraph 2. The estimated consequences refer to the initial conditions in which no significant flood protection structures have been constructed. The peak discharges and the potential consequences are reproduced in Table 3.

In order to reduce the vulnerability of this flood-prone area, a system of flood protection levees is planned, protecting the area from floods up to the peak discharge of 140m^3/s which corresponds to a return period of 10 years. By studying the local data, the anticipated consequences (in monetary units) from events of various return periods are estimated, based on the conditions after the new system of levees is constructed (Table 3, column 4).

Table 3. Estimation of vulnerability improvement

i	***Return period (y)***	***Peak discharge (m^3/s)***	***Initial potential consequences (M€)***	***Consequences after improvement (M€)***	***Vulnerability (-)***
1	2	80	0		0.001
2	10	140	4 →	0	0.001
3	50	190	8 →	7.2	0.900
4	100	220	11.7 →	11.12	0.950
5	1000	360	30 →	29.1	0.970

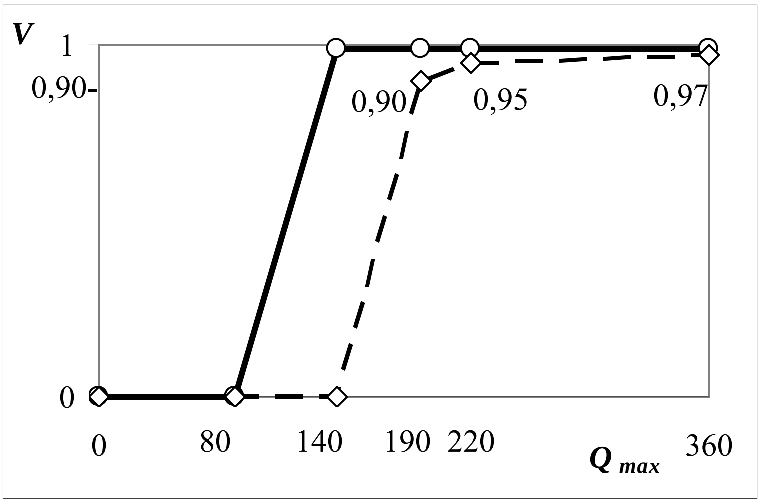

Figure 2. Vulnerability curve for the initial and improved conditions

The finally expected average risk is determined by:

$$R(D) = \sum_{i=1}^{n} \left(\frac{x_i + x_{i+1}}{2} \right) \cdot \left[F(x_{i+1}) - F(x_i) \right] \cdot \left(\frac{V_i + V_{i+1}}{2} \right) = 0.561 \ M€/y \qquad (9)$$

Compared to the initial conditions, the reclamation project resulted in average risk of 0.561 *M€/y* compared with 1.596 *M€/y* before the improvement. This is a decrease in the average risk of 64.8%. The average risk decrease in monetary units can now be compared with the cost of the reclamation project in annual values. By doing so, it can be rationally decided whether the project is economically justified.

5.2 Drought in Rainfed Agriculture

The following data (Table 5) refers to the probabilities of occurrence of drought episodes in an agricultural area cultivated by cereal crops (Tsakiris, 2007). Annual drought severity is represented by the Reconnaissance Drought Index (RDI) which is assumed to be effectively linked with the losses in crop yield (Tsakiris and Vangelis, 2005). No irrigation or other drought protection system is in operation therefore both exposure and vulnerability are equal to one.

Table 5. Drought classes and anticipated economic losses

Severity of annual drought	***Probability of occurrence***	***Anticipated losses (k€)***
0>RDI>-1	1:3	20
-1>RDI>-1.5	1:7	150
-1.5>RDI>-2	1:12	400
RDI<-2	1:25	900

From the above Table the following Table 6 is prepared:

Table 6. The anticipated economic losses for each drought class

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

The average risk is 20·0.333+150·0.142+400·0.083+900·0.040=97.16 *k€/y*

To decrease the above average risk several measures have been taken. For example, the existing irrigation system is put into operation only during the most sensitive period by using expensive water conveyed from outside the area in question. The cost of the water transferred is provided by the state. By taking these measures, the following results are expected (Table 7).

Table 7. Estimation of Vulnerability of the improved system

$\bar{x}_{i,i+1}$ **(1)**	$F(x_{i+1})-F(x_i)$ **(2)**	**Anticipated losses k€ (3)**	$V(\bar{x}_{i,i+1})$ **(4)**
0	0.333	0	0
100	0.142	100	0.667
300	0.083	300	0.750
850	0.040	850	0.944

The vulnerability of the system is therefore improved, compared to vulnerability 1 of the system in the initial case. The vulnerability is now calculated for each level of $\bar{x}_{i,i+1}$ (column 4 of Table 7). In Figure 4 the vulnerability of the initial and the improved system are plotted against the classes of drought severity represented by the reconnaissance drought index (RDI).

Considering that the exposure remains equal to one, the average risk calculated for the improved system is:

$$R(D) = \sum \bar{x}_{j,j+1} \cdot V(\bar{x}_{j,j+1}) \cdot f(\bar{x}_{j,j+1})$$
$$= 0 \cdot 0.333 + 100 \cdot 0.142 + 300 \cdot 0.083 + 850 \cdot 0.040 = 73.10\ k€/y$$

Therefore, it can be concluded that the improvement reduced the average risk from 97.16 to 73.10 *k€/y* that is by 24.06 *k€/y* or 25%. This means that improvements of such effectiveness may be justified if their average annual cost is smaller than this average risk decrease.

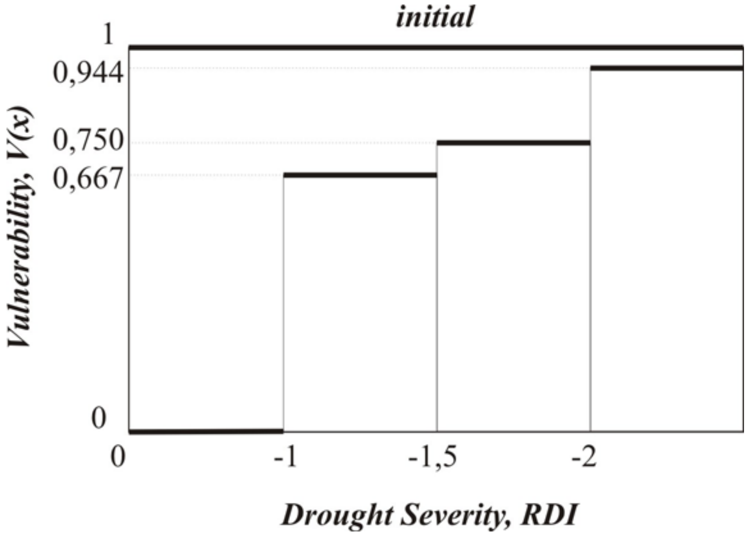

Figure 4. Vulnerability plotted against the drought index RDI

6. DISCUSSION

In the previous paragraphs a methodology was presented for estimating the risk caused by a natural hazard. By calculating the average or annualised risk, a representative figure, encompassing the entire stochastic process of hazard episodes over a great period of time, is derived. In this proposal risk is evaluated in some physical terms such as economic (damages) or social (lives lost). Although the examples were focused on the economic losses, an appropriate extension should follow to incorporate the anticipated losses of lives. In conclusion such a procedure seems to be appropriate for prioritisation of human interventions in various areas under risk at the planning stage.

From the above analysis it is easily deduced that the calculation of annualised risk is a gross figure representing the average (annual) loss due to a natural hazard. This figure seems to be very conservative since it does not include most of the indirect losses and all the intangible consequences. Also this figure is calculated based on parameters with high uncertainty. For these reasons risk values could be increased by say one standard deviation of any other justified increase.

Important issues when calculating the risk are the characteristics of the cause initiating the failure mode leading to damage. These causes may be natural or due to human error or involvement. If the risk is calculated on the basis of probabilities on extreme events or processes care should be taken on the possibility of two or more causes of failure occurring at the same time. An estimation of the final probability in case of various causes of initiating failure could be searched in historical records of failure of similar or nearly similar situations.

If the type of hazard is dependent on human intervention or activity, then the proposed probabilistic process cannot be valid. It is also important to remember that apart from the risk which may be calculated, there is always a hidden uncertainty which cannot be easily quantified. Therefore, in order to assess the risk threatening a certain area (area at risk) or population (population at risk), under conditions which may be influenced by factors not following probabilistic rules, the worst scenario should be considered. For example, the breach of leeves protecting an area can occur in the night under adverse conditions instead of midday on a sunny day. The assumption of the worst scenario is compulsory when calculating the risk, if lives or important properties or heritage are at risk.

This worst scenario should be the basis of any warning system which may be planned for the area under risk. For example, let us consider the break of an embankment dam protecting an area from floods. The break of the dam may be caused by an extreme storm event (natural initiation of failure) or by a human error or activity (man made initiation of failure). The worst scenario in this case is the shortest possible duration of failure (dam break) which may last only some minutes. This worst scenario should be the basis of calculating the inundation area and the time of arrival of the waves from the collapsing dam.

In the presented methodology both hazard and risk were calculated by the anticipated consequences. Another school of thought has proposed hazard to be calculated in terms of the adverse conditions created and risk reflecting the consequences (mostly in monetary terms). This type of approach can be seen in the EU directive on floods in which hazard is assessed by the inundated area caused by a flood of certain probability of occurrence and risk is the total economic loss due to flooding (Directive 2007/60). The directive proposes to the member states to conduct studies in the flood-prone areas for linking large, medium and small probability flood events with the flooded area and the economic consequences in form of hazard and risk maps. Although this type of analysis is very important for understanding the level of risk of each flood-prone area studied, it is not sufficient for assessing the average level representing the entire stochastic development of the flood hazard and the average level of anticipated consequences.

7. CONCLUSIONS

An attempt was made to devise a comprehensive methodology for calculating hazard and risk of a natural cause. The key determinant in this methodology is the average (annualised) values of hazard and risk which are both expressed in terms of consequences. The average risk is the quantity, mainly expressed in economic terms, which is the key for rationalisation of decisions related to system improvements with the objective to resist to the adverse conditions of natural extreme phenomena. Examples of water related hazards were presented to illustrate the application of the proposed methodology.

In case of hazards initiated or dependent on direct human induced causes or caused which cannot be described by probabilities the "worst scenario" is proposed as the basis of any protection initiatives.

ACKNOWLEDGEMENTS

The thesis presented in this paper is partly the result of discussions between the participating researchers in three projects DISMA and PRODIM and MEDROPLAN which are convened under the coordination or participation of the Centre for the Assessment of Natural Hazards and Proactive Planning of the National Technical University of Athens. All the scientists who contributed in one way or another for devising the proposed methodology are acknowledged.

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