Flood Risk Assessment: A Methodological Framework

Aimilia PISTRIKA, George TSAKIRIS
Centre for the Assessment of Natural Hazards & Proactive Planning, National Technical University of Athens, Greece, E-mail: pistrika@central.ntua.gr, gtsakir@central.ntua.gr

Abstract: The concepts of hazard, vulnerability and risk have been extensively used in various disciplines with a different meaning, impeding cross-disciplinary cooperation for facing hazardous events. Even for natural hazards, such as floods, no unique definitions and assessment procedures have been widely accepted. In this paper we propose a comprehensive way for defining and assessing flood risk and vulnerability in the flood-prone areas. The suggested methodology follows a three-step assessment approach: a) annualised hazard incorporating both probabilities of occurrence and the anticipated potential damages b) vulnerability (exposure and coping capacity) in the flood-prone areas and c) annualised flood risk (estimated on annual basis). The methodology aims to assist water managers and stakeholders in devising rational flood protecting strategies.

Keywords: Flood Hazard, Vulnerability, Annualised Flood Risk, Flood Risk Assessment

1. INTRODUCTION

The assets at risk from flooding can be enormous and include private housing, transport and public service infrastructure, commercial and industrial enterprises, and agricultural land. The International Committee on Large Dams (ICOLD, 2003) conducted a survey to determine the social and economic impacts of the floods in 20 countries, where are located about 80% of the total number of the world's largest dams. The greater number of victims due to floods is produced in Asian countries, as it is shown in the Table 1.

Table 1. "Mean" number of victims per year(ICOLD, 2003).

Victims	Countries
0 – 10	Argentina, Australia, Brazil, Canada, France, Ireland, Italy, Netherlands, Norway, South Africa, Sweden, Russia
10 – 20	Spain
50 – 100	Indonesia, USA
100 – 150	Japan
>150	Korea (250), Bangladesh (200), India (1500), China (2000-3000)

In addition to economic and social damage, floods can have severe consequences, where cultural sites of significant archaeological value are inundated or where protected wetland areas are destroyed. Regarding floods in Europe, two trends point to an increased flood risk and to greater economic damage from floods. First, the scale and frequency of floods are likely to increase in the future as a result of climate change, inappropriate river management and infrastructure development in flood risk areas. Second, an increase in vulnerability has been noted due to the number of people and economic assets located in flood risk zones. Therefore the coming decades are likely to see a higher flood risk in Europe and greater economic damage.

On 18th of January 2006 the European Commission proposed a Directive on the assessment and management of floods (COM, 2006). Its aim is to manage and ultimately to reduce the risks that floods pose to human health, environment, infrastructure and property. Under the proposed Directive the Member States are obliged to deliver the following for river basins and sub-basins:

1. Preliminary flood risk assessment
2. Flood risk maps
3. Flood risk management plans

The provision of structural flood defenses can have a major impact on the environment and there has been an expression of concern by many members of the public for the degradation of river corridors. Therefore, it is becoming common practice for central and local governments to subject flood management plans to public discussion (COM, 2006).

It is obvious from the above that concepts such as hazard, risk and vulnerability are the most commonly used terms to describe the potential threats that natural disasters pose to human life, the environment and the infrastructure. Additionally, these terms are used to question the capacity of various structural and non-structural measures, which are applied for protection from these threats. In the absence of regulatory establishment of a common accepted terminology platform, the confusion on the context of these terms grows. Furthermore quantification of the terms is not an easy task. It is possible that some parameters affecting the above concepts are beyond quantification and also that these parameters vary in space and time (Brauch, 2005; Thywissen, 2006).

However, in order to accomplish a comprehensive and participatory approach to flood risk management, it seems that a clear comprehension of the processes of hazard, vulnerability and risk perception is necessary. The primary focus of this paper is to clarify these concepts and to highlight a methodology for the assessment of flood hazard and flood risk. Particular attention is also given to the concept of vulnerability with regards to its social nature and the factors on which it depends.

2. DEFINING TERMS AND CONCEPTS

2.1. Flood Hazard

Hazard may be defined as:

- a source of potential harm.
- a threat or condition that may cause loss of life or initiate any failure to the natural, modified or human systems.

The initiating causes of a hazard may be either an external (e.g. earthquake, flood or human agency) or an internal (defective element of the system e.g. an embankment breach) with the potential to initiate a failure mode. Hazards are also classified as either of natural origin (e.g. excessive rainfalls, floods) or of man-made and technological nature (e.g. sabotage, deforestation, industrial site of chemical waste). Regarding hazard identification and estimation, two approaches can be identified based on the ANCOLD Guidelines (2003) and the ISDR principles (2004):

a. *Traditional deterministic approach:* a first level estimation of the potential adverse consequences, if the hazard occurs, in order to classify the system under threat, identify the necessity or not of further investigation. This approach is also the most comprehensive way of estimating man-induced and /or technological hazards, e.g. a forest fire hazard that can not be captured by a probability distribution.

b. *Probabilistic approach*: it is based on the theory of probability and regards hazard estimation as the estimation of the probability of occurrence of a particular natural event with an estimated frequency within a given period of time. It can be applied on hazards of natural origin and it represents a very common method used in most flood plain delineation studies when the potential for loss of life is considered negligible in terms of historical floods. The probabilistic approach tends to assume that events in the future are predictable based on the experience of the past.

Concentrating on the flood hazard, it can be supported that the capture of the natural phenomenon requires the frequency of the flood events as well as their magnitudes (and thus their anticipated flood damages) (Alexander, 1991). Since the magnitudes of flood events can be modeled by a probability density function, flood hazard can be estimated by the probability that the flood damage that occurs in any one year, in the case of a flood event with specified frequency, will not exceed a specified value x_1. If X is the random continuous value of flood damage then the cumulative distribution function of the variable X will be:

$$F_X(x_1) = P(0 \leq X \leq x_1) = \int_0^{x_1} f(u)du = F(x_1) - F(0) \tag{1}$$

where *f(u)* is the probability density function (p.d.f.). This way, the probability of occurrence of various potential magnitudes of flood damages $X \in [0, x_1]$ can be expressed by a single number by summing the products of all possible values of flood damage and their probability of occurrence.

However, due to the random nature of flood damage it is impossible to predict the exact value of damage that would be incurred or prevented in any year. Therefore, flood hazard estimation could be based on long-term statistical averages, also known as expectations that give a measure of the location of the p.d.f. The expected value E(X) of annual inundation damage *X* is computed as:

$$E(X) = \int_{-\infty}^{\infty} x \cdot f(x) dx \qquad \text{(for a continuous random variable X)} \qquad (2)$$

Finally, the variance of the annual inundation damage X, var(X), is a measure of the spread of the p.d.f about its mean and it can be calculated as follows:

$$Var(X) = E(X^2) - \{E(X)\}^2 = \int_{-\infty}^{\infty} x^2 f(x^2) dx - \{\int_{-\infty}^{\infty} xf(x) dx\}^2 \qquad (3)$$

Regarding the derivation of the damage-probability function can be estimated via the method illustrated by Figure 1 (USACE, 1996). Initially, a discharge-probability function (Figure 1a) is developed. If stage and discharge are uniquely related, a rating function (Figure 1b) can be developed and the discharge-probability function can be transformed through this rating function in order to develop a stage probability function. Similarly, if stage and damage are uniquely related, a stage-damage function (Figure 1c) can be developed, and the stage-probability function can be transformed through that function to yield the required damage-probability function. Finally, to compute the expected damage, the resulting damage-probability function is integrated.

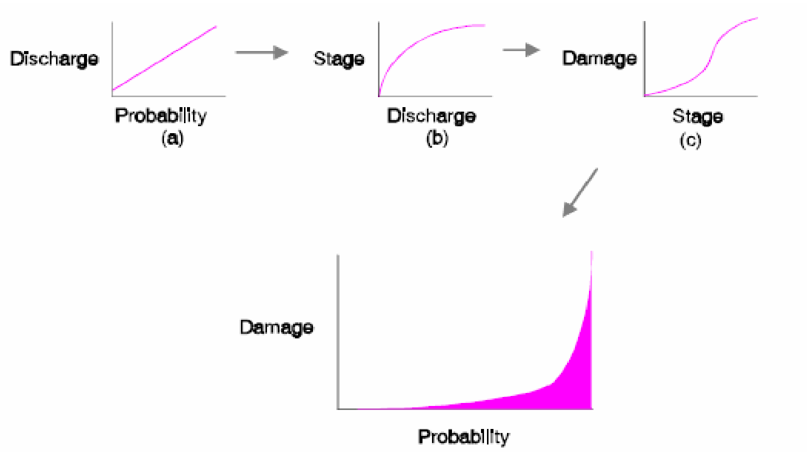

Figure 1. *Transformation for traditional expected annual damage computation (USACE, 1996).*

2.2. Vulnerability in the Flood-prone areas

One of the best-known definitions of vulnerability was formulated by the International Strategy for Disaster Reduction (ISDR, 2004), which regards it as “a set of conditions and processes resulting from physical, social, environmental and economical factors, which increase the susceptibility of a community to the impact of hazards”. A basic consensus has emerged, that the concept of vulnerability addresses a double structure consisting of an external side (exposure) (Bohle, 2001), and also that vulnerability (Pelling M.; Uitto J., 2001) is:

- multi-dimensional and differential (varies across physical space and among and within social groups).
- scale-dependent (with respect to time, space and units of analysis, such as individual, household, region, system).
- dynamic (characteristics and driving forces of vulnerability change over time, certainly exceeding that time of the extreme event itself).

Generally, the vulnerability of a system against a certain hazard is not easily assessed. Three routes for the assessment can be distinguished:

- economic
- social
- cultural

The vulnerability function could be treated as a function between 0 and 1 (see figure 2). The most appropriate approaches for the case of vulnerability of the society and the cultural heritage are thought to be qualitative (Laoupi and Tsakiris, 2007). Given the above thoughts, vulnerability assessment in flood prone areas depends on the following factors (Tsakiris, 2006):

i) the Exposure of the system (E).
ii) the initial coping capacity (resources availability) of the system (S).
iii) the magnitude and intensity of the hazardous event (Qmax).
iv) the social response of the system (early warnings, indigenous experience, public awareness etc)(SF).
v) the fuzziness of the interrelated sides of vulnerability (coping capacity & exposure) (I).

and therefore in mathematical terms vulnerability can be expressed as the following function:

$$V = f(E, S, SF, Q_{\max}, I) \tag{4}$$

A vulnerability analysis in the event of a flood hazard considers the population and structures at risk within the affected area. In the start of the analysis, a reference level of the system’s vulnerability should be determined that usually refers to existing flood protection systems of the affected area. The vulnerability analysis evaluates the potential costs of flooding in terms of damages to buildings, crops, roads, bridges and critical infrastructure. Normally the analysis is carried out for various probabilities of flood occurrence, and an elevation-damage curve is plotted.

The aim of the additional reclamation and protection works is to reach a lower level of the system's vulnerability. Consequently, this analysis is valuable for reaching at decision about the desired level of flood protection. Ideally, this analysis should initiate a public process to establish the "acceptable level of risk" that would refer to the flood discharge magnitude appropriate for the delineation of the affected areas. A comprehensive measure of the improvement of a system is the ratio of anticipated consequences after the improvement divided by the initial potential consequences.

Figure 2 depicts a simplified representation of vulnerability and its reduction versus the magnitude of the hazardous phenomenon. As it can be seen the improvement of the capacity of the system is schematically represented by a shift of the vulnerability curve to the right.

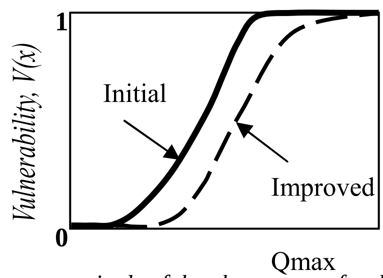

Figure 2. *Vulnerability vs magnitude of the phenomenon for the initial and the improved capacity of the system (Tsakiris, 2006).*

2.3. Flood Risk

According to EU Directive (COM, 2006) for flood management, *"flood risk"* is the likelihood of a flood event together with the actual damage to human health and life, the environment and economic activity associated with that flood event. In this context flood risk can be considered as the actual threat, in other words the real source of flood hazard to the affected areas. The quantification of flood risk results either in monetary units or in loss of life units, if the losses are measurable, or in qualitative terms (e.g. allocation in classes) in the case of intangible damages (social, environment, cultural) to the affected areas.

In general, risk as a concept incorporates the concepts of hazard {H} (initiating event of failure modes) and vulnerability {V} (specific space/time conditions). It is customary to express risk (R) as a functional relationship of hazard (H) and vulnerability (V).

$$\{R\} = \{H\} \square \{V\} \quad (5)$$

in which the symbol □ represents a complex function incorporating the interaction of hazard and vulnerability. Consequently in mathetical terms it can be expressed as:

$$R = \{H\} \text{ x } \{V\} \tag{6}$$

Since vulnerability is a dimensionless quantity (Villagran, 2006), risk could be measured in the same units as hazard. In quantitative terms, annualised risk can be estimated as the product of probability of occurrence of the hazardous phenomenon and the actual consequence, combined over all scenarios. According to the methodology of estimating average (annualised) hazard, the expected value of flood risk can be calculated as follows:

$$E(X) = \int_{-\infty}^{\infty} x \cdot V(x) \cdot f(x) dx \tag{7}$$

where *X* is the actual flood damage caused by the flood hazardous phenomenon, *f(x)* is the p.d.f. that describes this phenomenon and *V(x)* is the vulnerability of the system towards the corresponding magnitude of the phenomenon. It is obvious that such an estimation involves major restrictions such as:

- can be applied only on hazards of natural origin due to probabilistic analysis
- although it abides to a general methodological framework , it is highly case-specific
- highly dependable on expert's judgment

3. A METHODOLOGY FOR ASSESSING FLOOD RISK

Based on the ANCOLD Guidelines 2003 there is a basic consensus towards the methodological framework of risk identification and estimation. In this context, the general methodological framework for risk assessment can be, more or less, determined and it is given by the following steps:

1. *risk identification*: refers to the identification of the hazard source.
2. *risk analysis or risk estimation*: refers mostly to the probabilistic quantification of the average annualised risk and it is measured in the same units as hazard. It involves the estimation of the probability of occurrence of the hazardous phenomenon, the estimation of the actual consequences and the vulnerability estimation of the affected system over the selected hazard scenarios.
3. *risk evaluation*: refers to the identification of the local society's tolerable risk policies and criteria as well as to the comprehension of the local society's perception of the hazard impacts by the decision makers. One's willingness to pay for risk reduction is controlled by the perceived and not the actual

risk. Simultaneously the perceived risk reflects the human attitude towards various kinds of risks and it is therefore of high importance to assess it.

4. *risk assessment*: refers to the evaluation of the tolerability of the estimated risks based on the local society's acceptability criteria. The comparison of the estimated risks with acceptable ones results in the decision of what risk will be acceptable in the particular affected system and what risk reduction measures will be applied; if needed.

Under the auspices of INTERREG IIIC - Project OCR NOE - sub project DISMA, it was decided, by the local stakeholders, that the flood risk management framework will be mainly oriented towards non-structural measures (e.g. land use planning, flood warning systems, evacuation plans, insurance policy); that is towards measures that are mainly driven by the need of cultural heritage protection and also by the socio-economic conditions of the Eastern Attica Prefecture. In this context the authors developed a workflow chart, in order to apply the aforementioned methodology over flood hazard scenarios to the specific case-study areas of special cultural interest within the same Prefecture. Figure 3 depicts the applied methodological framework for flood risk assessment.

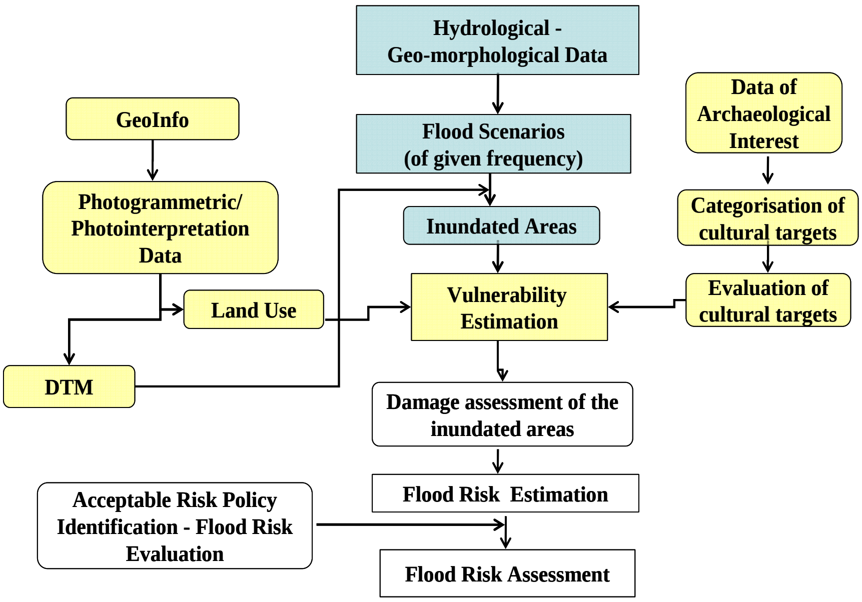

Figure 3. *Methodological Framework for Flood Risk Assessment*

The procedure for the assessment of flood risk is developed by allocating the workload into three categories of steps that can be initiated independently and represented with different colour. The first category (coloured yellow) refers to the task of collection and processing the necessary data in order to determine the boundaries of the system under risk (in this case particular cultural sites) and subsequently to identify the socio- economic conditions of the surrounding areas (for instance to detemine the local land use establishment). At this stage the identification of the system's vulnerability takes place and that is mainly the definition of the system's exposure to a potential flood hazard and the system's carrying capacity to cope with flood events. The second category involves (coloured blue) the development of hazard scenarios, the estimation of their probability of occurrence. At each scenario the production of the respective floodplain mapping delineation is given in Arc-GIS environment so as to identify the flood-prone areas and therefore the cultural sites that are under the inundation threat.

The third category in the workflow depends on the results of the two previous ones and so it is always performed last. It assesses the expected damage of the affected system and consequently it estimates the annualised flood risk in monetary units, if possible. Moreover, in this last stage, an attempt is made so that the local acceptable flood risk policy and the public risk perception are identified. The comparison between the acceptable flood risk setting and the estimated flood risk figures can significantly assist the decision makers to apply a series of effective flood risk reduction measures. Such measures can support the process of prioritising, justifying and targeting investments and developing sustainable policies and strategies and subsequently such measures can support flood risk management plans, spatial planning and emergency plans that can be acceptable from the majority of the local society.

4. CONCLUDING REMARKS

The EU Directive recognises the need for methodologies for the effective assessment and management of flood risk. In this paper an attempt was made to contribute to the ongoing scientific discussions on these issues. It is well-known that both the probabilistic risk based methodology and the deterministic methodology face heavy criticism and questioning regarding their applicability on a wide range of systems under threat. The proposed procedure incorporates elements from both of the above methodologies highlighting the significance of the vulnerability analysis within the flood-prone areas with the aim to contribute to a more rational assessment of risk.

Acknowledgements

The work presented in this paper was supported by the INTERREG IIIC - Project OCR NOE - sub project DISMA, which was conducted in the Centre for the Assessment of Natural Hazards and Proactive Planning of NTUA, in close collaboration with the Prefecture of Eastern Attica.

REFERENCES

Alexander, D.: 1991, Natural disasters: a framework for research and teaching. Disasters 15 (3), pp. 209–226.

ANCOLD (Australian National Committee on Large Dams): 2003, Guidelines on Risk Assessment.

Bohle H.-G.: 2001, Vulnerability and Criticality: Perspectives from Social Geography.<http://www.ihdp.unibonn.de/html/publications/update/update01_02/IHDPUp-date01_02_bohle.html>, 12 September 2006.

Birkmann J.: 2005, Research Brief: Danger need not spell disaster. But how vulnerable are we?. Publication of United Nations University–Institute for Environment and Human Security (UNU–EHS). November 2005.

Birkmann, J.:2006, Measuring Vulnerability to Natural Hazards. Towards Disaster Resilient Societies. Publication of United Nations University–Institute for Environment and Human Security (UNU–EHS). UNU-Press,Tokyo,New York,Paris.

Birkmann J. and Wisner B.: 2006, Measuring the Un-measurable - The Challenge of Vulnerability. Publication of United Nations University–Institute for Environment and Human Security (UNU–EHS). SOURCE No.5/2006; pp.10-12.

Brauch H.G.: 2005, Threats, Challenges, Vulnerabilities and Risks in Environmental and Human Security. Publication of United Nations University–Institute for Environment and Human Security (UNU–EHS). SOURCE No.1/2005.

Commission of the European Communities: 2006, Proposal for a Directive of the European Parliament and of the European Council on the assessment and management of floods. {SEC (2006) 66}; pp.1-5.

ICOLD (International Committee on Large Dams): 2003, Dams and Floods. Guidelines and Case Studies. Bulletin 125; pp.42-43.

ISDR (International Strategy for Disaster Reduction): 2004, Living with Risk. A Global Review of Disaster Reduction Initiatives. www.unisdr.org.

Laoupi A. and Tsakiris G.: 2007, Assessing Vulnerability in Cultural Landscapes. EWRA Symposium "Water Resources Management: New Approaches and Technologies, Chania, Crete, Greece 14-16 June 2007.

Pelling, M.; Uitto, J.: 2001, Small Island Developing States: Natural Disaster Vulnerability and Global Change. In: Environmental Hazards.Vol. 3,pp. 49–62.

Thywissen K.: 2006, Components of Risk. A Comparative Glossary. Publication of United Nations University–Institute for Environment and Human Security (UNU–EHS). SOURCE No. 2/2006.

Tsakiris G.: 2006, Practical Application of Risks and Hazard Concepts in Proactive Planning. Report in the framework of NOE Interreg IIIC (DISMA subproject). DISMA Coordination Meeting, 14-15 Dec. 2006, Athens.

USACE (U.S. Army Corps of Engineers): 1996, Engineering and Design. Risk - based Analysis for Flood Damage Reduction Studies. Manual No. 1110-2-1619, chapter 2.

Villagran De Leon J.C.: 2006, Vulnerability – A Conceptual and Methodological Review. The Institute for Environment and Human Security. United Nations University. SOURCE No.4/2006; pp. 8-14, 48-50.