Hybrid loss exceedance curve (HLEC) for risk assessment

César Velásquez[1], Omar Cardona[2], Luis Yamin[3], Miguel Mora[1], Liliana Carreño[1,4] and Alex H. Barbat[1,4]

[1]*Centro Internacional de Métodos Numéricos en Ingeniería, CIMNE, Barcelona, 08 03 4 , Spain*
[2]*IDEA, Universidad Nacional de Colombia, Manizales, 170004 , Colombia*
[3]*ICYA, Universidad de los Andes, Bogotá, 111711, Colombia*
[4]*Departamento RMEE, Universitat Politècnica de Catalunya, Barcelona, 08 03 4 , Spain*

Summary

Countries need to assess the expected risk due to natural hazards as a permanent activity in their financial plan; otherwise, they will experience a lack in the information required by the application of disaster risk reduction policies. In this article, a risk assessment methodology is proposed that uses, in one hand, empiric estimations of loss, based on information available in local disaster data bases, allowing to estimate losses due to small events; on the other hand, it uses probabilistic evaluations to estimate loss for greater or even catastrophic events for which information is not available due the lack of historical data. A "hybrid" loss exceedance curve, which represents the disaster risk in a proper and complete way, is thus determined. This curve merges two components: the corresponding to small and moderate losses, calculated by using an inductive and retrospective analysis, and the corresponding to extreme losses, calculated by using a deductive and prospective analysis. Applications of this new probabilistic risk assessment technique are given in this article for three countries.

KEYWORDS: risk, prospective analysis, retrospective analysis, loss exceedance curve, hybrid loss exceedance curve.

1. INTRODUCTION

The impact of natural hazards in terms of human and economic losses is continuously increasing all around the globe due to several factors like urban developing, population growth and migration, off-code constructions and climate change, among others. It has been infrequent, so far, for disaster risk management (DRM) to play a role in urban planning, even if many developing countries include in their budgets allocations for disaster mitigation.

But these go mostly for preparedness and response during the emergencies and only in some cases efforts are being made to direct resources towards planning activities related to risk mitigation. In order to understand risk, we need to define it along with its components. Hazard, H, is understood as the possible occurrence of a natural event which can affect a community, cause damage and human and economic losses. Exposure, E, refers to the assets (from houses to infrastructure) existent in the hazard prone area that can be impacted during a hazard event. Vulnerability, V, is the susceptibility of the exposed elements to suffer damage or to be affected due the hazard.

Finally, risk, R, is defined as the potential consequences over the community if the natural event materializes. Accordingly, UNDRO (1980) proposed the following definition of risk.

$$R = E \cdot H \cdot V \tag{1}$$

The probabilistic assessment of catastrophic risk requires specialized computational tools and we choose for this research the CAPRA platform (ERN-AL, 2010). This platform has been developed within an initiative sponsored by the WorldBank Group, the Inter-American Development Bank and UN-ISDR, among others, and allows evaluating the natural hazards, the exposure and the disaster risk at different scales (ERN-AL 2010; Cardona et al. 2010a, Cardona et al 2010b).

A new comprehensive methodology for risk assessment is proposed herein, in which the effect of minor and frequent past events, in terms of accumulated impact, is combined with that of expected future catastrophic events, allowing this methodology to achieve a closer insight within disaster risk (Marulanda et al. 2010; Cardona et al. 2008a).

The objective of this article is to develop a risk assessment approach that allows measuring the impact of multiple minor events which, when taken together, have a considerable cost and significant social and environmental effects. At the same time, this approach considers the potential occurrence of extreme events whose impact can have consequences affecting the fiscal sustainability and sovereignty of a country. Thus, the proposed approach considers both, the extensive, repetitive, risk which must be mitigated with effective intervention strategies, as well as the intensive risk, for which are needed contingent liabilities that must be the object of strategies for financial protection and risk transfer.

The effect of insurance policies or risk transfer instruments has been not considered herein. Results obtained by using the proposed method are finally given for three countries: Colombia, Mexico and Nepal.

2 THE CAPRA PLATFORM

The CAPRA platform (ERN-AL, 2010) is a compendium of tools developed for the assessment of probabilistic hazard risk, as a main component for disaster risk reduction (DRR) policies. These tools consider the variability and, in the characteristics of the natural phenomena, in the definition and location of the exposed assets and in the vulnerability of the building and infrastructure types.

The occurrence of the natural hazard is assumed to follow a Poisson process; accordingly, all the possible events are independent from each other. When calculating risk with CAPRA, a special file is required, called AME file, in which all the possible occurrences of the considered natural phenomena have to be defined but in which one event has to be included only once. Each hazard scenario is defined as a raster map, where each location is defined as a statistical pair (by its mean value and standard deviation).

For the exposure, the CAPRA platform uses a geospatial database which has the format of a shape file. The different exposed assets are represented using geographic located points, lines or polygons and their main characteristics (e.g. building type, number of stories, economic value, and others) are linked. The CAPRA platform includes the necessary procedures to gather the information regarding the exposed elements based on the scale of analysis. Moreover, in certain cases the cadastral information of the city is available but, in others, this information has to be generated from remote sensing and in other cases, it has to be generated by using proxy models.

CAPRA evaluates the expected behavior of the different assets by means of vulnerability functions which correlate a certain characteristic of the natural phenomena (like gust speed, spectral acceleration, depth of flood, among others) with the mean damage ratio, MDR. The vulnerability functions are not available for each individual element but for a set of elements with similar characteristics, that is, for the building and infrastructure types included in the portfolio of the exposed assets.

As shown in Figure 1, a vulnerability function has to account for the dispersion and uncertainty of the expected damage. This dispersion has its origin in several factors, like the construction process, the quality of construction materials, the weather during construction phase, maintenance, etc., and also due to the uncertainties and the approximations made during the design phase.

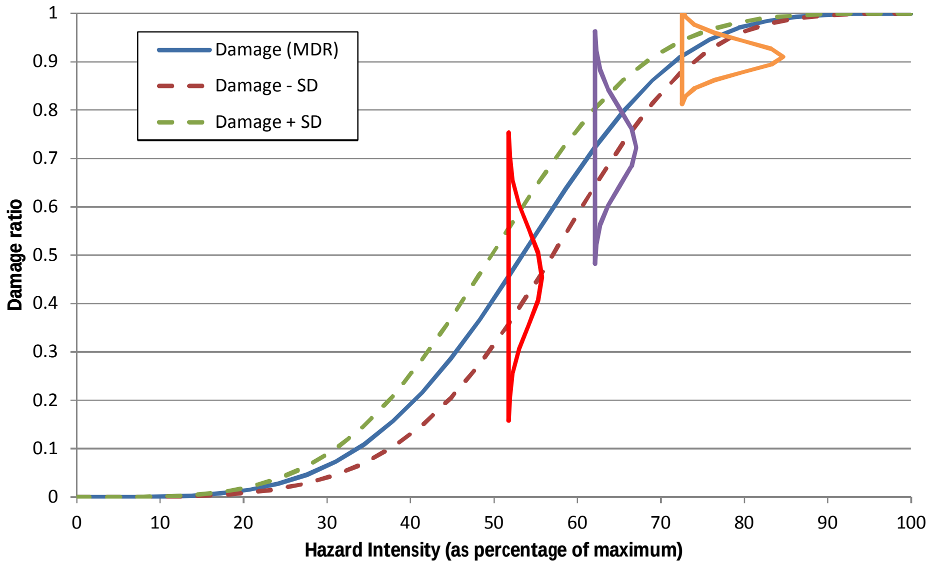

Figure 1. Probabilistic vulnerability function. It can be seen the expected mean damage ratio, MDR, and the dispersion characterized by the standard deviation, SD.

For risk calculations, CAPRA considers all the terms of equation 1 and accounts for all the uncertainties in its different components

$$v(p) = \sum_{i=1}^{Events} \Pr(P > p | Event_i) F_A(Event_i) \tag{2}$$

In this equation, $v(p)$ is the exceedance rate of loss, p; $F_A(Event_i)$ is the annual frequency of occurrence of the $Event_i$; $\Pr(P > p | Event_i)$ is the probability of the loss to be greater than or equal to p, conditioned by the occurrence of the $Event_i$.

The loss exceedance curve, LEC, is a graphical representation of risk, usually made in logarithmic scales. It shows the relation between a given loss (usually economical) and the annual frequency of occurrence of that loss or of a larger one. Figure 2 shows a LEC and it can be seen that it correlates an expected loss represented in the horizontal axis with an estimated frequency represented in the left vertical axis. As the frequency is the inverse of the return period, the loss can also be represented in function of the return period (the right vertical axis).

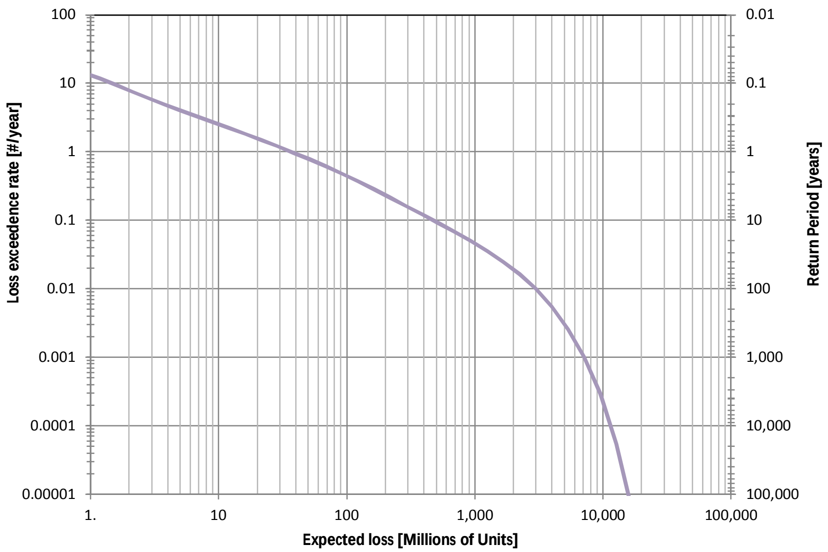

Figure 2. Loss exceedance curve. The vertical axis shows the frequency (left) and his inverse value, the return period (right); the horizontal axis displays the expected loss.

Other risk metrics that can be obtained with CAPRA are the annual average loss, AAL, and the probable maximum loss, PML. The AAL is the loss expectation, that is, the weighted average of all plausible loss values; in other words, it is the value expected to be saved every year in order to cope with all the future losses. The PML is the maximum foreseeable loss for the exposed portfolio.

3 PROSPECTIVE RISK ASSESSMENT WITH CAPRA

Considering the possibility that highly destructive events might occur in the future, risk estimation must focus on probabilistic models which make possible using the available information to calculate possible catastrophe scenarios in which high uncertainties are inherent. Accordingly, risk assessment must also follow a prospective approach, anticipating the events and the expected possible consequences that can occur in the future, considering uncertainties associated to the severity and frequency of the events.

Over the past decades, risk estimation models have been based on historical data, on consequences of past events and on insurance claims; these models were characterized by the lack of information regarding major, catastrophic, events. For this reason, different academic models were developed which considered the hazard intensity and frequency, the increasing portfolio of assets and its vulnerability into the probabilistic estimation of the hazard risk (Barbat et al. 2010).

In general, it should be recognized that the reliable historical information is limited, in most cases, to the last decades, and many catastrophic events are expected to occur in the future. For this reason, it is impossible to predict the consequences of extreme events based on the available information. In other words, the existing disaster databases (EM-DAT, DesInventar, and others) lack of sufficient records for low frequency and high consequences events, because the window covered by those databases is very narrow.

3.1 Hazard assessment

The identification and evaluation of the intensity and the annual recurrence of certain hazards that can affect a specific region, constitutes a step prior to risk analysis. The historical knowledge about the occurrence of events with high consequences and of their characteristics provides an initial idea of the destructive potential of the phenomena. This allows the description of the hazard in the region and makes possible to establish the approximate return periods of the most significant events.

3.2 Characterization of exposure

Exposure refers to assets like infrastructure or population existing in the hazard prone area, which are susceptible of being damaged by a specific event. In order to define the exposure, it is necessary to identify each of the different elements along with their characteristics including the geographical location, their vulnerability to the considered hazard event and their economical replacement value. The exposure values of goods at risk are normally estimated using secondary information sources, such as existing databases, or can be derived by using simplified procedures based on general social and macroeconomic information, such as population density, statistics of constructions and other parameters.

To completely include the exposure in the model, other physical assets of special importance, such as main infrastructure, have to be included. This requires several assumptions when aggregation is made from a local to a national scale. In general, the exposure model includes information about the following exposed components or elements:

- Buildings and houses;
- Industrial facilities;
- Roads and bridges;
- Electricity systems;
- Communications systems;
- Distribution systems;
- Relevant infrastructure (like airports, ports and others).

The level of detail of the exposure model has to be changed according to the availability of the information, going from the small scale of the individual buildings or blocks to the larger scale of the neighborhoods, cities, regions or countries. This variability in the disaggregation of the exposed elements is reflected in the level of resolution of the results and, thus, in the use of those; nevertheless, the expected overall results will have certain similarities.

3.3 Characterization of vulnerability

The physical vulnerability of an exposed element is characterized by functions that relate the parameter used to describe the hazard with the level of loss or damage suffered by that element. The functions of vulnerability have to be evaluated for each of the principal construction types existing in the studied area; such a function has to be assigned to each of the elements of the exposure database. They allow estimating consequences produced in each of the assets under the action of an event. In a probabilistic way, a vulnerability function defines for each value of the hazard intensity a mean damage ratio, MDR, and its standard deviation, SD.

As an example, the figures 3 and 4 show vulnerability functions for different building types and infrastructure elements. Due the number of the represented elements, only the MDR has been plotted.

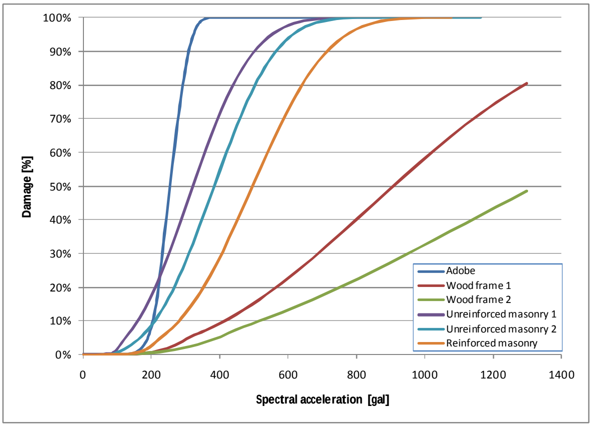

Figure 3. Seismic vulnerability functions for typical buildings

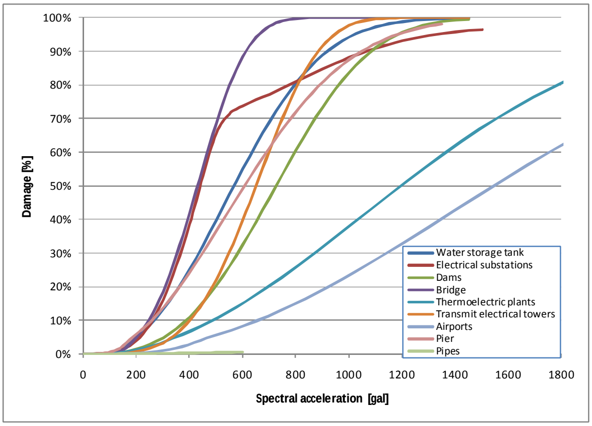

Figure 4. Seismic vulnerability functions for elements of infrastructure

Each vulnerability function corresponds to the expected statistical behavior of a typological group; this means that the results are valid only for the group of assets as a whole and not for each exposed element.

3.4 Results of the analysis

The results of the analysis can be presented for different portfolios or sectors, summarizing the annual average losses, AAL, and the probable maximum loss, PML, for the evaluated area. The PML values depend on the degree of dispersion of the evaluated assets. It should be kept in mind that the values obtained for different return periods correspond to the PML of the entire area and that these values, when evaluated for a part of this area, could significantly change because of the level of risk concentration.

For a given area the following portfolios could be considered:

- National: National infrastructure assets, private and also public buildings;
- Fiscal: Government assets, public health assets, public education assets and low income population assets;
- Public health: public assets used for medical and healthcare services;
- Public education: public assets used for educational and cultural services;
- Government: public assets used for administrative service;
- Private: assets of moderate and high income population sectors, industrial and commercial sectors.

The AAL, and the PML, for fiscal responsibility are obtained at country level. These correspond to the losses that the country would have to face due to potential damage in public and low income population assets, which would have to be covered by the government in the case of a major disaster.

The curve of Figure 5 is obtained analytically and only covers events such as strong earthquakes, hurricanes or other phenomena that can cause catastrophic consequences due to the correlation or simultaneousness of the effects on the exposed assets of the portfolio. It shows the fiscal LEC for an analyzed area following the previous methodology. This methodology can be resumed as follows:

- Construction of a hazard model. This model has to define all the possible scenarios in which the studied hazard can occur; for each one of those scenarios, the frequency, severity and expected deviation has to be included.
- Preparation of a geo-referenced database of exposed elements. It has to be built by using demographic and economic statistics.
- Assignation of vulnerability functions for each building and infrastructure type of the exposed elements. These functions are defined from the existing literature (HAZUS, Risk-UE) and by using computational models (Lagomarsino et al. 2006, Lantada et al. 2009, Vargas et al. 2012).

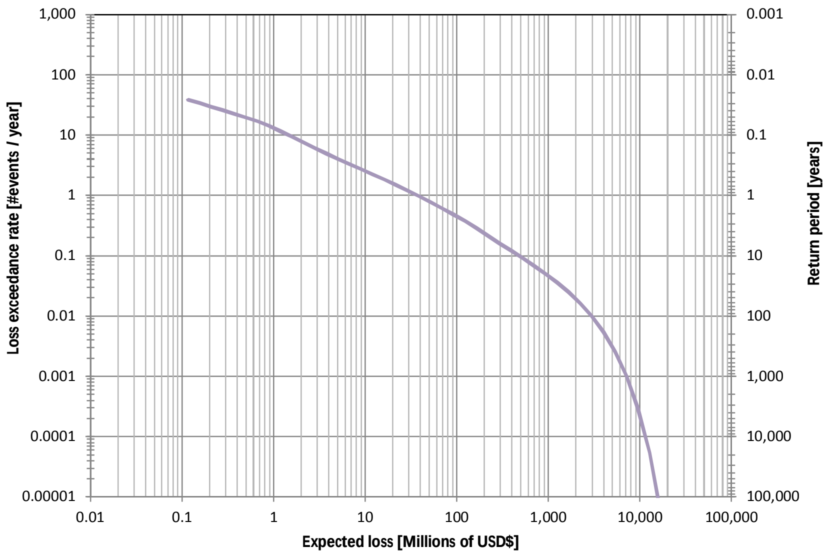

Figure 5. Prospective LEC. The vertical axis shows the frequency (left) and his inverse value, the return period (right); the horizontal axis displays the expected loss.

It should be noted in Figure 5 that there is a gap in the information related to small events with a high frequency, of more than 10 occurrences each year. The missing information in the LEC is because the prospective methodology considers only catastrophic hazards and dismisses the small and frequent hazards. Moreover, these small hazards require a large amount of data and a detailed analysis, beyond the normal capabilities of the existing risk evaluation models, including CAPRA. For example, the flooding hazard could be evaluated for a specific basin but not for all the basins of a large region at the same time; this is also true for landslides and other hazardous events which, many times, are considered as “minor”. That is why we propose a retrospective analysis, with its limitations and restrictions, but which can provide the solution we are searching for those small and frequent events.

4 RETROSPECTIVE RISK ASSESSMENT USING THE DESINVENTAR DATABASE

The retrospective risk assessment consists in the empirical estimation of economic losses due to events contained in the historical information databases, in which the losses caused by minor but frequent events are considered. Therefore, the DesInventar disaster database (Desinventar.net; Desinventar.org) has been chosen in order to perform the retrospective risk assessment because it contains numerous reliable records of past events, reasonably described by means of variables like: type of event; date of occurrence, geographical location, as well as other credible variables which can be used in the analysis, like the number of damaged houses, the number of destroyed houses, crops area, cattle and others.

For the effects of this analysis, the DesInventar records have to be submitted first to a process of filtering, merging and economic valuation, in order to develop a database that include, in addition to the available information, an estimate of the economic impact of each event, considering only the direct effects. The information included in the DesInventar database is used to estimate the economic cost associated with each event. The model used to evaluate losses takes into account criteria from the Manual for Assessment of the Socio-economic and Environmental Impact of Disasters (ECLAC, 2003) which is a guide for estimating the economic impact of individual events. The effects upon social sectors, infrastructure and economic sectors are considered along with the impact upon the environment, the women, employment and income.

Considering the small severity and the regional dispersion of most of the events contained in the DesInventar database records, we can conclude that they affect the more vulnerable sectors of society, which require the help of the government for shelter, healthcare and reconstruction after each event.

4.1 Steps of risk assessment

In order to carry out a retrospective risk analysis and the empirical development of a loss exceedance curve using minor but frequent events, the following steps have to be carried out:

- Selection of the database. In this study, we decided to use the DesInventar database because it has some relevant advantages: the number of countries covered by this database is increasing. The database is periodically updated to cover larger time periods and it contains a large set of fields which are useful in this study.

- Removing from the database the records corresponding to non-natural hazards. Due to the fact that we consider in the LEC only natural hazards, the records corresponding to other hazards, like biological technological, etc., have to be removed.
- General statistical analysis of the database. The selected database is analyzed for an adequate distribution of the number of records and of the consequences by year, for the distribution of the records over the studied area rather than their concentration at the main cities, etc. This statistical analysis permits the revision and check of the reliability of the database.
- Selection of the parameters for merging the records corresponding to the same events. In the specific case of DesInventar database, the consequences of a unique event can be stored over several records, each one corresponding to a different locality.
- Unification of the effects, by merging together records corresponding to the same hazardous event. Because the consequences of an event are stored in several records, it is necessary to sum those consequences in a unique record.
- Classification of the records by categories. The database includes several event types, allowing this a better understanding of the local risk. But this fact makes the database inadequate for regional or national analysis. The following hazards categories are considered in the DesInventar database: seismic (earthquakes and tsunamis), landslide, volcanic and hidro-meteorological (rainfall, flood, hail storm, and others).
- General statistical analysis of the record by categories. Statistics of the records are performed in order to establish the injured and dead people, the damaged or destroyed houses and several other aspects contained in the database by hazard category. This analysis allows a better understanding of the severity and spatial distribution of the events occurred in the studied region.
- Definition of the parameters necessary for the loss assessment by event. These parameters account for the affected assets over several sectors and have to be consistent with the variables existing in the database. For example, for evaluating the effects upon the house sector, the variables of the database corresponding to the number of damaged and destroyed houses can be used.
- Calculation of losses by event. The previously selected parameters are used in this step. Each record has to be processed for the estimation of economic value of the consequences.
- Statistical analysis of losses by hazard categories. The economic distribution of the losses for all an each one of the different hazards over the studied area and over the database time window is obtained in this step.
- Development of the LEC for each category of natural hazard. A loss exceedance curve is obtained for each natural hazard category considered in the analysis.

- Development of the multihazard LEC. A loss exceedance curve for all the events present in the database is obtained and will be used for the construction of the hybrid LEC.

4.2 Results of empirical risk assessment

Following the proposed methodology, the LEC for minor but frequent events is determined and it can be used for the assessment of the risk at regional level. Figure 6 shows which of the hazard categories have the highest economic effect for different return periods and over the time window covered by the database. It can be noted how the hydro-meteorological hazards have the most important annual impact and how the seismic hazard produces the most important losses in the long term.

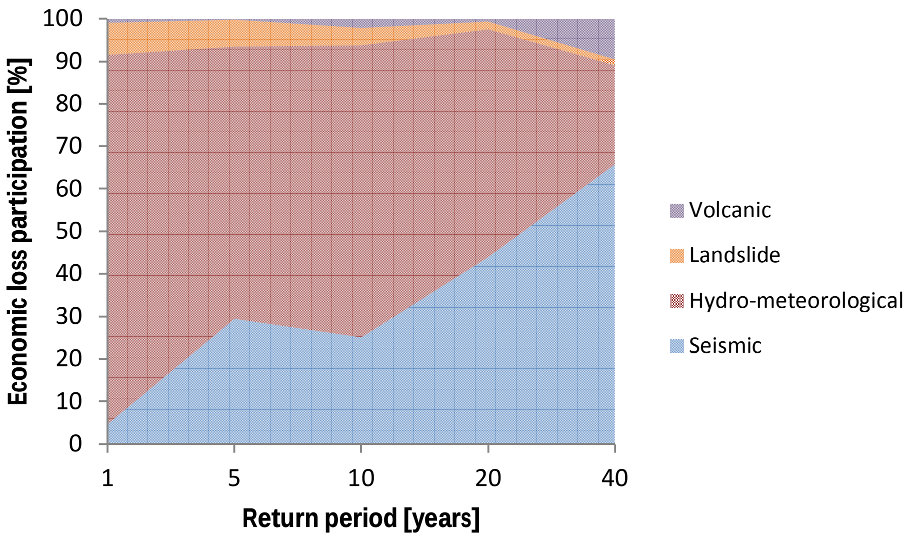

Figure 6. Economic losses by categories of hazards and return periods

Another result very useful for the awareness of political institutions is how the economic losses due to small but frequent events affect the communities over the years. Specifically, Figure 7 shows this effect for regular periods of 4 years which, for instance, can correspond to the government periods of a country; it shows how much of the budget is expected to be used by that government for risk response and recovering. In this case, using the purchase parity power (PPP) correction, it can be noted that the economic losses increase and are more frequent.

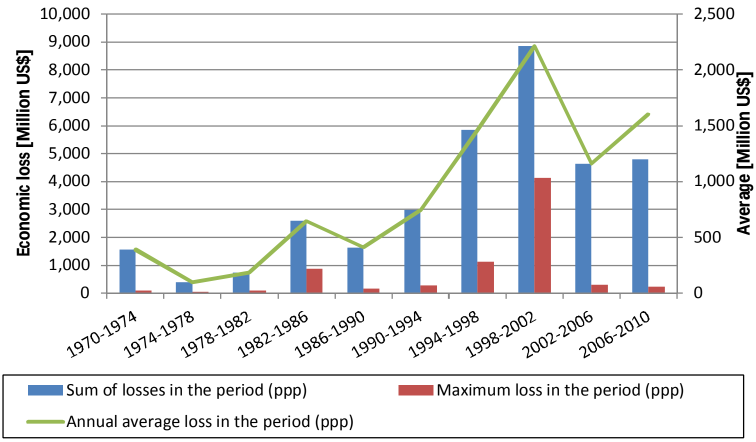

Figure 7. Economic losses (PPP) per presidential period.

Finally, the LEC can be obtained for each individual hazard category and also for all the events of the database, resulting in, a multihazard LEC, as it can be seen in Figure 8. The economic losses shown in this figure correspond to what a government or the society had to assume for a prompt community recovery, including replacing, repairing or compensating the suffered losses. In any case, the proposed procedure of assessment allows establishing the amount of resources that the government must spend every year to meet its fiscal responsibility, under the supposition that the affected private parties have been the most disadvantaged sectors of the society. In general terms, these losses are those which would be not covered by catastrophic risk insurance, if any is contracted by the government, because they correspond approximately to what the deductible would be. Those would be the losses that the governments should try to reduce by developing prevention-mitigation policies.

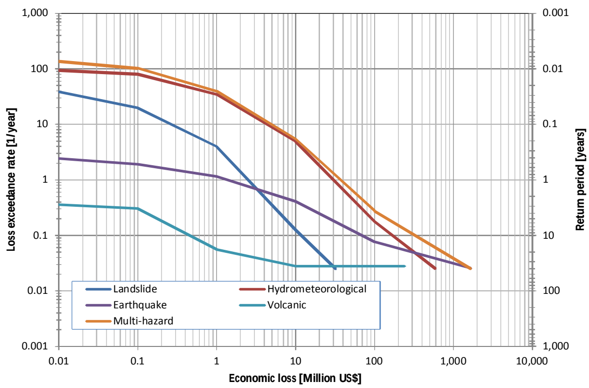

Figure 8. Economic LEC by hazard category and the multihazard LEC

5 THE HYBRID LOSS EXCEEDANCE CURVE (HLEC)

In the previous sections, two LEC where obtained, each one by using a different approach. The first one is the prospective LEC, shown in Figure 5, and it corresponds to large losses, with very low annual frequencies; the second one is the retrospective LEC, shown in Figure 8, which considers small but frequent losses. Now we represent both LEC in the same graphic as it can be seen in Figure 9, obtaining the whole picture of the risk in the study area.

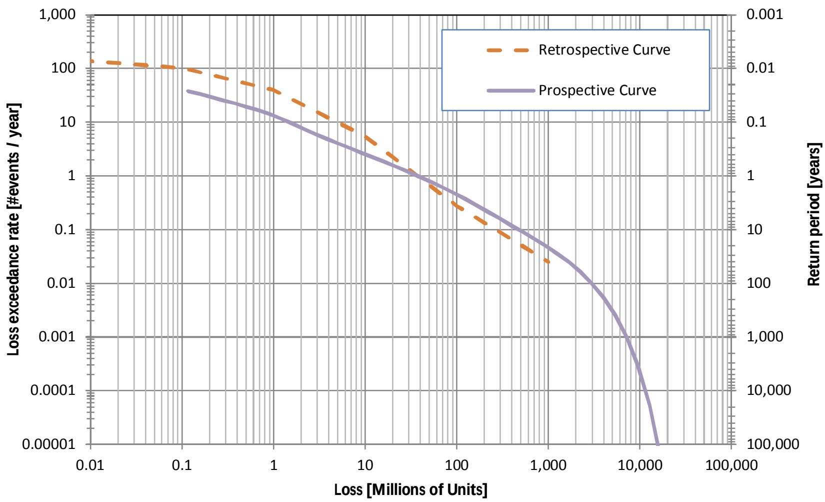

Figure 9. The retrospective and the prospective LEC represented in the same graphic

Using the previous obtained LEC's as input we build the new hybrid loss exceedance curve, HLEC, by using the envelope values of both curves and by overlapping the common part making use of interpolation. This new LEC is shown in Figure 10. In other words, the proposed technique for risk analysis is based on combining the first LEC, corresponding to all natural hazard events, with the second LEC obtained for hazards that have the potentiality of producing catastrophic risk.

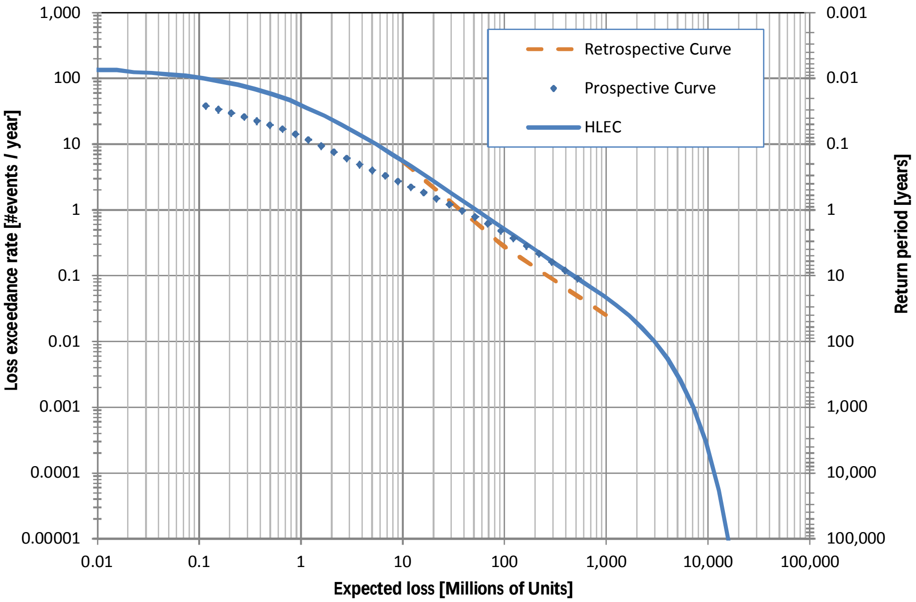

Figure 10. Hybrid Loss Exceedance Curve

In the insurance industry, an attachment point, or deductible, is defined for every insurance policy, as the value to be met by the policy holder and from which the insurance company starts his responsibility. In some cases, it can be understood as a discount from the total claimed value. This means that losses below the attachment point have to be completely covered by the policy holders. In this article, we present in the next section a few examples of LEC corresponding to three countries. In these cases, those countries have to assume the consequences caused by small intensity events from their own budget. The analytical, prospective, loss exceedance curves have been used so far by the insurance companies whose interest is not to evaluate losses below this deductible point, nor taking into account the accumulative effects and the implications of dealing repeatedly with small events that can lead to an administrative decline. In other words, "minor" and frequent events, which should be in the interest of the governments, are not of the interest of insurers.

6 APPLICATIONS OF THE PROPOSED HLEC

Three case studies were performed, considering the available information for the retrospective analysis and the necessary data for the prospective risk models. The selected developing countries are Colombia, Mexico and Nepal and the corresponding HLEC are shown in figures 11 to 13. The prospective analysis for all the countries was made for the seismic hazard and, only in the case of Mexico, also for hurricane wind. The required information for the risk model was gathered with the help of several institutions; among the collected information was the population census, the building census, the construction prices, utilities sector coverage and prices, macroeconomic indicators, etc.

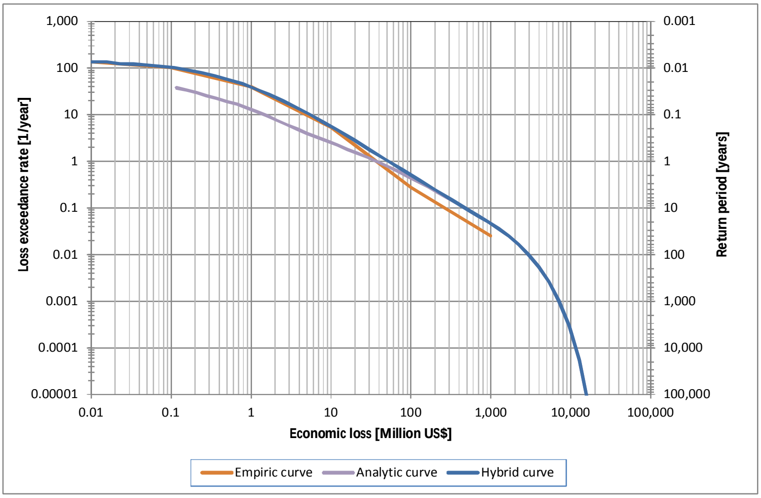

Figure 11. Hybrid loss exceedance curve for Colombia

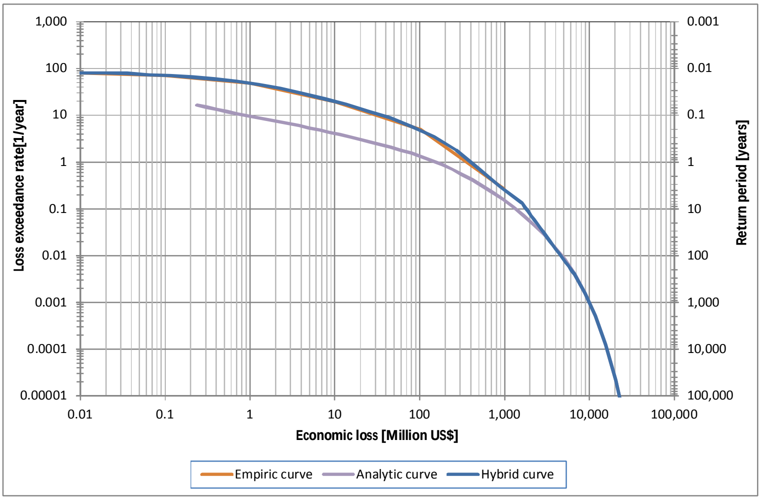

Figure 12. Hybrid LEC for Mexico

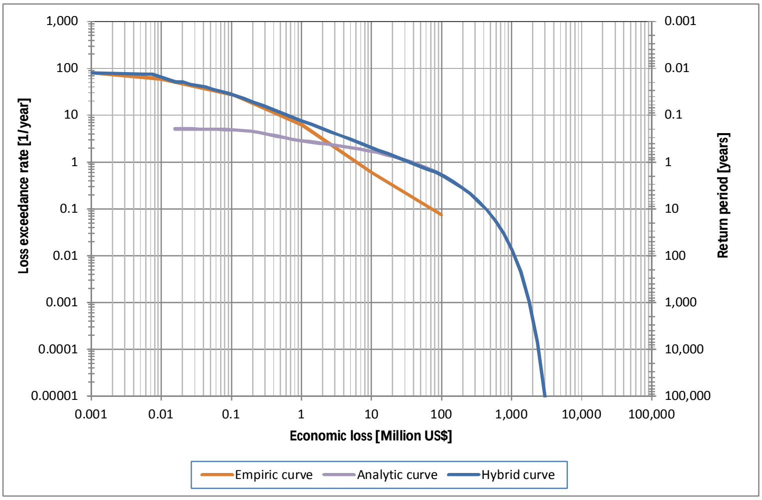

Figure 13. Hybrid LEC for Nepal

Table 1 illustrates the differences in the values of the AAL obtained by using the retrospective analysis, the prospective analysis of the fiscal responsibility of the Governments and the proposed HLEC.

Table 1. Comparison of expected AAL values

	Retrospective analysis	Prospective analysis – Fiscal Sector	Hybrid Curve
Colombia	360	316	490
Mexico	2,540	810	2,424
Nepal	52	207	235

It can be observed, in all the cases, an interesting situation: the AAL values obtained by using the hybrid loss exceedance curve are greater in the cases of Colombia and Nepal than the AAL values obtained by using the retrospective analysis. In the case of Mexico, this value is slightly lower than the one obtained by using the retrospective analysis but, even so, several times higher than the expected AAL value provided by the prospective analysis.

However, these AAL are the amount which the governments would have to pay annually in order to cover all the future disasters. In the case of insurance industry, a part of this value would have to be paid to the insurance and reinsurance companies; that part could well be the premium to cover the catastrophic risk. As seen before, the insurance companies cover losses only above a certain value, known as the attachment point or priority, and leave as deducible for each country the losses caused by small events. These events correspond to small losses, reason for which governments must have an explicit strategy of disaster risk reduction and management, through effective mitigation and prevention policies; otherwise, the losses due to minor events would continue to have a very high economic and social impact upon the countries.

7 CONCLUSIONS

In this article, a new risk analysis methodology has been proposed based on a hybrid loss exceedance curve, which represents risk in a proper and complete way. This loss exceedance curve has two components. The first one corresponds to multiple minor events usually producing small and moderate, but repetitive, extensive, losses and is calculated by using an inductive and retrospective analysis; the second one considers the potential occurrence of extreme events which produce intensive, huge losses and is calculated by using a deductive and prospective analysis. The extensive risk has to be mitigated with efficient intervention strategies while for the intensive risk, strategies of financial protection and risk transfer are required.

The study performed at the country level shows that it is indispensable to measure risk retrospectively, with an empirical focus, and, at the same time, prospectively, with a probabilistic focus. The lack of procedures to evaluate losses due minor and repetitive events has prevented until now that governs be aware of the enormous losses due to such events. The proposed approach and the case studies performed in this article permit not only to illustrate but also to promote the interest of decision makers for an effective risk management based on the complete and multihazard risk assessments facilitated by the hybrid loss exceedance curve. The proposed hybrid curve allows capturing aspects which the prospective LEC is not able to consider, avoiding the underestimation of the consequences of minor and repetitive events. And, obviously, it is important to have the possibility of estimating expected losses that a country may face perhaps every year and of planning the economical mechanism needed to recover more promptly.

The proposed methodology has been used as a background paperwork in the GAR2011 (UNISDR, 2011a) and it brought a new interest of the UNISDR, WB Group and the InterAmerican Development Bank to be used in their DRR policies.

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References

1. Barbat, A. H., Pujades, L. G., Lantada, N., & Moreno, R. (2008). Seismic damage evaluation in urban areas using the capacity spectrum method: Application to Barcelona. Soil Dynamics and Earthquake Engineering, 28(10-11), 851 - 865.
2. Barbat, A. H., Carreño, M. L., Pujades, L. G., Lantada, N., Cardona, O. D., & Marulanda, M. C. (2010). Seismic vulnerability and risk evaluation methods for urban areas. A review with application to a pilot area. Structure and Infrastructure Engineering, 6(1), 17-38.
3. Cardona, O. D., Ordaz, M. G., Yamin, L. E., Marulanda, M. C., & Barbat, A. H. (2008a). Earthquake Loss Assessment for Integrated Disaster Risk Management. Journal of Earthquake Engineering, 12, 48-59.
4. Cardona, O. D., Ordaz, M. G., Marulanda, M. C., & Barbat, A. H. (2008b). Estimation of Probabilistic Seismic Losses and the Public Economic Resilience—An Approach for a Macroeconomic Impact Evaluation. Journal of Earthquake Engineering, 12, 60-70.
5. Cardona, O. D., Ordaz, M. G., Marulanda, M. C., Carreño, M. L., & Barbat, A. H. (2010a). Disaster risk from a macroeconomic perspective: a metric for fiscal vulnerability evaluation. Disasters, 34(4), 1064-1083.
6. Cardona, O. D., Ordaz, M. G., Reinoso, E., Yamin, L. E., & Barbat, A. H. (2010b). Comprehensive Approach for Probabilistic Risk Assessment (CAPRA): International Initiative for Disaster Risk Management Effectiveness. Presented at the 14th European Conference on Earthquake Engineering, Ohrid, Macedonia.
7. Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2007). A disaster risk management performance index. Natural Hazards, 41(1), 1-20.
8. Carreño, M. L., Cardona, O. D., & Barbat, A. H. (2006). Urban Seismic Risk Evaluation: A Holistic Approach. Natural Hazards, 40(1), 137-172.
9. CEPAL (2003). Manual para la estimación de los efectos socio-económicos de los desastres naturales (Report LC/MEX/G.5). México DF, México: CEPAL, Banco Mundial.
10. Desinventar.net - DesInventar Disaster Information Management System, Version 9.15 - June 2011. (n.d.). Geneva, Switzerland: UNISDR. Dirección web http://www.desinventar.net/index.html. Última visita 2 de febrero de 2012.
11. Desinventar.org - DesInventar Project. (n.d.). Cali, Colombia: Corporación OSSO. Dirección web http://desinventar.org/en/. Última visita 2 de febrero de 2012.
12. EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.net. (n.d.). Brussels, Belgium: Université catholique de Louvain. Dirección web http://emdat.be/. Última visita 2 de febrero de 2012.
13. ERN-AL (2010). CAPRA, Compressive approach for probabilistic risk assessment. World Bank, InterAmerican Development Bank. Retrieve from ecapra.org.
14. ERN-AL (2011). Probabilistic Modeling of Disaster Risk at Global Level: Development of a methodology and implementation of case studies. Phase 1A: Colombia, México and Nepal. Background paper prepared for the 2011 Global Assessment Report on Disaster Risk Reduction. Geneva, Switzerland. UNISDR.
15. FEMA (2006). Multi-hazard loss estimation methodology, HAZUS-MH MR2 technical manual, prepared for the Federal Emergency Management Agency, Washington DC, United States, Federal Emergency Management Agency and National Institute of Building Sciences.

16. Lagomarsino S., Giovinazzi S. (2006) Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bulletin of Earthquake Engineering; 4(4): 415-443.
17. Lantada N., Pujades L. G., Barbat A. H. (2009) Vulnerability index and capacity spectrum based methods for urban seismic risk evaluation. A comparison. Natural Hazards; 51(3): 501-524.
18. Lantada, N., Irizarry, J., Barbat, A. H., Goula, X., Roca, A., Susagna, T., & Pujades, L. G. (2009). Seismic hazard and risk scenarios for Barcelona, Spain, using the Risk-UE vulnerability index method. Bulletin of Earthquake Engineering, 8(2), 201-229.
19. Marulanda, M. C., Cardona, O. D., & Barbat, A. H. (2010). Revealing the socioeconomic impact of small disasters in Colombia using the DesInventar database. Disasters, 34(2), 552-570.
20. RISK-UE (2001–2004) An advanced approach to earthquake risk scenarios, with applications to different European cities. Website http://www.risk-ue.net
21. UNDP (2004). Reducing Disaster Risk: A challenge for development. Geneva, Switzerland. United Nations Development Programme, Bureu for Crisis Prevention and Recovery.
22. UNDRO (1980). Natural disasters and vulnerability analysis, Report of experts group meeting, UNDRO, Geneva.
23. UNISDR (2009). Global Assessment Report on Disaster Risk Reduction: Risk and poverty in a changing climate. Geneva, Switzerland: United Nations International Strategy for Disaster Reduction.
24. UNISDR (2011a). GAR2011: Global Assessment Report on Disaster Risk Reduction: Revealing risk, redefining development. Geneva, Switzerland: United Nations International Strategy for Disaster Reduction.
25. UNISDR (2011b). Desinventar.net Database: Nepal disaster inventory. Geneva, Switzerland. United Nations International Strategy for Disaster Reduction.
26. Vargas Y. F., Pujades L. G., Barbat A. H., Hurtado J. E. (2012) Evaluación probabilista de la capacidad, fragilidad y daño sísmico en edificios de hormigón armado. Métodos numéricos para cálculo y diseño en ingeniería; (in press).
27. Velásquez, C. A., Cardona, O. D., Yamin, L. E., Mora, M. G., & Barbat, A. H. (2011). Curva de excedencia de pérdidas híbrida para la representación del riesgo. Presented at the Cuarto Congreso Nacional de Ingeniería Sísmica, Granada, España.