Holistic Urban Seismic Risk Evaluation of Megacities: Application and Robustness

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1 Risk from a Holistic Perspective

Disaster risk has been defined, for management purposes, as the potential economic, social and environmental consequences of hazardous events that may occur in a specified period of time. However, in the past, the concept of risk has been defined in a fragmentary way in many cases, according to each scientific discipline involved in its appraisal (Cardona, 2004). Based on the formulation of disaster risk of UNDRO (1980) several methodologies for risk assessment have been developed from different perspectives in the last decades. From a holistic perspective, disaster risk requires a multidisciplinary evaluation that takes into account not only the expected physical damage, the number and type of casualties or economic losses (direct impact), but also the conditions related to social fragility and lack of resilience conditions, which favour the second order effects (indirect impact) when a hazard event strike an urban centre (Cardona and Hurtado, 2000; Masure, 2003; Carreño et al., 2007a).

Cardona (2001) developed a conceptual framework and a model for disaster risk analysis of a city from a holistic perspective. It considers both "hard" and "soft" risk variables of the urban centre, taking into account exposure, socio-economic characteristics of the different localities (units) of the city and their disaster coping capacity or degree of resilience. The model was made to guide the decision-making in risk management, helping to identify the critical zones of the city and their vulnerability from different professional disciplines. Carreño (2006) developed an alternative method for Urban Risk Evaluation, based on Cardona's model (Cardona, 2001; Barbat and Cardona, 2003). The urban risk is evaluated using composite indicators or indices. Expected building damage and losses in the infrastructure, obtained from future loss scenarios are basic information for the evaluation of a physical risk index in each unit of analysis.

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Often, when historical information is available, the principal hazard can be usually identified and thus the most potential critical situation for the city.

The holistic evaluation of disaster risk is achieved affecting the physical risk with an impact factor, obtained from contextual conditions, such as the socio-economic fragility and the lack of resilience, that aggravate initial physical loss scenario. Available data about these conditions at urban level are necessary to apply the method. A brief explanation of the model is made forward to illustrate the benefits of this approach that contributes to the effectiveness of disaster risk management, inviting to the action identifying the hard and soft weaknesses of the urban centre. Figure 1 shows the theoretical framework of the alternative model.

From a holistic perspective risk, R, is a function of the potential physical damage, D_j, and an aggravating coefficient, I_f. The former is obtained from the susceptibility of the exposed elements, $\boldsymbol{\gamma}_{Di}$, to hazards, H_i, regarding their potential intensities, I, of events in a period of time t, and the latter depends on the social fragilities, γ_{Fi}, and the issues related to lack of resilience, γ_{Ri}, of the disaster prone socio-technical system or context. Using the meta-concepts of the theory of control and complex system dynamics to reduce risk, it is necessary to intervene in corrective and prospective way the vulnerability factors and, when it is possible, the hazards directly. Then risk management requires a
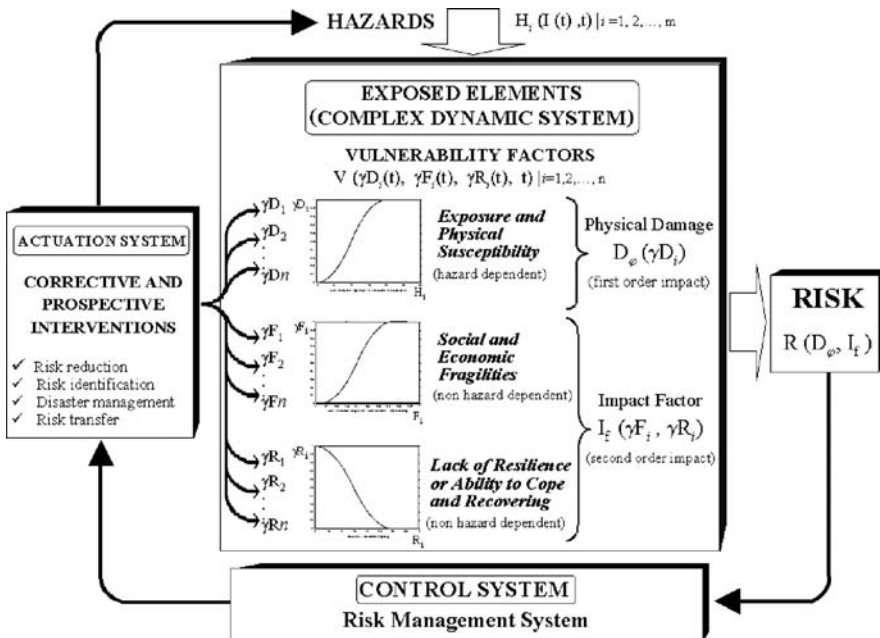

Fig. 1 Theoretical framework and model for holistic approach of disaster risk (adapted from Cardona and Barbat, 2000)

system of control (institutional structure) and an actuation system (public policies and actions) to implement the changes needed on the exposed elements or complex system where risk is a social process.

1.1 The Urban Seismic Risk Index – USRi

The USRi is a composite indicator –or index– that measures seismic risk from an integrated and comprehensive perspective and guides decision-making identifying the main multidisciplinary factors of vulnerability to be reduced or intervened. The first step of the method is the evaluation of the potential physical damage (hard approach) as the result of the convolution of seismic hazard and physical vulnerability of buildings and infrastructure. Subsequently, a set of social context conditions that aggravate the physical effects are also considered (soft approach). According to this procedure, a physical risk index is obtained, for each unit of analysis, from existing loss scenarios, whereas the total risk index is obtained by factoring the former index by an impact factor using an aggravating coefficient, based on variables associated with the socio-economic conditions of each unit of analysis.

The proposed holistic evaluation of risk is performed using a set of input variables, herein denominated descriptors. They reflect the physical risk and the aggravating conditions that contribute to the potential impact. Those descriptors are obtained from the loss scenarios and from socio-economic and coping capacity information of the exposed context (Carreño et al., 2005a).

The USRi depends on the direct effect, or physical risk, and the indirect effects expressed as a factor of the direct effects. Therefore, the USRi for each unit of analysis is the total risk that can be expressed as follows:

$$USRi = R_T = R_F(1 + F) \tag{1}$$

expression known as the Moncho's Equation in the field of disaster risk indicators, where R_T is the total risk index, R_F is the physical risk index and the indirect effects given by an impact factor $(1 + F)$, based on an aggravating coefficient, F is the aggravating coefficient.

The physical risk index, R_F, depends on the weighted sum of a set of component factors

$$R_F = \sum_{i=1}^{p} F_{RFi} \, w_{RFi} \tag{2}$$

where p is the total number of descriptors of physical risk index, F_{RFi} are the component factors and w_{RFi} are their weights respectively. The factors of physical risk, F_{RFi}, are based on the gross values of physical risk descriptors such as the number of deaths, injured or the destroyed area, and so on. It has to be mentioned that the calculation of physical risk scenarios is not the objective

of the methodology developed in this chapter, but the physical risk index is obtained starting from existing loss evaluations.

The coefficient, F, is another index evaluated in the same way. It depends on the weighted sum of a set of aggravating factors related to the socio-economic fragility, F_{FSi}, and the lack of resilience of the exposed context, F_{FRj}

$$F = \sum_{i=1}^{m} F_{FSi}\, w_{FSi} + \sum_{j=1}^{m} F_{FRj}\, w_{FRj} \qquad (3)$$

where w_{FSi} and w_{FRj} are the weights or influences of each i and j factors and m and n are the total number of descriptors for social fragility and lack of resilience respectively. Figure 2 shows the process of calculation of the total risk index for the geographic units of analysis, which could be districts, municipalities, communes or localities. See Carreño et al. (2007a) for measurement units of each descriptor and a detailed explanation of the method.

It is estimated that the indirect effects of hazard events, sized by the coefficient F in Equation (1), can be of the same order than the direct effects. According to the Economic Commission for Latin America and the Caribbean

F_{RF1}	Damaged area	w_{RF1}
F_{RF2}	Dead people	w_{RF2}
F_{RF3}	Injured people	w_{RF3}
F_{RF4}	Damage in water mains	w_{RF4}
F_{RF5}	Damage in gas network	w_{RF5}
F_{RF6}	Fallen lengths on HT power lines	w_{RF6}
F_{RF7}	Electricity substations affected	w_{RF7}
F_{RF8}	Electricity substations affected	w_{RF8}

→ R_F Physical risk

→ R_T Total risk

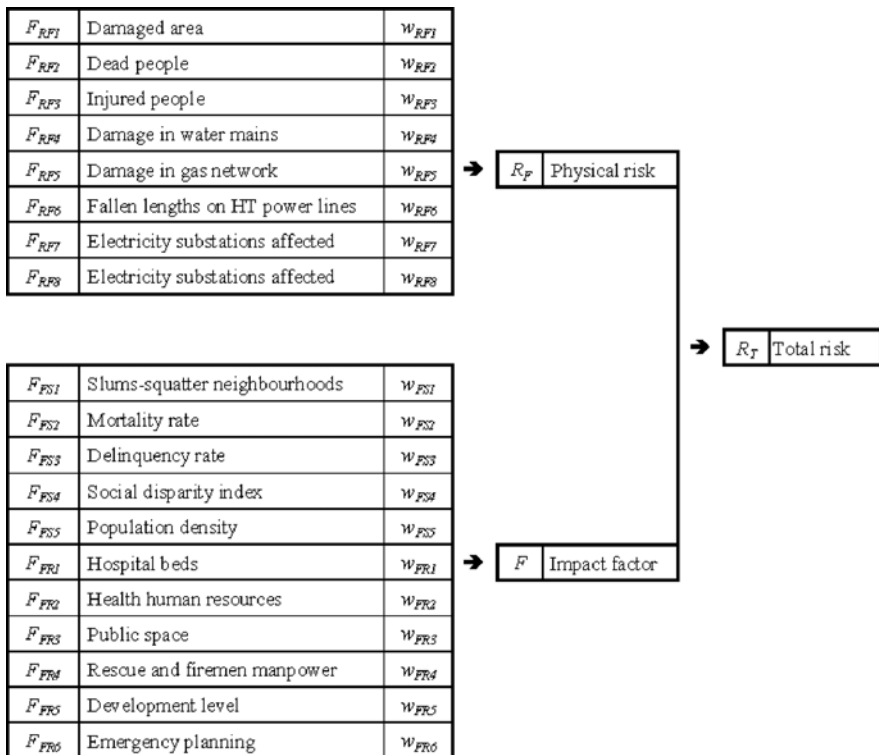| F_{FS1} | Slums-squatter neighbourhoods | w_{FS1} |
F_{FS2}	Mortality rate	w_{FS2}
F_{FS3}	Delinquency rate	w_{FS3}
F_{FS4}	Social disparity index	w_{FS4}
F_{FS5}	Population density	w_{FS5}
F_{FR1}	Hospital beds	w_{FR1}
F_{FR2}	Health human resources	w_{FR2}
F_{FR3}	Public space	w_{FR3}
F_{FR4}	Rescue and firemen manpower	w_{FR4}
F_{FR5}	Development level	w_{FR5}
F_{FR6}	Emergency planning	w_{FR6}

→ F Impact factor

Fig. 2 Factors of physical risk, social fragility and lack of resilience and their weights

(Zapata, 2004), it is estimated that the indirect economic effects of a natural disaster depend on the type of phenomenon. The order of magnitude of the indirect economic effects for a "wet" disaster (as one caused by a flood) could be of 0.50–0.75 of the direct effects. In the case of a "dry" disaster (caused by an earthquake, for example), the indirect effects could be about the 0.75–1.00 of the direct effects, due to the kind of damage (destruction of livelihoods, infrastructure, housing, etc.). This means that the total risk, R_T, could be between 1.5 and 2 times R_F. In this method, the maximum value selected was the latter. For this reason, the aggravating coefficient, F, takes values between 0 and 1 in Equation (1).

The factors of physical risk, F_{RFi}, and the aggravating factors F_{FSi} and F_{FRj} are calculated using transformation functions as the shown in the Fig. 3. These examples of transformation functions for physical risk, social fragility and lack of resilience (or coping capacity) show the values of the descriptors in the *x-axis* and the corresponding factors, or scaled values, in the *y-axis*.

These functions describe the intensity of the risk for each descriptor and standardise the gross values of the descriptors transforming them in commensurable factors. Sigmoid functions were used in most of the cases to develop the transformation functions. All their maximum and minimum values (corresponding to the values 1.0 or 0.0 of each factor) were fixed using existing information about past disasters as well as the expert opinion. For example, the transformation function for damaged built area defines a minimum risk (0.0) when this descriptor is zero and, the maximum risk (1.0) was established for a potential damaged area of 20% of the overall constructed area.

The weights w_{RFi}, w_{FSi} and w_{FRj} represent the relative importance of each factor and are calculated by means of the Analytic Hierarchy Process (AHP),
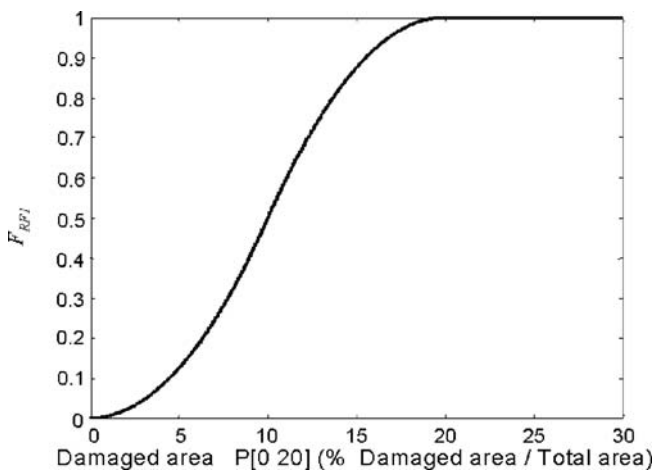

Fig. 3 Example of transformation functions used to standardise physical risk, social fragility and lack of resilience factors

which is used to derive ratio scales from both discrete and continuous paired comparisons (Saaty, 2001). This process has been performed starting from experts opinions collected by means of the Delphi method. This is the most adequate way of judging the relative importance of variables having different nature and calculating their relative weights.

1.2 Improvement of the Previous Approach

The model of holistic urban risk evaluation proposed Carreño et al. (2007a,b) improves conceptual and methodological aspects of the first proposal of Cardona (2001), refining the applied numerical techniques and turning it into a more versatile tool. The conceptual improvements provide a more solid theoretical and analytical support to the new model, eliminating unnecessary and dubious aspects of the previous method and giving more transparency and applicability in some cases. Cardona's model allows the evaluation of the seismic risk in an urban center taking into account the characteristics of the physical risk, seismic hazard, physical exposure, socio-economical fragility and lack of resilience, what permits to identify those characteristics of the city that increase the level of risk and also the critical areas. This model studies different types of information by means of indicators and uses a normalization process of the results based on the mean and on the standard deviation which is applied to each indicator. As a consequence, the results obtained with Cardona's method allow a comparison of the holistic seismic risk among the different areas of a city in a relative way, but not a comparison in absolute terms with other urban areas. Cardona's model uses of a neuro-fuzzy system, with fuzzy sets which identify the linguistic qualifications of the descriptors, but the necessary information for the calibration of this system do not exist.

The new method proposed in this chapter conserves the approach based on indicators, but it improves the procedure of normalization and calculates the final indices in an absolute (non relative) manner. This feature facilitates the comparison of risk among urban centers. The exposure and the seismic hazard have been eliminated in the method proposed in this chapter because they have been included into the physical risk variables calculation. The descriptor of population density, a component of the exposure in Cardona's model, is now included as a descriptor of social fragility. The new approach preserves the use of indicators and fuzzy sets or membership functions, proposed originally by Cardona, but in a different way. Other improvements of the proposed model refer to the units of some of the descriptors; in certain cases it is more important to normalize the input values respecting the population than with respect of the area of the studied zone. This is, for example, the case of the number of hospital beds existing in the studied urban area. The socio-economic fragility and the lack of resilience are a set of factors (related to indirect or intangible effects) that aggravate the physical risk (potential direct effects).

2 Application to Megacities

The Urban Seismic Risk Index was proposed and applied to Barcelona (Spain) and Bogota (Colombia) by Carreño (2006) and by Carreño et al. (2005b, 2007a) and by Suarez (2007) to Manizales (Colombia). Recently, the USRi has been applied to Metro Manila (The Philippines) by Earthquake Megacities Initiative (EMI, 2006). In the case of Bogota the scenarios of losses building by building were developed by Universidad de Los Andes (2005). For the city of Barcelona probabilistic and deterministic scenarios were developed by ICC/CIMNE (2004). In Manizales the damage scenarios were made by ERN (2005). This section presents the summary of the USRi results for the all cities of Metro Manila to illustrate its application to other metropolitan urban centre.

2.1 Results for Metro-Manila

Metropolitan Manila, the capital city the Philippines is officially called the National Capital Region (NCR). Although it is the smallest region, it is the most densely populated region of the country. Metro Manila is composed by 4 municipalities and 13 cities thereof into an integrated unit with the manager or commission form of government. They are the cities of: Quezon, Kaloocan, Valenzuela, Muntinlupa, Las Piñas, Marikina, Manila, Parañaque, Makati, Mandaluyong, Malabon, Pasay, Pasig. And the municipalities of: Taguig, Pateros, San Juan and Navotas (see Fig. 4).

In order to evaluate the USRi for each city, the physical risk index was calculated using physical risk descriptors based on the earthquake damage
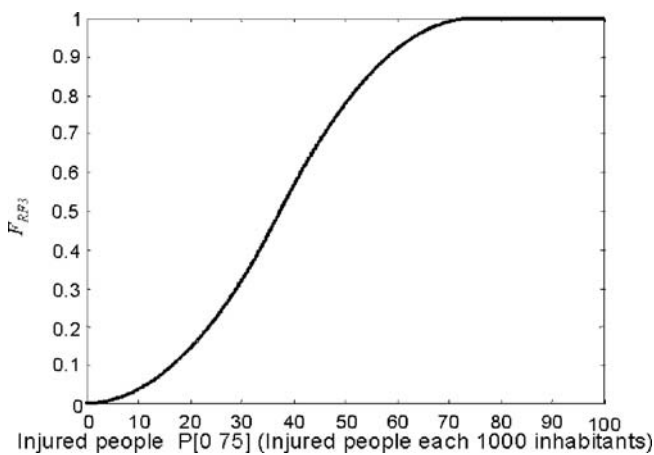

Fig. 4 Territorial division of Metro Manila, Philippines
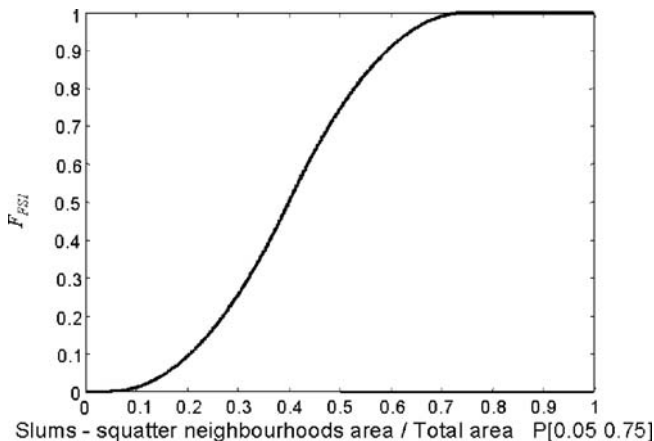
Fig. 5 Physical risk index for Metro Manila

MMEIRS-08, obtained from the Earthquake Impact Reduction Study of
Metro Manila (MMEIRS). This scenario corresponds to an earthquake of
Magnitude 7.2, in the West Valley Fault, with 2 km of depth. Figures 5, 6, 7
show the results for the physical risk index, the aggravating coefficient and
the total risk index (USRi) for Metro Manila using the model above
described.

Cities in Metro Manila were clustered according to their level of risk in four
different arrays according to the total USRi and its components, physical risk
and aggravating factor (social fragility + lack of resilience), this grouping is
show, on Table 1.
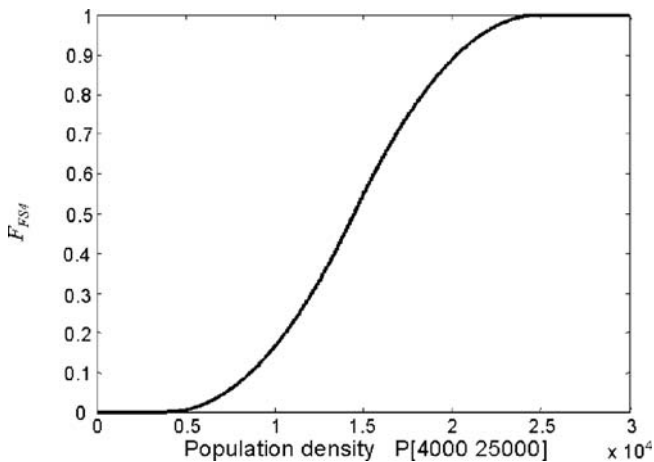
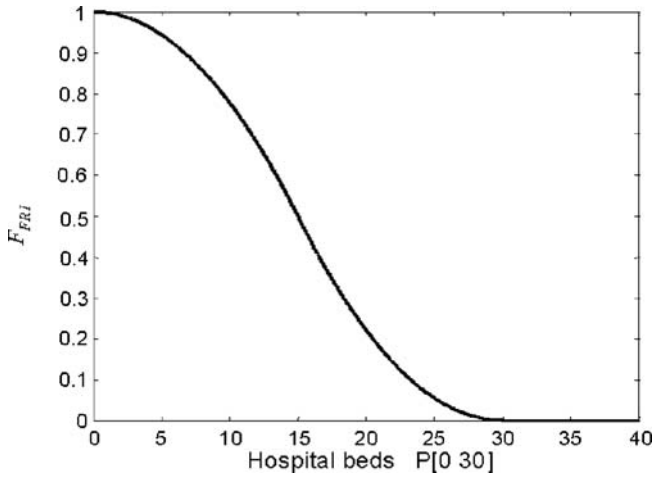**Fig. 6** Aggravating coefficient for Metro Manila

Fig. 7 Total risk index for Metro Manila

Table 1 Holistic urban seismic risk of Metro Manila

Feature	Ind.	Degree	Range	Cities of metro manila
Physical Risk	R_F	Very high	0.45–1.00	Pasig Pasay
		High	0.30–0.44	
		Medium-High	0.20–0.29	Pateros Muntinlupa Marikina Makati Manila Navotas Taguig Mandaluyong Paranaque
		Medium-Low	0.10–0.19	Las Piñas Quezon Malabon San Juan
		Low	0.00–0.09	Valenzuela Kalookan
Aggravating Coefficient	F	Very High	0.65–1.00	Navotas Malabon Taguig San Juan
		High	0.55–0.64	Kalookan Valenzuela Pasay Pateros Las Piñas Quezon Pasig
		Medium-High	0.40–0.54	Marikina Paranaque Mandaluyong Manila Makati Muntinlupa
		Medium-Low	0.20–0.39	
		Low	0.00–0.19	
Total Risk	USRi	Very High	0.70–1.00	Pasay Pasig
		High	0.45–0.69	Navotas Pateros Marikina Taguig
		Medium-High	0.30–0.44	Muntinlupa Manila Makati Mandaluyong Paranaque
		Medium-Low	0.15–0.29	Las Piñas Quezon Malabon San Juan
		Low	0.00–0.14	Kalookan Velenzuela

2.2 Sensitivity Analysis

Sensitivity analysis is also referred to as robustness analysis of the model. In this case, the sensitivity analysis studies how the variation in the values of the index of Total Risk, R_T, can be apportioned, qualitatively or quantitatively, to different sources of variation, and how this given composite indicator, depends upon the information fed into it. In other words, once the proposed model (composite indicator) is determined, it is important to analyse how much the results are influenced by uncertainty in the source data or uncertainty in the weights and transformation functions, due to the stakeholders' subjectivity or plurality of perspectives. For this analysis a Monte Carlo-based simulation was performed.

The Monte Carlo method is a technique that uses sets of random numbers as input parameters and probability distributions for iteratively evaluating a deterministic model. This method is often used when the model is complex, non-linear or involves more than just a couple uncertain parameters. The Monte Carlo simulation is one of many methods for analysing uncertainty propagation, where the goal is to determine how random variation affects the sensitivity, performance or reliability of the model. In this case, the values of the R_T for each territorial unit were obtained five thousand times, using random sets of input data, transformation functions and weights; each value sampled within an acceptable range of variability.

The random values, for each set previously mentioned, were obtained individually by using uniform distributions in each interval. In the same way, random values for simultaneous variation of the all sets were obtained. The minimum and maximum values were chosen according to expert opinions to define the interval of variation for each input parameters. By this way, thousand of stochastic results were created with random inputs of each parameter (input data, transformation functions, weights and all simultaneously) for each territorial unit of analysis. In order to provide a concise summary of the results, the mean, median, standard deviation, maximum and minimum values and a few other summary statistics to describe the resulting distribution were reported. Likewise, a histogram was created for visualizing the uncertainty of results, which illustrates the profile of results, the uncertainty degree and the existing distribution. In addition, the cumulative distribution function was included in each graph to illustrate the percentage of data points that are below a value or point of interest.

Figure 8 shows an example of a histogram and Table 2 illustrates an example of a statistic summary of the Monte Carlo simulation.

Once the results were calculated through Monte Carlo procedure, the variability or volatility graphics were built to compare the stochastic results of R_T to the fixed results obtained from the methodology. Figures 9 and 10 illustrate minimum ($\triangleright$), maximum ($\times$) and mean ($\blacksquare$) values and the bars represent the fixed values obtained for each territorial unit. It can be seen that for the
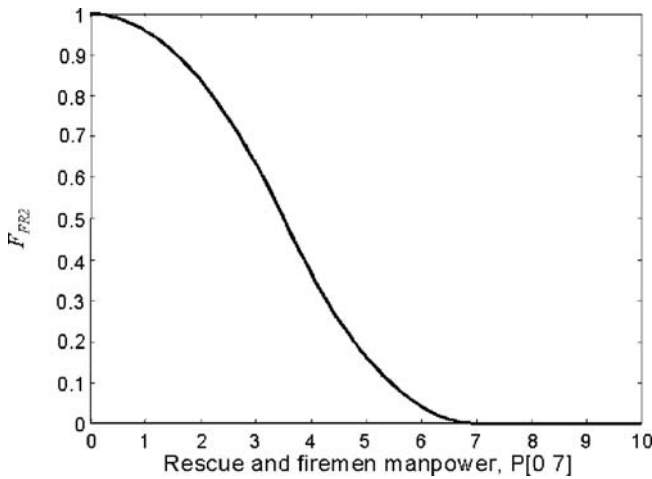
Fig. 8 Example of a histogram of the results of RT for Mandaluyong City with stochastic weights

variability of each parameter the volatility of values is not so big. The uncertainty is bigger in the case of the simultaneous variation of all parameters.

Table 3 shows that the results obtained through the simulation are very similar to the results obtained using fixed values of input data, weights and transformation functions of the method previously described and applied to Metro Manila. The overall results show that the cities of the metropolitan area vary slightly in their rankings. Some units fluctuate at the most by one position. In other urban centres, as Barcelona and Manizales, where the method has been applied and where a similar sensitivity analysis has been made, the results are similar than in Metro Manila. Only in the case of

Table 2 Example of statistic summary of the results for Mandaluyong City with stochastic weights

| Central tendency (location)				Quantiles, percentiles, intervals			
Sample Size (N):	5000			90% Interval		95% Interval	
				Q(.05):	0.343	Q(.025):	0.34
Mean	0.40	**Median**	0.40	Q(.95):	0.459	Q(.975):	0.47
StErr:	0.00						
Skewness	0.0435			**Alpha** (a):	0.05	Q(a/2):	0.34
Kurtosis	−1.0225			% Interval:	95%	Q(1-a/2):	0.47
Spread				**Probabilities**			
StDev	0.04			**Pr (y < 0.33) =**			0.44%
Max:	0.49	Q(.75):	0.43	**Pr (y > 0.40) =**			49.93%
Min:	0.32	Q(.25):	0.37	Pr (0.33 < y < 0.4) =			49.63%
Range	0.17	**IQ Range:**	0.06	Alpha (a):			0.5037
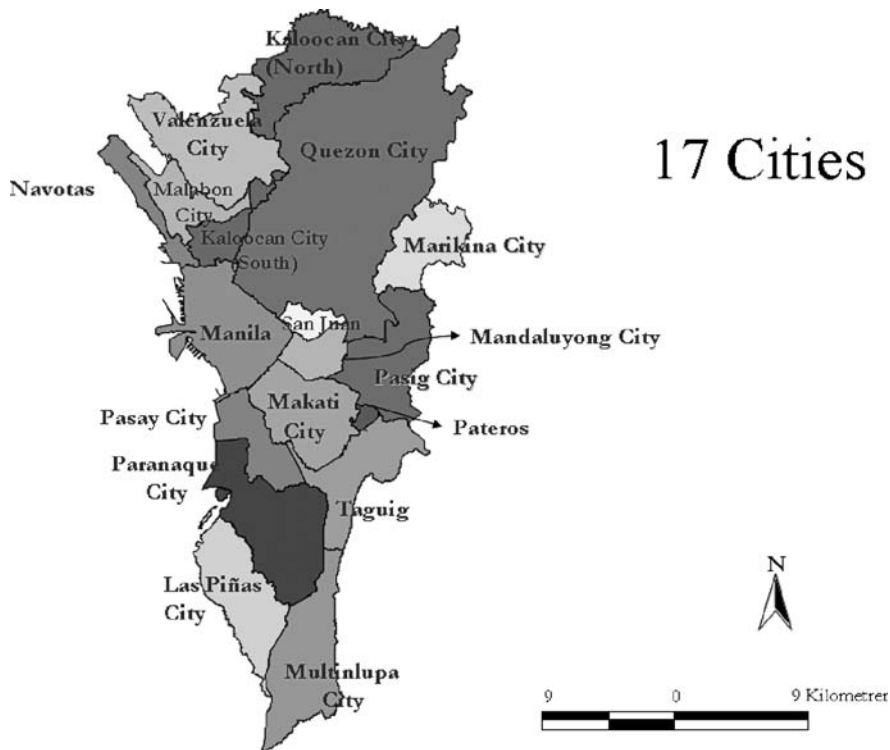
Fig. 9 Variation of the simulation results and fixed results for stochastic weights and stochastic data

Bogota some territorial units have been more volatile with position changes of two and three ranks; however it is not very relevant.

Therefore, according to the classification of the total risk by levels, all cities maintain the same level with exception of San Juan city which presents a change of range from medium-high to medium-low because the total risk result for fixed values is equal to 0.29 and for stochastic values the result was above 0.30. Classification by ranges of risk has special interest, because it is more relevant to have into account the level of risk where a territorial unit is located than its final numerical value for risk management implications.

According to the comparison of the results of sensitivity analysis, based on Monte Carlo simulations, and the results obtained by the holistic seismic risk evaluation here described, it is possible to conclude that the methodology is robust. It is not very sensible to slight variations in the input data and small changes in the modelling parameters, such as weights and transformation functions. The results do not present important or extreme changes. If the range of variation of data and parameters is reasonable, as it is in the case of seismic risk, in general the results of the model will be stable and reliable.
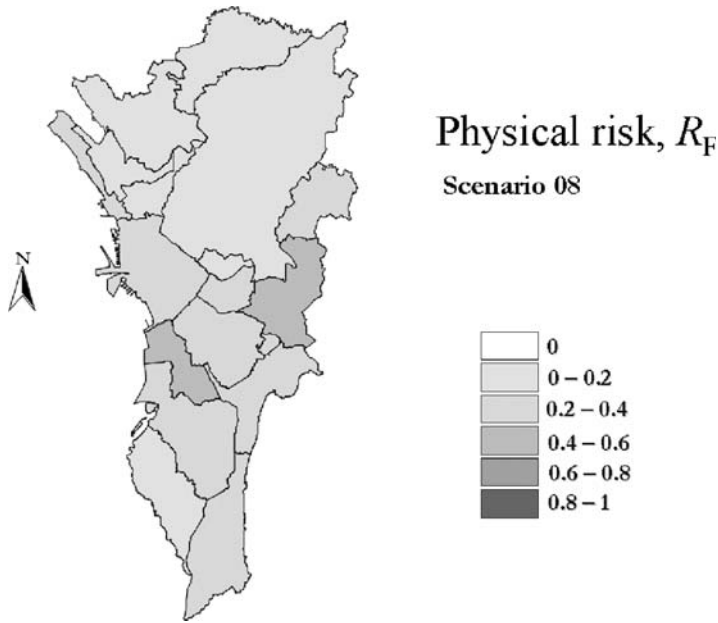
Physical risk, R_F

Scenario 08

	0
	0 – 0.2
	0.2 – 0.4
	0.4 – 0.6
	0.6 – 0.8
	0.8 – 1

Fig. 10 Variation of the simulation results and fixed results for stochastic transformation functions and simultaneous stochastic data, weights and transformation functions

2.3 Comparison of Results

The results obtained for Metro Manila have been compared with those obtained for Barcelona, Bogota and Manizales. Table 4 shows the average risk values for the four cities, corresponding to the most significant scenarios in each case. Metro Manila and Bogota are located in zones with intermediate seismic hazard, whereas Barcelona is located in a zone with low to moderate seismic hazard and Manizales is placed in a zone with a high seismic hazard. The average values obtained for the physical risk index, R_F, reflect not only the seismic hazard but also the level of physical vulnerability in each city. It is interesting to remark that the results obtained for the aggravating coefficient, F, are not so different for the four cities. The highest value of physical risk is for Bogota, but the worst situation, taking into account the aggravating coefficient, is for Metro Manila.

3 Conclusions

Disaster risk estimation requires a multidisciplinary approach that takes into account not only the expected physical damage, the number and type of casualties or economic losses, but also other social, organizational and

Table 3 Comparison between fixed values and stochastic results of RT, positions and classification of Metro Manila cities by risk levels

Level of risk	Fixed values		Data		Weights		Fuctions	
	City	R_T	City	R_T	City	R_T	City	R_T
Very High	Pasay	0.72	Pasay	0.70	Pasay	0.71	Pasay	0.70
	Pasig	0.71	Pasig	0.70	Pasig	0.70	Pasig	0.70
High	Navotas	0.49	Manila	0.52	Manila	0.53	Manila	0.53
	Manila	0.48	Navotas	0.49	Navotas	0.49	Navotas	0.49
	Pateros	0.47	Pateros	0.49	Pateros	0.49	Pateros	0.49
	Marikina	0.45	Marikina	0.47	Marikina	0.46	Marikina	0.47
	Taguig	0.45	Taguig	0.46	Taguig	0.46	Taguig	0.46
Medium-High	Muntinlupa	0.43	Makati	0.43	Makati	0.43	Makati	0.43
	Makati	0.42	Muntinlupa	0.43	Muntinlupa	0.42	Muntinlupa	0.43
	Mandaluyong	0.39	Mandaluyong	0.40	Mandaluyong	0.40	Mandaluyong	0.40
	Paranaque	0.31	Paranaque	0.33	Paranaque	0.33	Paranaque	0.33
Medium-Low	San juan	0.29	San juan	0.31	San juan	0.31	San juan	0.32
	Malabon	0.26	Malabon	0.27	Malabon	0.27	Malabon	0.27
	Quezon	0.19	Quezon	0.21	Quezon	0.21	Quezon	0.22
	Las pinas	0.17	Las pinas	0.19	Las pinas	0.19	Las pinas	0.19
Low	Kalookan	0.05	Kalookan	0.09	Kalookan	0.09	Kalookan	0.09
	Valenzuela	0.03	Valenzuela	0.07	Valenzuela	0.06	Valenzuela	0.06

Table 4 Comparison between the worst scenarios for the studied cities

Index	Barcelona	Bogota	Manizales	Metro manila
Physical risk, R_F	0.08	0.32	0.27	0.24
Aggravating coeff. F	0.42	0.55	0.56	0.59
USRi = Total risk, R_T	0.11	0.50	0.44	0.38

institutional issues related to the development of communities that contribute to the creation of risk. At the urban level, for example, vulnerability seen as an internal risk factor should be related not only to the level of exposure or the physical susceptibility of the buildings and infrastructure material elements potentially affected, but also to the social fragility and the lack of resilience or capacity to cope of the exposed community. The absence of institutional and community organization, weak preparedness for emergency response, political instability and the lack of economic health in a geographical area contribute to risk increasing. Therefore, the potential negative consequences are not only related to the effects of the hazardous event as such, but also to the capacity to absorb the effects and the control of its implications in a given geographical area.

For the modelling, a simplified but multidisciplinary representation of urban seismic risk has been suggested, based on the parametric use of variables that reflect aspects of such risk. This parametric approach is not more than a model formulated in the most realistic possible manner, to which corrections or alternative figures may be continuously introduced. The consideration of physical aspects allowed the construction of a physical risk index. Also, the contextual variables (social, economic, etc.) allowed the construction of an aggravating coefficient. The former is built from the information about the seismic scenarios of physical damage (direct effects) and the latter is the result from the estimation of aggravating conditions (indirect effects) based on descriptors and factors related to the social fragility and the lack of resilience of the exposed elements.

This new model for holistic evaluation of risk facilitates the integrated risk management by the different stakeholders involved in risk reduction decision-making. It permits the follow-up of the risk situation and the effectiveness of the prevention and mitigation measures can be easily achieved. Results can be verified and the mitigation priorities can be established as regards the prevention and planning actions to modify those conditions having a greater influence on risk in the city. Once the results have been expressed in graphs for each locality or district, it is easy to identify the most relevant aspects of the total risk index, with no need for further analysis and interpretation of results. Finally, this method allows to compare risk among different cities around the world and to perform a multi-hazard risk analysis.

apply the method in Metro Manila, The authors are grateful with Earthquake and Megacities Inititative (EMI) and with the representatives of the institutions of Metro Manila for their participation in the review and test of the methodology in the city.

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