Global Risk And Vulnerability Index Trends per Year (GRAVITY)

Phase II: Development, analysis and results

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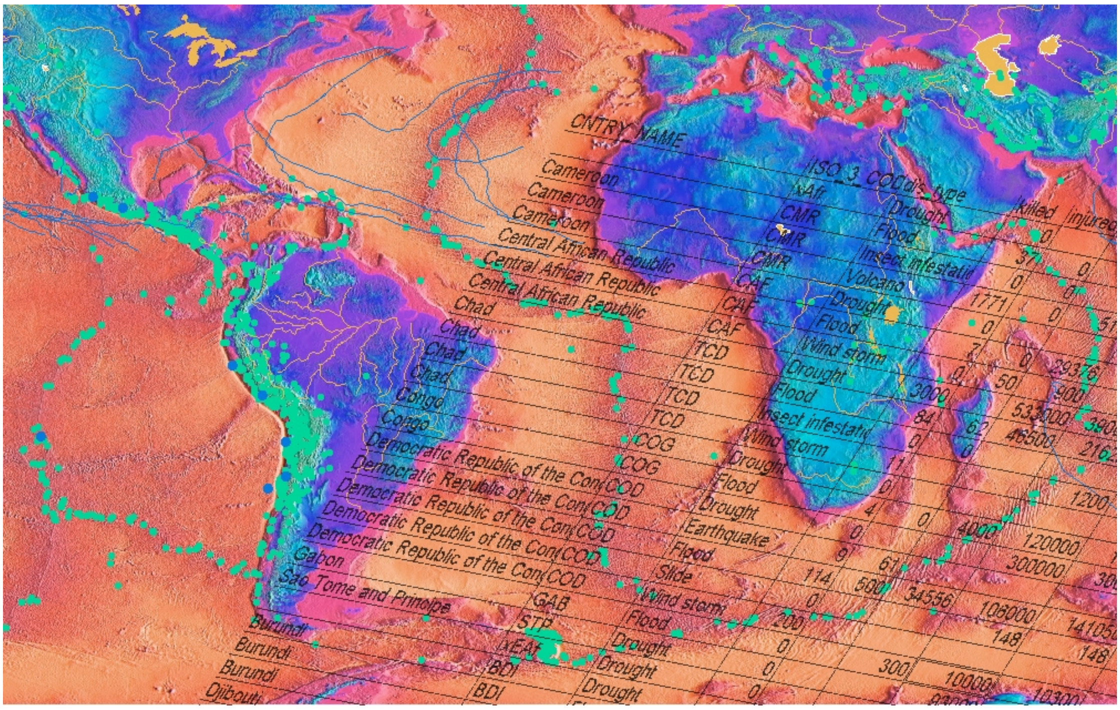
For
United Nations Development Programme
Bureau of Crisis Prevention & Recovery
UNDP/BCPR (formerly ERD)

February 2002



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Acknowledgements

We would like to thanks the following persons whose work has directly or indirectly contributed to the success of this research: Greg Holland and Bruce Harper for their useful advices on cyclone modelling. Haris Sanahuja and Maxx Dilley for helping us to achieve a unification of definitions for the concepts used. Nanette Lomarda from WMO for the contacts and documentation on cyclones. The Fiji Meteorological Service and the Japan Meteorological Agency for their quick response in providing the data for cyclones tracks. Debarati Guha-Sapir, Regina Below and Caroline Michelier from CRED for providing us the access to their most updated version of their database. The GEO3 team from UNEP/GRID-Geneva for prioritising their tasks according to our need in socio-economical data sets.

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Table of acronyms

AVHRR	Advanced Very High Resolution Radiometer
BCPR	Bureau for Crisis Prevention and Recovery
CDIAC	Carbon Dioxide Information Analysis Centre
CNSS	Council of the National Seismic System
CRED	Centre for Research on Epidemiology of Disasters
ERS SAR	European Remote-Sensing Satellite - Synthetic Aperture Radar
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GIS	Geographical Information System
GRAVITY	Global Risk And Vulnerability Index Trend per Year
GSHAP	Global Seismic Hazard Assessment Program
HDI	Human Development Index
IDNDR	International Decade for Natural Disasters Reduction
IFRC	International Federation of the Red Cross
ISDR	International Strategy of Disaster Reduction
NGDC	National Geophysical Data Centre
NOAA	National Oceanic and Atmospheric Administration
OCHA	Office of Coordination of Human Affairs
OLS	Ordinary Least Squares
OFDA	Office of US Foreign Disaster Assistance
PGA	Peak Ground Acceleration
UNDP/BCPR	United Nation Development Programme, Bureau for Crisis Prevention and Recovery
UNEP/GRID	United Nation Environment Programme, Global Resource Information Database
USGS	United States Geological Survey
VEI	Volcanic Explosivity Index
WFP	World Food Programme
WHO/OMS	World Health Organisation
WMO	World Meteorological Organisation

INTRODUCTION

The United Nation Development Programme, Bureau for Crisis Prevention and Recovery (UNDP/BCPR) has initiated an effort for identifying the countries with the highest needs. The World Vulnerability Report (WVR) aims to highlight causes leading to human vulnerability and identifying population at risk. In order to identify these populations, the localisation of the areas at risk as well as a comprehensive understanding of the different causes turning hazardous events into disasters constitutes a compulsory step. This includes the collection of information and data sets for estimating this risk and the identification of the actions needed to decrease the future casualties.

A risk exists when there is an intersection between population and a potential occurrence of hazards. The first task is to identify where these events are more likely to strike human settlements. Countries are not equally exposed to natural hazards; differences in geophysical factors (slopes, elevation, proximity from the shore or geological fault, inter-tropical location, …) are parameters leading to higher occurrence and severity of natural hazards. The reasons why people are living in these areas are multiple: lack of other choices may account for a certain number, but access to resources (such as fishing for the seashore, fertile soils around volcanoes and flood plains, …) and also ignorance of the risk faced due to low frequency (returning period) of most events are significant parameters among others.

With growing population and infrastructure’s complexity the humanity is facing higher risk of casualties. So far the international community has mostly reacted after the events. However, using appropriate measures of risk reduction, casualties may have been drastically reduced. Although there are no means of stopping earthquakes or cyclones from happening, reducing the risk can be done in several ways: one can contain floods by building dams or stabilise slopes for decreasing the number of landslides (prevention measures). One can help the populations living in hazard prone areas to adopt appropriate settlement planning, building codes, access to information and early warning systems as well as acquiring appropriate means of intervention. Prevention, mitigation and preparedness capabilities can be enforced. All of these are means of risk reduction, either by decreasing hazards through prevention or decreasing vulnerability by reinforcing population resilience.

The difficulties when trying to compare human vulnerability consist on differentiating whether populations are affected because of a high frequency and/or magnitude of events, or because of a high vulnerability as different situations require different types of action. This supposes the access to extensive geographical data sets in order to estimate the physical exposure (frequency, magnitude and population exposed), as well as precise socio-economical factors, which can be correlated with the percentage of victims estimated. The main limitation while mixing geophysical and socio-economical parameters lies in the difference of time scale. Earthquakes or volcanoes may have a returning period measured in several centuries, whereas socio-economical features can change extensively during a simple decade! Other difficulties are inherent to global scale, how to compare the situation of earthquakes in South America with the problem of drought in Africa? Not only the number of people affected is very different, but also the percentage of occurrence varies largely for each continent. Hazards impacts differs in: scale, (local; regional or global), in coverage (punctual; large area), in danger (frequency or magnitude), in duration (short tem or long terms). Extensive normalisation is needed for comparing countries.

Achievements

This study presents the results from the second phase of the project Global Risk And Vulnerability Index Trend per Year (GRAVITY) developed by UNEP/GRID-Geneva for the UNDP/BPRD. At the end of the first phase - *the feasibility study* - which consisted on the identification of global data sets and indicators for explaining casualties from natural hazards, twelve recommendations were made. They mostly consisted on the creation of geographical links (georeferencing) of the impacts from past events as recorded in the database from the Centre for Research on Epidemiology of Disasters (CRED). By deriving the extent, magnitude of the event, the exposed population could be extracted and a percentage of victims computed.

The second phase has concentrated on the delimitation of this physical exposure based on methodologies and collection of data sets previously developed at UNEP/GRID-Geneva [PREVIEW project, 2000], in order to highlight places of high natural hazard occurrences. The number of population living in exposed area was extracted using Geographical Information Systems (GIS). Socio-economical data were downloaded from various sources, thirty six indicators for the period 1980-2000 were introduced into a database. The research focus on four hazards namely earthquakes, volcanoes, cyclones and floods.

The main results achieved consist on an improved evaluation of the physical exposure as well as the identification of socio-economical variables leading to higher vulnerability. Using GIS for spatial analysis, areas of intersection between hazards occurrence and population were identified. Except for volcanoes, significant relationship between the number of casualties, physical exposure and socio-economical parameters were found. A statistical analysis demonstrated that physical exposure constitutes the major factors leading to casualties, but other socio-economical parameters are contextual variables leading to higher human vulnerability. These results show the role of the development in the resilience capacity. This corroborates what was often intuitively understood, however, this is now confirmed by statistical evidence. If several factors of vulnerability were identified, a model of prediction can not be derived. This is a consequence of the method used, based on average of victims over a twenty years period. The variation in number of victims within the same country is also depending on time and context factors, thus producing a large variation of casualties within the same country. If prediction for a single event cannot be produced, estimation of losses for longer terms (e.g. 10 years) should be relevant. Categories of country facing equivalent risk can be produced. Thus allowing to identify countries with the highest needs.

1 GENERAL APPROACH

1.1 Hazards, vulnerability and risk, definitions and concepts

A flurry of disciplines are studying hazards and their impacts, ranging from geologists, geographers, economists, social scientists, chemists, insurance, media,… a mixture of common language and technical terminology is being used thus leading to some confusion. In order to avoid confusions this terminology based on UN and other experts is explained in the following paragraphs.

Risk

The term "risk" is used to describe potential losses resulting from expected future hazard. "*The term risk refers to the expected losses from a particular hazard to a specified element at risk in a particular future time period. Loss may be estimated in terms of human lives, or buildings destroyed or in financial terms*" [UNDRO, 1979; in Burton et al. 1993, p.34]. This research is concentrating on the human aspects (i.e. killed persons) resulting from natural hazards. The economical aspect was left for further developments as it requested numerous procedures for comparing financial losses. Indeed, the loss of one million US$ does not have the same impact in Switzerland or in Bangladesh. This could be normalised by using the purchasing power parity, however the number of normalisation for "translating" local currency, at a specific date, into equivalent of international reference currency (such as US$ or €), taking into account local inflation and exchanging rate, is a highly time consuming task, not compatible with the time at disposal. Moreover, if banks and insurance have developed numerous researches on the economical risk, the human aspect did not benefit from so much interest, hence the need for a more human focus research.

There was a need for selecting which indicators should be used for representing the risk to human development. This was based on the availability of the data, as well as on the robustness of the indicators. The economical losses were not an option as explain above. Several other options were available within the CRED database: "killed"; "wounded"; "homeless", "affected" and "total affected". However, by comparing two updates of the database, it quickly appeared that except "killed" the other information were varying by more than 16% ! "Homeless", "affected" and "total affected" were simply not usable, whereas wounded was causing several problems: it is too vague as the severity is unknown and its evaluation likely to vary depending on countries and culture. Furthermore, the number of wounded reported is much probably depending on the quality of the health system, hence the fewer the hospital, physician,… the fewer the wounded… reported!!! At the end the results may delineate more wounded people in developed countries because of higher health facilities and standard. So, finally only the number of killed was taken as risk indicators and not killed plus wounded as originally analysed in GRAVITY-I.

Hazard

If the risk represents the losses, "*the hazard can be defined as a potential threat to humans and their welfare*" [Smith, 1996]. Type of threats can be broadly separated into two categories such as human made hazards (e.g. conflicts, technical accidents,...) and natural hazards resulting from climatic, tectonic or biologic causes (e.g. respectively floods, earthquakes or epidemics). A certain number of hazards can be considered as being at the intersection of both human and natural causes. Typically, food insecurity might be resulting from tense political situation (such as conflicts) in conjunction with extreme climatic or biological causes (drought, locust). Some natural hazards are produced by the conjunction of two or three types of causes: in Peru, an earthquake has induced an avalanche, which fell in a lake producing a large mudflow. Or the conjunction of heavy rain following a volcanic eruption is producing lahars (e.g. in 1985 a volcanic eruption and rain in *Nevado Del Ruiz* has killed 22800 person in Colombia). In this research the hazards taken into consideration include floods, cyclones, earthquakes and volcanics eruptions. This choice was needed in order to balance the resources with time at disposal. The impacts from these four hazards are the highest after food insecurity and epidemics.

The hazards itself, do not only vary in types but also according to a certain number of variables, which makes the event more or less dangerous for the exposed population. Thus the hazardous events varies in terms of magnitude as well as in "*frequency, duration, area extent, speed of onset, spatial dispersion, and temporal spacing.*" [Burton et al. 1993, p.34].

The estimation of risk

By UN definition [UNDRO, 1979], the risk is resulting from three components:

"***Hazard occurrence probability****, defined as the probability of occurrence of a specified natural hazard at a specified severity level in a specified future time period,*
Elements at risk*, an inventory of those people or artefacts which are exposed to the hazard and*
Vulnerability*, the degree of loss to each element should a hazard of a given severity occur*" [Coburn et al. 1991, p. 49].

In the case of risk of human losses, the element at risk is the exposed population and the hazard occurrence probability refers to the frequency or returning period of a given magnitude of a hazardous event, i.e. the average number of potential future events during a precise length of time. The combination of both frequency and population exposed provides the number of persons exposed during the certain length of time and is called the physical exposure which "*reflects the range of potentially damaging events and their statistical variability at a particular location*" [Smith, 1996]. This, however, does not explain the discrepancy of casualties when comparing two different human settlements of similar number of population exposed to an equal magnitude of event. The difference of casualties or impacts measured between the two societies might be explained by their respective resilience and vulnerability. Intuitively, one can understand that improved infrastructures and building constructions, lower density of population, access to information should lead to a lower number of casualties. However, deriving a formula that directly connects the number of victims to the contextual factors is a much higher step. "*The concept of vulnerability is perhaps the most difficult to approach*" [Coburn et al. 1991, p.49]. Extensive normalisations are needed to separate the physical exposure from the vulnerability.

1.2 Formula and method for estimating risk and vulnerability

Formula

The formula used for modelling risk was derived from UN definition [UNDRO, 1979] (see above): the risk is a function of hazard occurrence probability; element at risk; and vulnerability.

Because the study concentrated on the impacts on population, the element at risk is substituted by the exposed population. Then the following hypothesis was made for modelling the risk:

First hypothesis: T**he three factors explaining risk should be multiplying each other**.

This was introduced because, if the hazard is null, then the risk is null:

As 0 (hazard) x population x vulnerability = 0 (Risk)

The risk is also null if nobody lives in an area exposed to hazard (population = 0), same situation if the population is invulnerable, (vulnerability = 0, induce a risk = 0). Following the definition from UNDRO and the stated hypothesis the Equation 1 was derived:

Equation 1: First hypothesis, the equation of risk is a multiplication of 3 factors

$$R = H \cdot Pop \cdot Vul$$

Where:

R is the risk, i.e. the number of expected human impacts (killed).
H is the Hazard depends on frequency and strength of a given hazard,
Pop is the population living in a given exposed area.
Vul is the vulnerability and depends on socio-politico-economical context of this population.

From the previous discussion the physical exposure was defined as the *combination of both frequency and population exposed* (see p.3) to a given magnitude for a selected type of hazard. The hazard multiplied by the population could then replaced by the physical exposure:

Equation 2: Risk evaluation using physical exposure

$$R = PhExp \cdot Vul$$

Where:

PhExp is the physical exposure e.i. the frequency and severity multiplied by exposed population

One way of estimating the risk is to look at impacts from previous hazardous events. The physical exposure can be obtained by modelling the area extent affected by one event. The frequency is computed by counting the number of events for the given area divided by the number of years of observation (in order to achieve an average frequency per year). Using the area affected, the number of exposed population can be extracted using a GIS, the population affected multiplied by the frequency provides the physical exposure. Remains the estimation of the vulnerability. If the Equation 2 is correct, then a proxy for the vulnerability can be computed by dividing the impacts from previous hazardous events by the physical exposure. This constitutes the second hypothesis.

Equation 3: Second hypothesis, computation of a proxy for vulnerability

$$Vul_{proxy} = \frac{impacts}{PhExp}$$

Where:

Impacts are the number of killed as recorded by CRED during the period 1980-2000.

If the number of realised risk is known, as well as the physical exposure, then the vulnerability of a population can easily be derived. The quality of this ratio depends on the quality of the observations from past casualties and the precision of geophysical data and model for physical exposure. This is why the greatest precautions were taken while computing the physical exposure.

Once the proxy for vulnerability is computed, the ratio can then be correlated with socio-economical indicators. The normalisation of the victims by the physical exposure allows comparisons between countries, as it suppresses the difference of exposed population (populated and less populated countries), the number of events is also normalised. This proxy is then equivalent to the percentage of the impacts on the population exposed per event of a given severity. Further detailed explanations on how the physical exposure is determined can be found in chapter 3 (p.16).

Equation 4: Third hypothesis, computation of risk as a function of independent variables

$$Risk = f(PhExp, VulnerabilityFactors)$$

Where:

VulnerabilityFactors are socio-economic factors having an influence on the level of losses for a given hazard type.

In this case, number of victims from past hazardous events is considered to be a function of physical exposure and of a set of vulnerability factors. Both linear and non-linear approaches were explored in order to define the function, using both parametric or non-parametric methods (see chap.4, p.23). In order to avoid a totally empirical approach in the identification of relevant factors, broad categories of potential vulnerability factors were defined before performing the actual computation of the formula[1]:

- Economy
- Dependency and quality of the environment
- Demography
- Health and sanitation
- Politic
- Infrastructure, early warning and capacity of response
- Education
- Development

Apart from problems rising from data quality, it is crucial to distinguish mitigation factors (inputs, action taken) from vulnerability factors (outputs, resulting state of the people). The idea is to find at least one indicator for each of these categories, available for the 1980-2000 period and for the countries exposed to the different disaster types. The identified usable indicators are presented in chap. 2 (p. 9).

From risk to selected hazard to the total risk for a country

The physical exposure or the vulnerability to a specific hazard can not be added or compared to another hazard. Indeed, the vulnerability to flood will not follow the same trend as for earthquakes. However, the risk, can be added. The risk can be expressed in different ways (e.g. number of killed, percentage of killed, percentage of killed as compared to the exposed population.) as shown in Table 1.

Table 1: Advantages and inconveniences of respective risk indicators

Indicators for risk	Advantages	Inconveniences
1. Number of killed	Each human being has the same "weight"	10.000 persons killed split between ten small countries does not appeared in the same way as 10.000 killed in one country. Smaller countries are disadvantaged.
2. Killed / Population	It allows comparisons between countries. Less populated countries have the same weight as more populated countries.	The "weight" of human being is not equal, e.g. one person killed in Honduras equal 160 killed in China.
3. Killed / Population affected	Regional risk is highlighted even thought the population affected is a smaller portion of the total national population.	This may highlight local problem that are not of national significance and give wrong priority for a selected country.

No scientific arguments can be used for selecting one indicator instead of another. At the end this is a political decision. If needed a mixture of indicators can be used. It was

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[1] The list of potential factors was thoroughly discussed with Christina Bollin (GTZ), who's responsible to identify the indicators for mitigation for the WVR.

decided to provide both killed and killed per population. The third indicators will be, in a way, represented by the killed per physical exposure used as a proxy for vulnerability.

These numbers can be added for a selected country. The expected losses due to natural hazards are equal to the sum of all types of risk faced by a population in a given area as provided by the Equation 5:

Equation 5: Estimation of the total risk

$$\mathrm{Risk}_{\mathrm{Tot}} = \Sigma\ (\mathrm{Risk}_{\mathrm{Flood}} + \mathrm{Risk}_{\mathrm{Earthquake}} + \mathrm{Risk}_{\mathrm{Volcano}} + \mathrm{Risk}_{\mathrm{Cyclone}} + \ldots + \mathrm{Risk}_{n}\ )$$

Providing the total risk for a country induces the need to estimate the probability of occurrence and severity of each hazard, the number of persons affected by them, the identification of population vulnerability and mitigation capacities. This is of course not possible in absolute, however the aim is to provide indicators which will be refined years after years in order to approach the concept of risk.

Spatial units

The spatial definition of vulnerability and risk is a crucial topic. First, a distinction must be made between display units and observation units. In the context of the present study, display units are countries: the vulnerability/risk evaluation is presented on a country by country basis, according to UNDP requirements. But collection of data is not only performed at the country level; for instance, data on a particular event refers to the area affected by this event, not to the country as a whole. Several observation units were considered:

Table 2: Spatial units

Observation units	Remarks
Countries	Most of the socio-economic vulnerability factors are only available at this resolution (GDP, literacy rate, life expectancy, HDI, etc.
Areas at risk (=all potential areas of disaster, where probability of occurrence > 0)	Defined by the probabilities of occurrence of disaster types. Allows for the evaluation of population/areas that can potentially be affected by disasters
Area of a particular event	Extent of a particular event. Losses reported in the CRED database implicitly refers to this type of area. The link between the impacts and the extent of the hazardous event had to be implemented, this had request extensive work for georeferencing the CRED. This was performed for earthquakes, cyclones and floods, in the case of volcanoes, the CRED database includes the name of the volcano, thus helping the automation of the link.
Pixels	Some data like population density, probabilities of cyclones are already available according to this type of regular grid

The spatial definition of risk/vulnerability differs if only damages are considered or if causal factors are to be explored. Spatial circumscription of damages is in principle relatively easy to depict, although it may also depends on the time frame considered (direct or indirect, induced damages). On the contrary, the spatial extent of causal factors does not necessarily coincide with the observed damages: for example, illegal occupation of exposed slopes by migrants in a region may be caused by the disastrous economic situation in an other region.

In the methodology developed to estimate vulnerability from socio-economic indicators, the figures used were only available at the country level (except for population), which might not be sufficient or even not relevant. On the other hand, hazard data, originally raster grids or vector coverage, have been aggregated to produce figures on a country by country basis.

The correct use (i.e. appropriate scale, pixel size, type of representation, …) of data at various spatial resolution is the major concern when performing environmental modelling, both from the GIS and from the geographical point of view.

Temporal units

Like the spatial definition of risk/vulnerability, its temporal definition is subject to discussion. First, the temporal circumscription of a disaster is very different if only direct losses are considered or if longer term and/or indirect effects are also included.

The periodicity of disaster types (centuries, decades, years, …) is also a very important aspect. Considering vulnerability, repetitive disasters have an influence on the future capacities of response and recovery of a country. Considering data availability, the access to information on natural disaster (number of events, number of victims,…) has considerably risen in recent years following the significant improvement in telecommunication technologies, however such rise is not uniform in all the regions worldwide. Furthermore, the 20-30 years long time-series of more or less complete records provided by various databases may not be adequate to depict geological or climatic phenomenon following trends over hundred or thousand years.

Finally, when exploring relations between disasters and vulnerability, it may appear that causal factors may be shifted in time as compared to observed disasters: the actual vulnerability of a country may be caused by past economic situations.

In the present study, the model of vulnerability factors is based on the analysis of direct human losses on a disaster by disaster basis (as reported by CRED, with all its inherent limitations including the definition of the disaster type). The observed losses over a 21 year period are then used to validate the estimation of risk provided by the socio-economic factors.

2 DATA

To have access to a global and a spatially as well as timely consistent data coverage is without any doubt one major challenge of any global scale study as the present one. Furthermore, because of the range of domains related with risk and vulnerability, ranging from physical geography to economic, social and cultural aspects of societies, there is no other choice than to rely on specialised groups or institutions compiling relevant data at a global scale. The value-adding task of the GRAVITY team is to organise the bulk of data in a uniform structured manner and, next, to compute aggregates on a country by country basis.

2.1 Socio-economic data

As discussed in chap.1.2, p.6, a number of vulnerability indicators are compiled using the best available sources, mainly the GEO Data Portal[2] and the World Development Indicators CD-ROM. This list of indicators is strictly limited by the data availability; many other indicators are potentially very relevant (like the quality of buildings, the level of freedom or democracy, etc.) but data is unfortunately often either incomplete or non-existent. Hence, the following list is the intersection of what was desirable and what is actually available:

Table 3. Vulnerability indicators

Categories of vulnerability	**Indicators**	**Source**
Economic	1. Gross Domestic Product per inhabitant at purchasing power parity,	GEO
	2. Total dept service (% of the exports of goods and services),	GEO
	3. Inflation, food prices (annual %),	WB
	4. Unemployment, total (% of total labour force)	WB
Type of economical activities	5. %age of arable land	GEO
	6. %age of urban population,	GEO
Dependency and quality of the environment.	7. Forests and woodland (in %age of land area),	GEO
	8. %age of irrigated land	GEO
Demography	9. Population growth,	GEO
	10. Urban growth,	GEO
	11. Population density,	GEO
	12. Age dependency ratio,	WB
Health and sanitation	13. Average calorie supply per capita,	GEO
	14. %age of people with access to adequate sanitation,	GEO
	15. %age of people with access to safe water (total, urban, rural)	GEO
	16. Number of physicians (per 1000 inhab.),	WB
	17. Number Hospital Beds	WB
	18. Life Expectancy at birth for both Sexes	GEO
Politic	19. Transparency's CPI (index of corruption)	TI
Infrastructure, early warning and capacity of response	20. Number of Radios (per 1000 inhab.)	WB

(continued next page)

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[2] The GEO Data Portal is based on data from the FAO, World Resource Institute, the World Bank and many other institutions. It offers 40-year time series for around 200 countries plus aggregates GEO sub-regions and regions.

Categories of vulnerability	**Indicators**	**Source**
Education	21. Illiteracy Rate,	GEO
	22. School enrolment,	GEO
	23. Secondary (% gross),	GEO
	24. Labour force with primary, secondary or tertiary education	WB
Development	25. Human Development Index (HDI)	UNDP

GEO : Global Environment Outlook Data Portal (UNEP), based on data from FAO, WRI, World Bank and other sources / WB : World Development Indicators (World Bank) / TI : Transparency International / UNDP : Human Development Report (UNDP)

2.2 Data on hazards

A number of institutions worldwide are concerned with the collection of data on hazards at a global scale. In the context of the present study, specific characteristics are needed which are not always directly available from the identified sources:

- time, location and extent of the disasters
- severity (i. e. any information permitting the distinction between major and minor events)
- frequency of events

Table 2.2 (p. 10) summarises the main characteristics of each of the identified data sources on hazards.

2.3 Population data

Two main datasets were available : the ONRL Landscan population grid at a resolution of 0.5” (1 km at the equator) and the CIESIN, IFPRI, WRI Gridded Population of the World (GPW, Version 2) at a resolution of 2.5’ (5 km at the equator). Despite its 5 times lower resolution, GPW 2 was preferred for two main reasons:

- the original information on administrative boundaries and population counts is almost two times more precise in GPW 2 than in the Landscan dataset (127,093 administrative units against 69,350 units)
- the Landscan dataset is the result of a complex model which is not explained thoroughly. Furthermore, the model is based, among other variables, on environmental data (land-cover), making it difficult to use for further comparison with environmental factors (circularity).

In the GPW 2 grid dataset, population totals of each administrative unit were proportionally distributed in the cells composing the units. When a cell is at the border of two or more units, these units contribute to the cell total according to their relative share of area. Country population totals were also adjusted to UN country figures, allowing for easier comparison with statistics coming from UN and other international agencies.

This method is straightforward but it is based on the assumption that population is homogeneously distributed within each administrative. This assumption is certainly not valid when looking at individuals but it is compensated by the use of high-resolution demographic data. Knowing the limitations induced by the original data and the rasterisation method employed, it is necessary to interpret the data only at a relevant resolution (for example at the mean administrative unit size) and not on a cell by cell basis. In the case of GPW 2, the mean resolution of the original demographic data is 34 km ($\sqrt{total\_area/nb\_of\_units}$), around 100 times coarser than the mean grid resolution (3.5 km). In other words, interpretation of areas less than 100 pixels (1'200 km²) should be considered with caution. Typically, this would be the case for volcanoes.

2.4 Data on victims

Data on victims was extracted from the EM-DAT, The OFDA/CRED International Disaster Database, as of Nov. 2001. Since the first GRAVITY report (may 2001), a number of improvements have been implemented to the EM-DAT database, in particular after remarks from the GRAVITY team: corrections of errors on victims, more data on the location of disasters, ... Only figures on killed people were used in this study, figures on injured and affected people are considered to be too volatile, due to conceptual uncertainties (what is the definition of an injured person ?) as well as to the difficulty of measuring these types of losses. As discussed on chap.1.1 p.3.

Another major limitation of the EM-DAT data is the lack of information on disaster scales (magnitude, intensity, ...). Consequently, it is not possible to define sub-types of disasters based on their severity (i.e. *large* floods versus *small* floods), which would have allowed for finer comparisons of losses with the physical exposure extracted from the geo-physical datasets.

2.5 Precision and limitations

Several general remarks and cautions must be discussed further before any analysis and interpretations of results are performed.

Although the statistical analysis and final results are displayed on a country by country basis, it must be reminded that the spatial units of the original geo-physical data are very heterogeneous: grid cells at various resolutions, lines, polygons, points. Most of these units do not match administrative boundaries : for example, 5° by 5° grid cells of cyclones occurrences lead sometimes to erroneous figures when intersected with country boundaries, specially when very small areas are concerned. In order to summarise all geo-physical information on a country by country basis, aggregation and interpolation methods were needed. Aggregation was less a problem since it is based on actual data that is, for example, summed up for each country. Interpolation is used when an information must be estimated: for instance, data on volcano locations are available, but the extent of the successive eruptions is modelled based on the intensities of the events.

An other source of errors in the data raises for its incompleteness. In several cases, both geo-physical and socio-economic datasets show missing years and/or missing countries. Two examples: cyclone tracks are only available for 11 years, but not for India, Pakistan and Bangladesh; Human Development Index (HDI) is not provided for all countries and only every 5 years. When possible and relevant, interpolation is performed to estimate missing figures: in the case of HDI, values are simply duplicated for every five-year intervals; indicators showing a clear trend are interpolated using linear or exponential functions, etc.

Although best possible interpolation methods were applied, it must reminded that the analysis was performed on both observed/measured and estimated/modelled data.

Even if only original data were used, the problem of error evaluation would remain because the appropriate meta-information was sometimes not provided. For example, CDIAC data on cyclone occurrences is simply presented as “ extracted from a variety of sources ”; the time range considered for the computation of probabilities of occurrences was not mentioned, nor the actual method used. The level of precision of the socio-economic values (vulnerability indicators) taken individually is not known; in general, these data were provided by national statistical offices and their level of confidence is not provided.

These negative remarks may be counterbalanced by the fact that more often data will be used in the future, more errors will be corrected and better documentation will be required by the users.

To summarise, two major limitations must be considered:

- concerning the vulnerability factors, weaknesses may arise from the absence of data (like HDI for Afghanistan) which may reject from the analysis either the indicator or the country; on the contrary, when data is provided, either from original sources or from careful interpolation, it must be considered as valid;
- physical exposure (extracted from geo-physical and population datasets) must be considered with caution when a few people or small exposed areas are concerned. For instance, when simple circular or elliptic areas around volcanoes and earthquakes epicentres are considered, some cities may have been erroneously omitted or included by the definition of exposed areas, leading to important errors. In less densely populated areas, and due to the interpolation method applied for the GPW 2 dataset (uniform distribution of population), population counts can be easily over- or underestimated by a factor of 2 or more; this margin of error on physical exposure is higher for disaster types having a smaller spatial extent like volcanic eruptions:

Table 4. Spatial extent of hazards

Disaster type	**Av. extent[3] (km)**	**Remarks**
Earthquake	229	Elliptic buffers do not take into account the types of soils and rocks
Flood	4710	Entire basins are considered whereas only a portion of them is actually flooded
Volcano	75	Circular buffers do not take into account site specific configurations
Cyclone	255	Grid cells (squares) are a gross representation of a phenomenon occurring as a wide track

When these figures are compared with the 34 km average resolution of the population data, cautions to be taken become clear. These figures are only averages, in densely populated areas, the resolution of the population dataset might be largely sufficient enough even in the case of volcanoes.

These considerations clearly highlight the difficulties for producing an analysis based on event per event. By taking an average on a 21 years period, most of these potential risks of error are reduced. This prevents the use of such model for predictive purpose, but should allow the identification of trends.

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[3] Average extent is the average resolution of the spatial units considered: drainage basins for floods, buffers for volcanoes and earthquakes, grid cells for cyclones

Table 5. Data sources for hazards

Theme	**Data source**	**URL**	**Resolution/scale**	**Spatial units**	**Intensity**	**Frequency**
Earthquakes	Global Seismic Hazard Assessment Program : Global Seismic Hazard Map (1999)	http://www.seismo.ethz.ch/GSHAP/	0.1 degree ≅ 8.5 km in average	Grid cells	Peak Ground Acceleration	PGA hazard; not possible to convert into frequencies
	Council of the National Seismic System (CNSS) : Earthquake Catalog	http://quake.geo.berkeley.edu/cnss/	0.01 degree ≅ 0.8 km in average (coordinates precision)	Points (buffered to produce ellipses as function of magnitude)	Magnitude	Frequency of events over 36 years
Cyclones 1	Unisys Weather:	http://weather.unisys.com/hurricane/	0.01 degree ≅ 0.8 km in average	Polylines (buffered to produce polygons, using Greg Holland formula)	Max. Sustainable Wind Speed and Central Pressure (Saffir-Simpson)	# Events per number of years
	Typhoon 2000:	http://www.typhoon2000.ph/				
	Australian Severe Weather:	http://australiasevereweather.com/cyclones/				
	Atlantic Hurricane Track Maps & Images:	http://fermi.jhuapl.edu/hurr/index.html				
	Hawai'I Solar Astronomy:	http://www.solar.ifa.hawaii.edu/index.html				
	Bureau of Meteorology, Australia:	http://www.bom.gov.au/				
	Japan Meteorological Agency:	http://www.kishou.go.jp/english/				
	Fiji Meteorological Service:	http://www.met.gov.fj/				

Theme	**Data source**	**URL**	**Resolution/scale**	**Spatial units**	**Intensity**	**Frequency**
Cyclones 2	Carbon Dioxide InformationAnalysis Center : A Global Geographic Information System Data Base of Storm Occurrences and Other Climatic Phenomena Affecting Coastal Zones (1991)	http://cdiac.esd.ornl.gov/	5 degrees ≅ 415.1 km in average	Grid cells	Wind speed	Annual probability; converted to frequencies as follows : F = - ln (1-P)
Floods	U.S. Geological Survey, HYDRO1k Elevation Derivative Database (1997)	http://edcdaac.usgs.gov/gtopo30/hydro/	original DEM : 30’’ or 0.00833 degree ≅ 0.8 km in average	Polygons (drainage basins)	*Information not available*	Frequency 1980 – 2000 (from EM-DAT)
Eruptions	National Geophysical Data Center : Worldwide Volcano Database (as of Dec. 2001)	http://www.ngdc.noaa.gov/seg/hazard/volcano.shtml	n.a.	Points (buffered to produce polygons)	Volcanic Explosivity Index	Frequency VEI 2-3: 1950 – 2000 VEI 4-7: 1500 – 2000
Tsunamis	National Geophysical Data Center : Tsunami Database (as of May 2001)	http://www.ngdc.noaa.gov/seg/hazard/tsu.shtml	n.a.	Points	Maximum runup	Frequency 1900 – 2000

Table 6. Data sources for victims

Theme	Data source	URL	Resolution/scale	Spatial units	Intensity	Frequency
Victims	Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (as of Nov. 2001)	http://www.cred.be/emdat/	n.a.	Polygons (area affected by each event); lat/long coordinates (centers of affected areas) are provided for 8% of the records	A disaster scale value is provided for 25% of the records	Frequency 1980 – 2000 (from EM-DAT)

Table 7. Data sources for population and vulnerability factors

Theme	Data source	URL	Resolution/scale	Spatial units	Values	Time range
Population (exposure)	CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2	http://sedac.ciesin.org/plue/gpw/	2.5' or 0.04167 degree ≅ 3.5 km in average	Grid cells	Population counts	1990, 1995
Population	Human Population and Administrative Boundaries Database for Asia	http://www.grid.unep.ch/data/grid/human.html	2.5' or 0.04167 degree ≅ 3.5 km in average	Grid cells	Population counts	1995
Vulnerability factors	UNEP/GRID : GEO-3 Data portal	http://geo3.grid.unep.ch/	560 km (average of square root of country areas)	Polygons (country)	23 socio-economic variables	1980-2000
	UNDP : Human Development Report	http://www.undp.org/		Country	Human Development Index (HDI)	1980,1985,1990,1995,2000
	Transparency international	http://www.transparency.org/		Country	Corruption Perceptions Index (CPI)	1995-2000

3 COMPUTATION OF PHYSICAL EXPOSURE

3.1 General description

In broad term, the physical exposure was estimated by multiplying the hazard by the population living in exposed area. The frequency of hazard was derived for different strengths of events and the physical exposure was computed as in Equation 6:

Equation 6: Computation of physical exposure

$$\mathrm{PhExp_{nat}} = \Sigma\ \mathrm{F_i} \cdot \mathrm{Pop_i}$$

Where:

$PhExp_{nat}$ is the physical exposure at national level (spatial unit)
F_i is the annual frequency of a specific magnitude event in one spatial unit
Pop_i is the total population living in the spatial unit

The main task was to evaluate the hazard (extent, strength and frequency). Two different approaches were used. The first one consisted on georeferencing the CRED data. For this purpose, to each event, geographical coordinates were provided (either points or polygons) using GIS tools and the number of victims was associated with the affected population. This was performed for 21 years for floods, earthquakes and volcanoes and for 11 years for cyclones.

In the second statistical approach, the average number of events, area extent and population affected were computed at national scale as needed in order to associate the victims from the last twenty years with the physical exposure and with socio-economical variables.

Depending on type of hazards and quality of data, different methods were applied. The population was extracted from the model of population UNEP-CIESIN as well as Human Population and Administrative Boundaries Database for Asia (in order to include Taiwan). This reflects the supposed population distribution for 1995. Corrections for population in function of the year were applied in the statistical analysis. For example the vulnerability approached by Killed / Physical exposure as in Equation 7:

Equation 7 : computation of vulnerability proxy with pondered average population

$$\mathrm{Vul} = \frac{1}{n} \cdot \left(\sum \frac{K_i}{\frac{Pop_i}{Pop_{1995}} \cdot PhExp} \right)$$

Where:

Vul: Vulnerability proxy
N = number of year
K_i = number of killed for the year "i"
Pop_i = population at the same year
Pop_{1995} = population in 1995
PhExp= Physical exposure computed with population as in 1995

The data set provides the number of population living in a 30'' grid resolution (equivalent to 5 x 5 km at the equator). Due to the resolution of the data set, the population could not be extracted for some small islands. This has lead to the non-consideration of the small islands (even for large archipelagos). Refined study should be carried out in a further research (see recommendations in conclusion). Data were also missing for Serbia. Apart from these limitations, the extraction of the population living in exposed area is a simple task performed with a GIS.

The main difficulty consists on the evaluation of hazard area extent, frequency and intensity. At a global scale, data are not complete and generalisation is the rule. Help of specialists was asked in order to review the necessary simplification. Out of the four hazards studied, only the case of floods requested the complete design of a global data set built on link between CRED information and USGS watersheds. For the other hazards, independent global data sets had already being updated, compiled or modelled by UNEP/GRID-Geneva and were just used as clip to extract the population. The Mollweide projection was used in order to minimise the deformation of surfaces, as this projection respects the area for global coverage.

The data is usually provided as a series of point with latitude, longitude coordinates and time references. An extensive work involving GIS processing and mathematical modelling was involved to transform these coordinates into buffers depicting the areas exposed, intensity and frequency of occurrence. The lack of access to global data set for floods, prevent the estimation of intensity and duration (see Discussion in Conclusions and recommendations p.39) some data sets are believed to be more detailed but no contact could be made with the centre developing this dataset.

Although the quality can always be improved, the greatest care was taken and the level of accuracy achieved is believed to be relevant and appropriate for a global scale study. Except for volcanoes. Details on how these physical exposures were derived are provided case by case.

3.2 *The case of Cyclones*

The vector approach

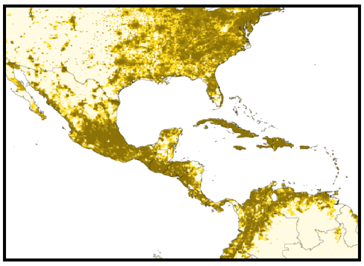
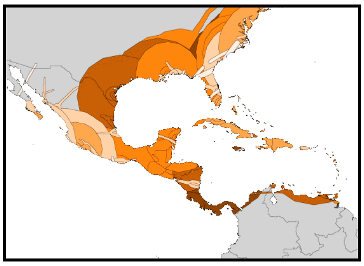
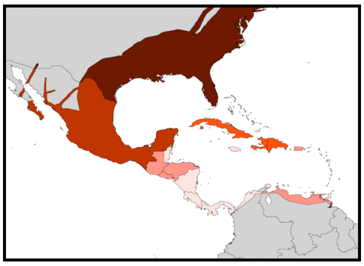
In order to extract the number of persons affected by a specific cyclone, tracks, sustainable wind and central pressure were obtained either from different websites when available or meteorological centres worldwide. All the centres contacted have replied and provided their data within few days at the exception of the centre of New Deli, which never answered to the multiple messages and requests sent. As a result, the data for India, Pakistan and Bangladesh is missing, this was overcome by the use of Carbon Dioxide Information Analysis Centre (CDIAC) for these countries.

Wind analyses in the hurricane boundary layer are difficult to construct and interpret. Observations are generally quite sparse, from different sources (islands, ships, coastal regions, aircraft, etc.) and are subject to substantial errors. Considerable variability occurs from one situation to the next, so that no standard horizontal structure can confidently be used to interpolate between these scarce observations over a period in which the cyclone is assumed to be in a relatively steady state. The problem with insufficient number of observations worldwide to define accurately the structure of tropical cyclones and adjacent synoptic features forced the use of parametric modelling for the horizontal wind structure.

The horizontal wind structure model

The modelling process is based on a formula developed by Greg Holland (1980) from an original approach by Schloemer (1954). This model calculates the symmetric winds and it assumes that the tropical cyclone surface pressure field follows a modified rectangular hyperbola.

Figure 1: Population, area of events and physical exposure for cyclones

Population	Area of events (11 years)	National physical exposure per year
		

In this case, the computation of a frequency could not be derived in absence of a coherent spatial unit (due to large discrepancies in country size). To overcome this difficulty, the computation was made by adding the population affected and then divided by the number of year as shown in Equation 8.

Equation 8: Physical exposure calculation without frequency

$$PhExp = \sum \frac{Pop_i}{Y_n}$$

Where:
Pop_i is the total population living in a particular buffer around a epicentre
Y_n is the length of time in year for the cyclones (11)
PhExp is the total physical exposure of a country is the sum of all physical exposure of this country

Raster approach

Because of the non-completeness of the data set, a supplementary approach was made, already applied in *GRAVITY feasibility study*. The data used to define cyclone hazard areas are produced by the Carbon Dioxide Information Analysis Centre (CDIAC, K. R. Birdwell K.R., Daniels, R.C., 1991). These delineate annual probabilities of occurrence of tropical cyclones. The spatial unit is a 5 x 5 decimal degrees cell. Probabilities are based on tropical cyclones activity of a specific record period, except for several estimated values attributed to areas that may present occasional activity but where no tropical cyclones were observed during the record period.

Table 8: Wind speeds and appellations

Wind speeds	**Name of the phenomenon**
≥ 17 m/ s	Tropical storms
≥ 33 m/ s	Hurricanes
	Typhoons
	Tropical Cyclones
	Severe cyclonic storm
	Depending on location[4]
≥ 65 m/ s	Super Typhoons

Saffir-Simpson tropical cyclones classification is based on the "maximum sustained surface wind". With winds of less than 17 m/s, they are called "tropical depressions". If the wind reaches speeds of at least 17 m/s, they are called "tropical storms". If the wind speed is equal to or greater than 33 m/s, they get one of the following names, depending on their location[4]: "hurricanes", "typhoon", "severe tropical cyclone", "severe cyclonic storm" or "tropical cyclone". At last, if the wind reaches speeds of 65 m/s or more, they are called "super typhoons" (Christopher W. Landsea, NOAA/AOML, 2000).

The CDIAC is providing probability of occurrence for these three types of events. The average frequency (per year) was computed using Equation 9:

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[4] *Hurricanes: North Atlantic Ocean, Northeast Pacific Ocean east of the dateline, or the South Pacific Ocean east of 160E);*

Typhoon :	*Northwest Pacific Ocean west of the dateline,*
Severe tropical cyclone:	*Southwest Pacific Ocean west of 160E and Southeast Indian Ocean east of 90E,*
Severe cyclonic storm:	*North Indian Ocean,*
Tropical cyclone:	*Southwest Indian Ocean*

Sources: NOAA/AOML, FAQ: Hurricanes, Typhoons, and Tropical Cyclones. http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqA.html#A1

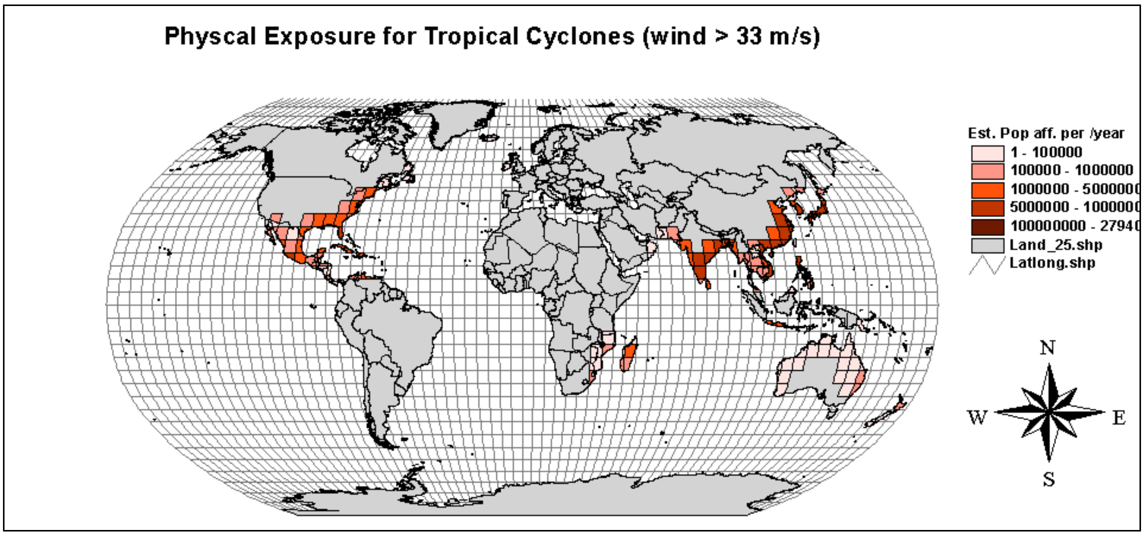
Equation 9: From probability to annual frequency for cyclones

$$E(x) = \lambda = -\ln(1 - P(x \geq 1))$$

<u>Where</u>:

E(x) is the "statistical esperence", i.e. the average number per year = λ
P(x)is the probability

Figure 2: Example of physical Exposure for Tropical Cyclones



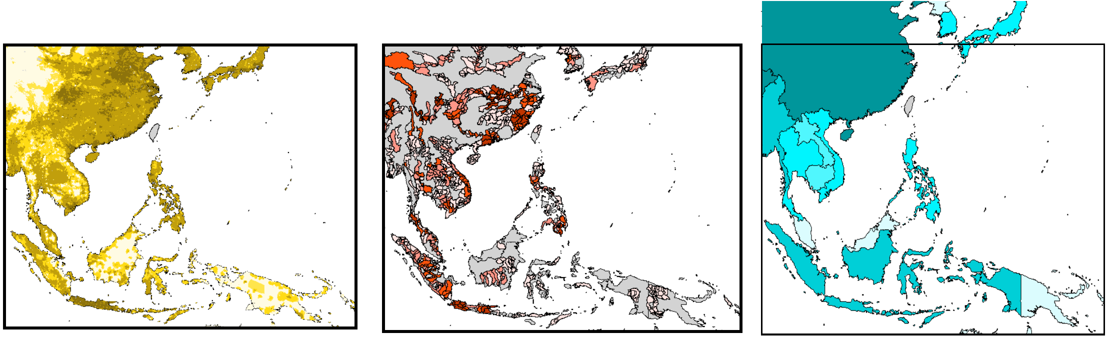
A frequency per year is derived for each cell. Cells are divided to follow country border, then population is extracted and multiplied by the frequency in order to obtain the average yearly physical exposure for each cell. This physical exposure is then added by country for the three types of cyclones.

Physical exposure to tropical cyclones of each magnitude was calculated for each country using Equation 6 p.16.

3.3 The case of Floods

For the floods the method is slightly different. No global database on floods could be found. Due to the lack of information on the duration and severity of floods, only one class of intensity could be made. Using the information in the column "comment" (e.g. name of town, river, valley,…) in the CRED database, a georeference of the floods was produced and a link between the watershed and the events was made. Watersheds affected were mapped for the period 1980-2000. A frequency is derived for each watershed by dividing the total number of events by 21 years. The watersheds are then split to follow country border, then population is extracted and multiplied by the frequency. The average yearly physical exposure is then added at a country level using Equation 6 p.16.

Figure 3: population, Frequency and Physical exposure for floods



Population

Frequency for each watershed

National physical exposure per

3.4 *The case of volcanoes*

In order to define hazard zones at a global level, the approach used the NGDC database to determine volcanic activity around the world and, broadly, areas that could be affected. The magnitude unit available in the NGDC eruption database is the Volcanic Explosivity Index (VEI). This is a magnitude established by Newhall and Self (1982), integrating quantitative data as well as descriptions of observers. The scale (0 to 8) describes an increasing explosivity. Each level corresponds, among others, to a particular volume of explosive products, eruptive cloud height and descriptive terms (Simkin and Siebert, 1994).

As the principal causes of direct deaths are linked to explosive events, the first two VEI levels (0 and 1) have been omitted. Then, two groups of magnitudes were defined. The first one corresponds to levels 2 and 3, described as explosive eruptions. The second correspond to levels 4 to 8, described as cataclysmic, paroxysmal or colossal eruptions. Zones following a radius of respectively 10 (for VEI 2-3) and 30 km (for VEI = 4-8) around the eruptive centres were taken in order to extract the population affected. The distance of 10 and 30 km was chosen based on Mollweide projection, according to several regional hazard maps, produced by various sources.

The last fifty years (1950-2000) records were considered to determine hazard zones and frequencies for the explosive eruptions (VEI 2 and 3). Indeed, histogram of the NGDC database shows that record for explosive eruptions is the most complete for this period. The selection of the strongest events (VEI 4 to 8) takes into account both the fact that the database completeness is better for the last 150 years and that most of the time intervals between eruptions of levels 4 to 8 are greater than hundred years (Simkin and Siebert, 1994). The records of the last five centuries are to be considered in order to define hazard zones and frequencies. A greater time interval would have clearly underestimated America's hazard (less records).

Link with CRED’s records was established using the volcano names and dates of eruptions.

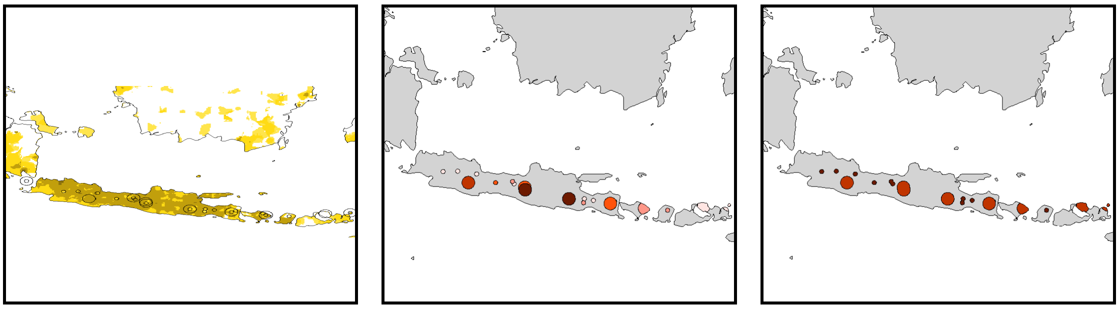
Physical exposure to volcanism activity was calculated for each country and each group of magnitude with the Equation 6 p.16. The annual eruptive frequency of a volcano, was based on the last five decades or the last five centuries record, depending on magnitude group.

This process generates hazard zones in a broad manner and it is clear that areas affected by specific events may vary significantly, depending on regional characteristics. For instance, lahars are linked to many parameters such as pluviometry, seismicity, topography and soils characteristics, among others. Tephra falls are directly influenced by wind dominant direction, and may affect areas hundreds kilometres away from eruption. Ground water access to the magma may produce phreatomagmatic eruption and thus might increase significantly the level of explosivity.

Furthermore, as time intervals between eruptions stretch extensively with magnitude (VEI) until tens of thousands of years, long periods without activity are commonly followed by more powerful explosive eruptions. Hence, high volcanic activity determines by historical record does not necessarily imply high volcanic hazard. The fact that some of the most explosive and fatal eruptions of the last two centuries were from volcanoes without historical activity recorded perfectly highlights this point. Therefore, in attempt to include in records all volcanoes that might erupt in a relatively short-term, modern geological and mineralogical investigations are and will be requested, along with the historical records (Simkin and Siebert, 1994).

However, the general trend of explosive volcanism at convergent plate margins and effusive volcanism at divergent plate margins and hot spots, is well shown by the results, and this was the purpose of this approach.

Figure 4: Population, Frequency and physical exposure for volcanic eruption



Population

Frequency[5]

Physical exposure

3.5 *The case of earthquakes*

A choice was made to produce seismic hazard zones using the seismic catalogue of the CNSS (Council of the National Seismic System). Hypocentres record of the last 21 years (1980-2000) was grouped in five magnitude classes and a buffer, which radius depend on these classes, was drawn around each point. Choices of specifics radius were made considering the next table. It shows estimations of duration of ground motions for specific acceleration and frequency ranges, according to magnitude and distance from epicentre (Bolt, Horn, Macdonald and Scott, 1975):

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[5] Sources: 1950-2000 events for VEI 2-3 and on last 500 events years for VEI between 4 and 8.

Table 9: Bracketed duration in second[6]

Distance	Magnitude						
(km)	5.5	6.0	6.5	7.0	7.5	8.0	8.5
10	**8**	**12**	**19**	**26**	**31**	**34**	**35**
25	**4**	**9**	**15**	**24**	**28**	**30**	**32**
50	**2**	**3**	**10**	**22**	**26**	**28**	**29**
75	**1**	**1**	**5**	**10**	**14**	**16**	**17**
100	**0**	**0**	**1**	**4**	**5**	**6**	**7**
125	**0**	**0**	**1**	**2**	**2**	**3**	**3**
150	**0**	**0**	**0**	**1**	**2**	**2**	**3**
175	**0**	**0**	**0**	**0**	**1**	**2**	**2**
200	**0**	**0**	**0**	**0**	**0**	**1**	**2**

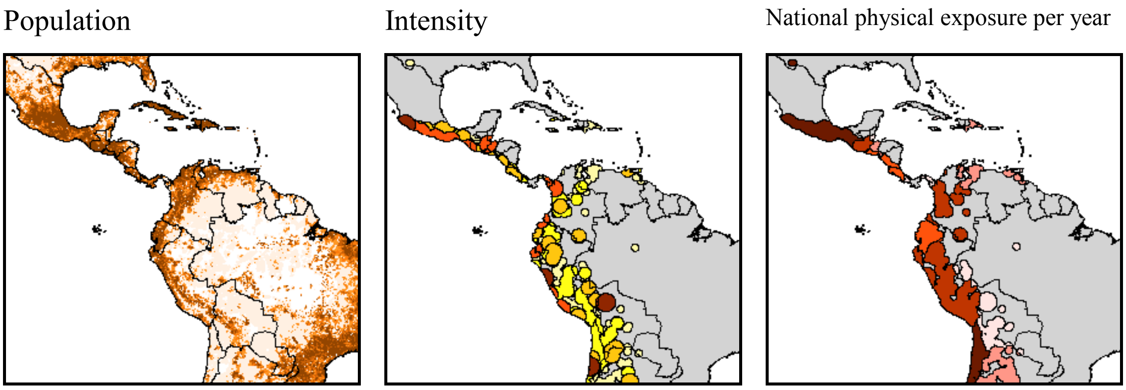
Acceleration > 0.05 g = ~ 0,49 m/s2, frequency > 2 Hz

Bracketed duration is “the elapsed time (for a particular acceleration and frequency range) between the first and last acceleration excursions on the record greater than a given amplitude level (for example, 0,05 g)” (Bolt, Horn, Macdonald and Scott, 1975).

According to these figures, a specific buffer distance was defined for each class of magnitude to limit area affected by ground motions: 75 km for Magnitude ≤ 6.2, 125 km for M = 6.3 – 6.7, 150 km for M = 6.8 – 7.2, 175 km for M = 7.3 – 7.7, 200 km for M ≥ 7.8. This is a general approach that does not take into account any regional effects, for instance soil conditions or geotectonic characteristics.

Physical exposure to earthquakes was calculated for each country and each magnitude class using the Equation 8 (p.18).

Figure 5: Population, intensity and physical exposure for earthquakes



Population

Intensity

National physical exposure per year

For the non-parametric statistical approach (event per event), a second task was needed in order to georeference the events recorded in the CRED database for the last tow decades (1980-2000). The events concerned were located in order to define socio-economic parameters for each of them. Geographic coordinates in decimal degrees of epicentres are available for about three hundred thirty events. Buffers were drawn around each point according to the same figures as these used to determine hazard zones.

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[6] Source: Bolt, Horn, Macdonald and Scott, 1975

4 STATISTICAL ANALYSIS

4.1 Introduction and methods used

Several methods have been tested in order to associate socio-economical variables with human vulnerability, namely linear regression model, non-parametric approach based on event per event analysis and finally multiplicative model (i.e. products and divisions of variables at different powers). The first two methods showed possible links with socio-economical parameters, however the correlations were weak. Finally the last method (logarithm regression of ratio) demonstrated the link with socio-economical context and allowed the identification of these parameters.

The non-parametric method

Although no relevant results could be derived from this attempt, some precision is included below to show what has been undertaken and also conclusions from the results.

In the case of the non-parametric model, for each event, a ratio between the sum of killed and the physical exposure was computed. This ratio was then introduced into a model to calculate the potential correlation with socio-economical variables. The overall process was probably too ambitious as there is a significant discrepancy of impacts assessed from two events in the same country. This variability has probably prevented the derivation of links between vulnerability and other variables. An event by event approach will request more precise data at a regional as opposed to national scale. The other conclusion that can be derived is that a non-parametric function (i.e. chain of additive polynoms with respective power) suppose the independence of the variable and cannot reflect the complexity of connected variable. For example a high urban growth alone may not be a problem, however the same urban growth combined with a low GDP per cap may present interesting relationship with vulnerability.

4.2 Multiplicative model

A first succinct attempt (Peduzzi, 2000) delineated that ratio of variables seemed to follow a multiplicative law. Products and ratios of variables allows the identification of combined effects, e.g. rapid urban growth and low GDP may lead to higher vulnerability, whereas the two factors taken individually can not be related to vulnerability.

The statistical analysis is based on two major hypotheses. Firstly, that the risk can be approached by the number of victims of past hazardous events. Secondly, that the equation of risk follows a multiplicative model as in Equation 10:

Equation 10: estimation of killed

$$K = C \cdot (PhExp)^{\alpha} \cdot V_1^{\alpha_1} \cdot V_2^{\alpha_2} \ldots \cdot V_p^{\alpha_p}$$

Where:

K = *Number of persons killed by a certain type of hazard.*

C = *Multiplicative constant.*

PhExp = *Physical Exposure: population living in exposed areas multiplied by the frequency of occurrence of the hazard.*

V_i = *Socio-economical parameters.*

α_i = *Exponent of* $V_{1,}$ *which can be negative (for ratio)*

Using the logarithmic properties, the equation could be written as follows:

Equation 12: logarithm properties

$$\ln(K) = \ln(C) + \alpha \ln(PhExp) = \alpha_1 \ln(V_1) + \alpha_2 \ln(V_2) + ... + \alpha_p \ln(V_p)$$

This equation provides a linear relation between logarithmic sets of values. Significant socio-economical parameters V_i (with transformations when appropriate) and exponents α_I can now be determined by the use of linear regressions.

4.3 Detailed process

Time period

The number of killed was derived from the CRED database, and computed as the average number of killed per year. The period taken in consideration was 1980-2000, this choice was made in order to compare period with approximately same access to information, following recommendations made in GRAVITY-I (Peduzzi, Dao, Herold, Rochette, 2001).

Selection of variables

All the variables used were normalised according to both size and population of countries. The variables that were either not reliable, incomplete or not available for a too large number of countries, were rejected.

Filtering the data

By intrinsic properties of logarithmic functions, the logarithm of zero cannot be computed. This forced to abandon the countries where physical exposure is null (which is anyway logical) but also the case where the number of killed is null (least vulnerable countries and least intensity) could not be incorporated into the model. This was not a problem for earthquakes, floods and cyclones, because it did not remove relevant data, however it reduced the number of country for volcanoes to nine countries.

In the model, extreme values and inappropriate cases where removed prior to calculation. This was based on three successive filters. Countries where physical exposure was known as being of mediocre resolution (e.g. the case of Kazakhstan for floods) were removed. Then countries where the exposed population is smaller to 2 percent of the total population were removed except for volcanoes where the threshold was lower due to the small size of the areas exposed. This was decided because socio-economical variables are collected at national scale. Attempts delineate that the exposed population needs to be of some significance at national level to reflect a relationship in the model. The last filter consists on eliminating the countries were no killed were reported for the period 1980-2000, for allowing the computation of the logarithm as previously explained.

Transformation of variables

The average of socio-economical parameters was computed for the twenty years period. For some of the indicators the logarithm was computed directly, for other parameters expressed in percentage, a transformation was applied in order that all variables are ranging between $-\infty$ and $+\infty$. This appeared to be relevant as some of the transformed variables were proved to be significant in the final result. For others no logarithmic transformation was needed, for instance the population growth already behaves in a cumulative way.

Equation 13: transformation for variables ranging between 0 and 1 (e.g. percentage)

$$\overline{V} = \frac{V_i}{(1 - V_i)}$$

Where:
V_i *= the socio-economical variable when expressed in percentage (or between a 0 to 1 scale)*

Choice between variables

One important condition, when computing regressions, is that the variables included in a model should be independent, i.e. the correlation between two sets of variables is low. This is clearly not the case of HDI and GDPcap purchasing power parity, which are highly correlated. GDPcap purchasing power parity was more used than HDI uniquely because HDI was not available for several countries. In order to keep the sample as complete as possible a choice of available variables had to be made. This choice has been performed by the use of both matrix-plot and correlation-matrix.

The stepwise approach

For each type of hazard, numerous stepwise (back and forth steps) linear regressions were performed in order to highlight significant variables. The validation of regression was carried out using R^2, variance analysis and detailed residual analysis.

Once the model was derived, the link between estimated killed and number of killed observed was provided by both graphical plots and computation of Pearson correlation coefficients in order to ease the visualisation of the efficiency by the readers (note: for the Pearson coefficient the closer to one, the better the relation).

If intuitively one can understand that physical exposure is positively related with the number of victims and that GDPcap is inversely related with the number of victims (the lowest the GDP the highest the victims), this is less obvious for other variables such as percentage of arable land for example. This method allows the estimation of the α_I coefficients. Their signs provide information on if the variables are in a numerator or denominator position.

This model allows the identification of parameters leading to higher/lower risk, but should not be used as a predictive model, because small differences in logarithm scale induce large ones in the number of killed.

The results following this method were surprisingly high and relevant, especially considering the independence of the data sources (no auto-correlation suspected) and the coarse resolution of the data at global scale.

5 RESULTS

5.1 Windstorms

Statistical analysis

The parameters highlighted show that besides the physical exposure, HDI and the percentage of arable land are selected indicators for vulnerability to cyclone hazard.

The percentage of arable land is probably an indirect way of measuring the dependency of a population from the agricultural activity. According to the analysis, a stronger dependence to agriculture is inducing a higher vulnerability. Although this was already mentioned by experts, it is now confirmed by statistical evidences. After a cyclone, economies relying on third sector are less affected than economy relying on agriculture, fields being devastated. The GDPcap is strongly correlated with the HDI or negatively with the percentage of urban growth. In most of the cases the variable GDPcap could be replaced by HDI as explain previously (see p.24). However, these results depict with confidence that poor countries and less developed in terms of HDI are more vulnerable to cyclones.

With a considerable part of variance explained by the regression ($R^2 = 0.863$) and a high degree of confidence in the selected variables (very small p-value) over a sample of 33 countries, the model achieved is solid.

In the model, the consequences of Mitch could easily be depicted. Indeed, Honduras and Nicaragua were far off the regression line (significantly underestimated). This is explained by the incredible difference of intensity of Mitch and other hurricanes. Mitch is a type of hazards on its own, the difference of intensity made this event impossible to compare with the other hurricanes.

Statistical model

Equation 14 cyclones multiple logarithmic regression model for cyclones

$$\ln(K) = 0.63\ln(PhExp) + 0.66\ln(\overline{Pal}) - 2.03\ln(\overline{HDI}) - 15.86$$

Where:
K is the number of killed
PhExp is the physical exposure to cyclones

$\overline{Pal}$ is the transformed value of percentage of arable land

$\overline{HDI}$ is the transformed value of the Human Development Index

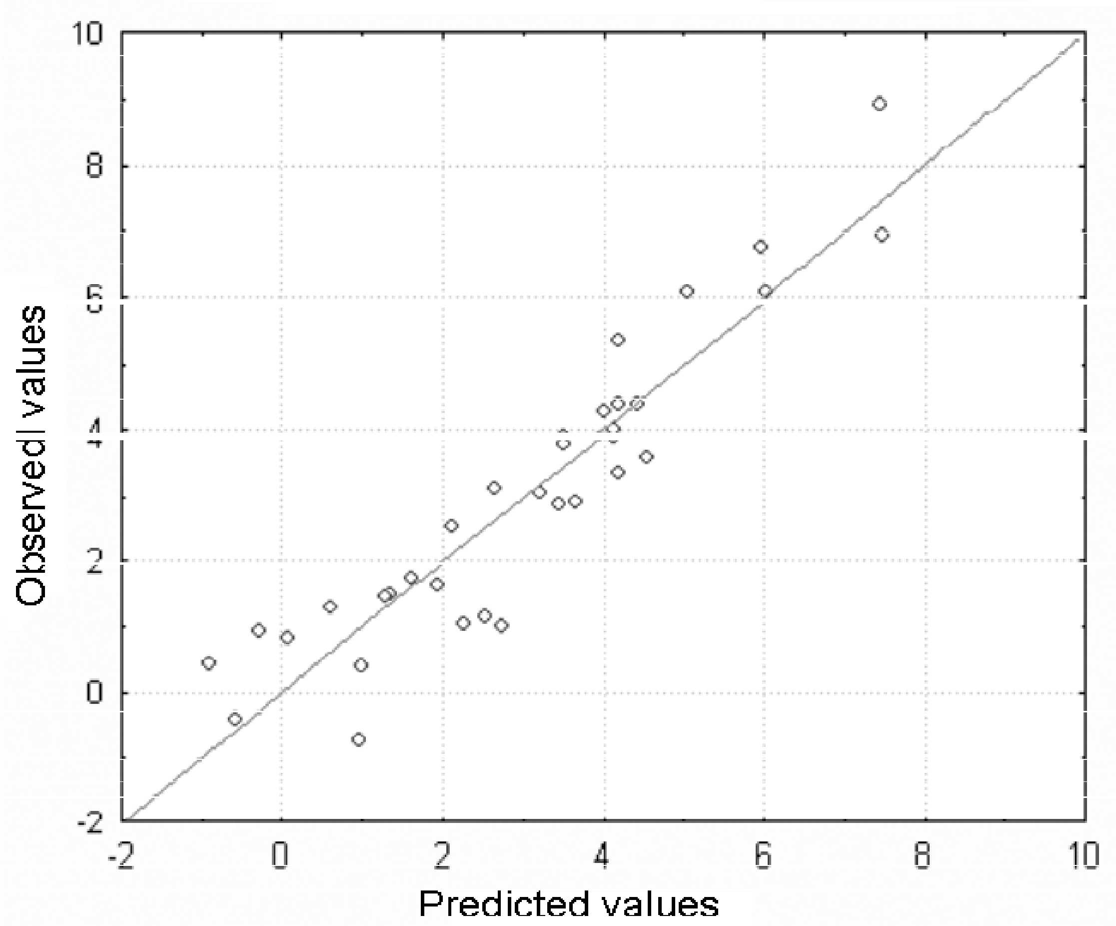
Table 10: Exponent and p-value for cyclones multiple regression

33 countries	B	p-value[7]
Intercept	-15.86	0.00000
ln(PhExp)	0.63	0.00000
$\ln(\overline{Pal})$	0.66	0.00013
$\ln(\overline{HDI})$	-2.03	0.00095

R= 0.93, R^2= 0.86, adjusted R^2= 0.85

The plot delineates a nice linear distribution of the data as seen in Figure 6:

Figure 6: Scatter plots of predicted vs observed casualties from cyclones



Improving physical exposure

The modelling of buffers around cyclone tracks has improved the evaluation of physical exposure as compared with the 5 x 5 degrees cells from CDIAC. However, since the tracks, central pressure and sustained wind could not be accessed for India, Bangladesh and Pakistan, the CDIAC was still used in the model for comparison. So far only 11 years of buffer were available at GRID-

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[7] In broad terms, a p-value smaller than 0.05, shows the significance of the selected indicator, however this should not be used blindly.

Geneva, however, automated methods have been designed and should allow much quicker way of designing cyclones buffers.

Completeness of the records for the world should be achieved. The mathematical model itself could be improved with an asymmetrical computation of wind, since the cyclones are turning, the right-hand side (in the northern hemisphere) is developing higher wind than the left hand-side, where the movement in the trajectory direction reduces the speed of the wind. This could be easily introduce in the model, however the level achieved proved to be already appropriate and correspond to on-ground observations of affected population. Links with CRED database can easily be performed using the name and the year of the cyclones. The CRED database could then be georeferenced and number of killed can be compared with population affected.

5.2 Floods

Statistical analysis

The variables selected by the statistical analysis are physical exposure, GDPcap and local density of population. Once again, GDPcap being highly correlated with HDI, this later could have been chosen as well. The GDPcap was chosen due to slightly better correlation between the model and the observed killed, as well as because of lower p-value. Regression analysis supposes the introduction of non-correlated parameters, thus preventing the use of all these variables.

Without surprise, the regression proves that highly exposed and poorer populations are more subject to suffer casualties from floods. More surprisingly, it shows that countries with low population density are more vulnerable than countries with high population density. Could this be due to higher level of organisation in denser area, or due to help from each other? This is left open. The part of explained variance ($R^2 = 0.70$) associated with significant p-value (between 10^{-23} and $2 \cdot 10^{-3}$) on 90 countries is confirming a solid confidence in the selection of the variables (see Table 11).

Statistical model

Equation 15 Flood multiple logarithmic regression model for floods

$$\ln(K) = 0.78\ln(PhExp) - 0.45\ln(GDP_{cap}) - 0.15\ln(D) - 5.22$$

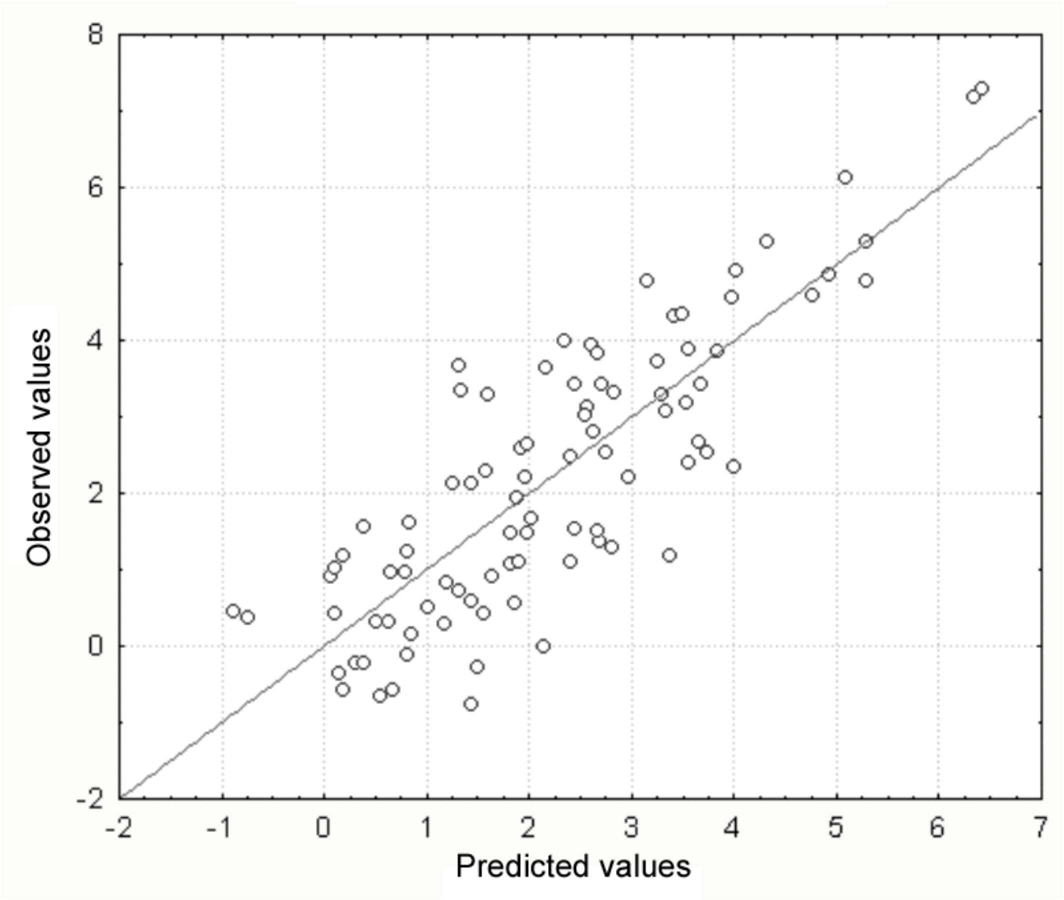
Where:
K is the number of killed
PhExp is the physical exposure to floods
GDP_{cap} is the normalised Gross Domestic Product per capita (purchasing power parity)
D is the local population density (i.e. the population affected divided by the area affected)

Table 11: Exponent and p-value for flood indicators

90 countries	B	p-value (7)
Intercept	-5.22	0.00000
ln(PhExp)	0.78	0.00000
ln(GDPcap)	-0.45	0.00002
ln(Density)	-0.15	0.00321

R= 0.84, R^2= 0.70, adjusted R^2= 0.69

Figure 7. Predicted versus observed casualties for floods



Improving physical exposure

Improvement of physical exposure for flood is needed, so far the limit of the watershed was taken in absence of a world database. The watersheds limits were derived initially from USGS elevation model with a low spatial resolution (30’’ cell). More precise data set for elevation (30m and 90m spatial resolution) will be available, probably by 2004. This should help to design better area at risk.

5.3 Volcanic eruptions

Statistical analysis

Although a correlation between the logarithm of the killed and the logarithm of the physical exposure divided by the GDPcap, was high, the model is considered as the worst evaluation. In fact this research delineates the impossibility of modelling physical exposure and vulnerability to volcanic eruption at global scale. If danger maps can be derived for a single volcano at local scale, the variability of the volcanic manifestations is far too complex to be generalised at a global scale.

In chapter 2.3, p.11, some cautions were discussed on the use of small areas and extraction of population, cautions should be taken with areas smaller than 100 pixels.

Another reason preventing a good appreciation of the risk results in the inversion of the frequency role: the less frequent the more dangerous. Indeed the larger impacts are resulting from volcanoes with low historical activity. The habitants of these areas are living in a false confidence. The examples of the three highest human losses from volcanic eruption since 1980 are all resulting from low frequency of eruption or even unknown historical eruptions. Indeed, the volcano *Ruiz*

(Colombia, 1985) which melting of its summit icecap provoked the South America's deadliest eruption (22’800 killed) had a large eruption in 1595 and smaller in 1828, 1829 and then has only been reported smoking in 1831, 1833 (Herd, 1982). Same situation with *Pinatubo* (Philippines, 1991) “*Prior to 1991 Pinatubo volcano was a relatively unknown, heavily forested lava dome complex with no records of historical eruptions*.” (Global Volcanism Program, Smithsonian Institution, 2001). And similar with the lake Monoun (Cameroun, 1986) “*No previous eruptions are known from Lake Monoun”* (Le Marechal, 1975a). These disasters demonstrated that low frequency does not mean low risk, this is completely different as for the other hazards.

The varieties of the volcanic phenomena are very complex to reflect. The following example demonstrates the impossibility for deriving physical exposure. In 1992, nine people died from a moderate *Galeras* volcanic eruption (Colombia). They were volcanologists in a workshop field trip: this can not be related to physical exposure! In 1984, the *Oku* volcanic field (Cameroon) released poisonous gas killing 34 people. Two years later, the socio-economical context has not changed, however 1746 persons died as a result of a 100m hight clouds of CO_2 gas. The direction of wind may even have played a significant role! In these conditions, trying to approach frequency, intensity and physical exposure for volcanoes at a global scale seems a very difficult mission if not impossible.

After these discoveries, no model is provided for cyclones.

Improving physical exposure

Improving physical exposure would request a volcano per volcano approach. Indeed the volcanic manifestations are numerous and complex, ranging from lahars (linked with precipitation level, seismicity, topography, soils characteristics,…), tephra falls (depending from wind direction and strenght), phreatomagmatic eruption,… . However, numerous experts are working on surveying these activities and each volcano is well described.

Data requested are probably existing. Finer resolution for elevation is a must, for showing shape and relief of volcanoes, computing slopes and lahars danger. Remote sensing analysis for local assessment of danger and population distribution would also be requested. Numerous maps of volcanoes can be found at http://www.nmnh.si.edu/gvp/volcano/index.htm.

5.4 Earthquakes

Statistical analysis

The variables retained by the regression include the physical exposure and the rate of urban growth. The part of explained variance is smaller than for flood or cyclones ($R^2=0.544$), however considering the small length of time taken into account (21 years as compared to earthquakes long return period), the analysis delineates a reasonably good relation. The physical exposure is of similar relevance than for previous cases, relevant p-value. The urban growth was expected to be select as indicators. A high rate of population moving into a city is usually synonym of low quality urban planning and building standard. The urban growth is also highly negatively correlated with GDP and HDI. Thus, similar correlation (but slightly inferior) could have been derived using HDI or GDP.

Statistical model

The closest regression model is as follows the

Equation 16 Earthquake multiple logarithmic regression model

$$\ln(K) = 1.26\ln(PhExp) + 12{,}27 \cdot U_g - 16.22$$

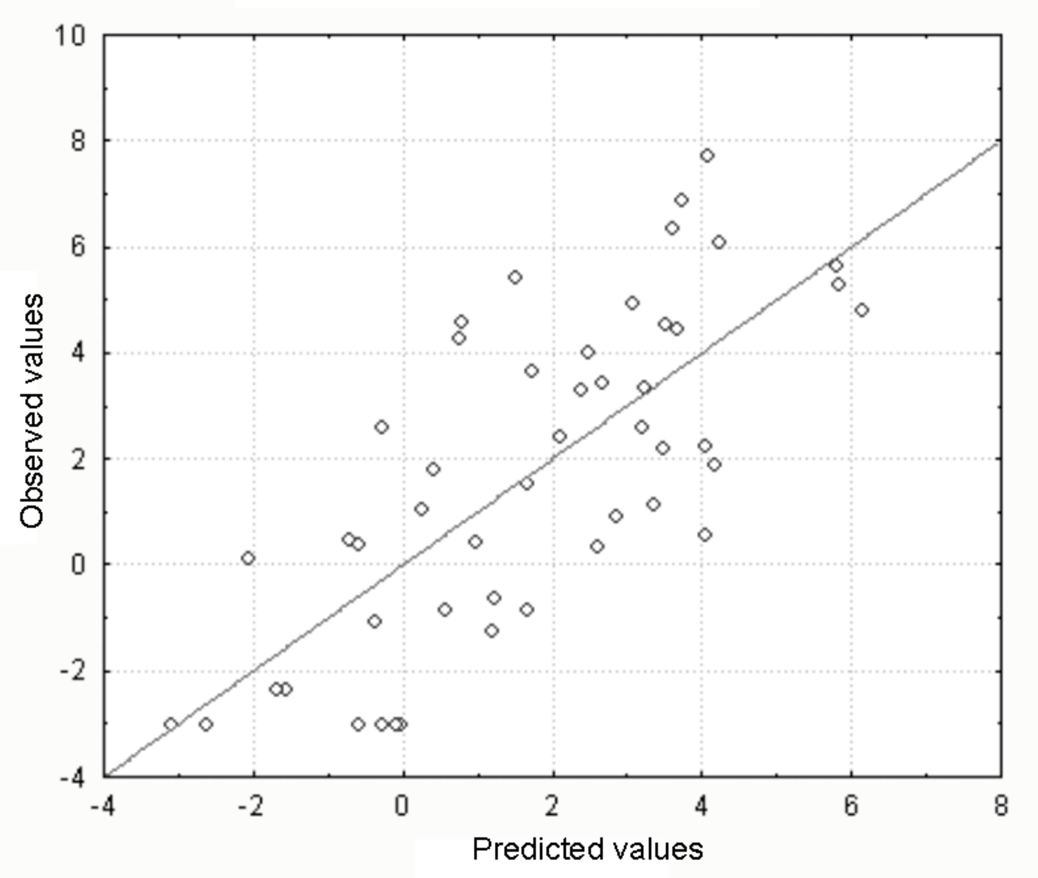
Where:
K is the number of killed from earthquakes
U_g is the rate of urban growth (rates do not request transformation as it is already a cumulative value)

Table 12: Exponent and p-value for earthquake multiple regression

48 countries	B	p- value (7)
Intercept	-16.22	0.000000
PhExp	1.26	0.000000
Ug	12.27	0.047686

R= 0.75, R^2= 0.56, adjusted R^2= 0.54

Figure 8: Modelled and observed victims for earthquakes



Logarithmic scale

Improving physical exposure

Orientation of fault lines and the implementation of type of soils should be the next steps to achieve. Soils at global scale are probably not available, however by concentrating on the areas concerns a collection of national soils may be available and digitised. The orientation of the fault would allow an improved accuracy.

5.5 The total risk computation

The physical exposure to a type of hazard cannot be auditioned with the physical exposure to another hazard. However, the number of killed is a standardised value that is comparable from one hazard to the next.

Equation 17 Sum of the risk for flood, cyclone & earthquake

$$K = PhExp_{Cyclones}^{0.63} \cdot \overline{Pal}^{0.66} \cdot \overline{HDI}^{-2.03} \cdot e^{-15.86} + PhExp_{floods}^{0.78} \cdot GDP_{cap}^{-0.45} \cdot D^{-0.15} \cdot e^{-5.22}$$
$$+ PhExp_{earthquakes}^{1.26} \cdot e^{12.27 \cdot U_g} \cdot e^{-16.22}$$

<u>Where:</u>
e is the Euler constant (=2.718…)

5.6 *Tables*

The tables (as well as other documents) can be download or open see Appendixes, p.56

Cyclones

Table 13: Physical exposure to cyclones (12 first countries)

Countries	Event / year	Killed /year	Killed /mio	Physical Exposure	Local Population	Local Density	Vul.	GDP cap	HDI
China	6.90	428	0.37	606788434	727892455	292.11	0.0007	1741	0.63
India	2.76	1023	1.24	396374185	507634334	297.20	0.0029	1424	0.51
Philippines	5.57	863	14.35	294510768	72644008	245.62	0.0033	3191	0.71
Japan	1.95	39	0.32	230917154	129004939	346.19	0.0002	18629	0.90
Bangladesh	3.43	7468	64.02	143946614	105294580	914.13	0.0550	1014	0.41
USA	12.14	223	0.86	92481610	186302424	59.558	0.0025	22494	0.91
Viet Nam	2.24	435	6.40	83045674	73034173	223.62	0.0056	1427	0.63
Mexico	1.57	81	0.93	68154551	88704629	47.049	0.0012	6453	0.76
Republic of Korea	1.00	72	1.67	39490682	44498774	454.28	0.0019	9243	0.81
Cuba	0.52	2	0.21	14508511	12644580	114.76	0.0002	---	---
Thailand	0.71	30	0.54	13412418	58840279	114.34	0.0024	3952	0.71
Dem.People's Rep. Korea	0.10	2	0.11	13114779	23669895	193.76	0.0002	---	---

Table 14: Vulnerability to cyclones (12 first countries hit more than twice in 21 years)

Countries	Events /year	Killed /year	Killed / mio	Physical Exposure	Local Population	Local Density	Vul.	GDP cap	HDI
Honduras	0.19	702.29	139.65	2444037	5185852	46	0.3214	2043	0.61
Nicaragua	0.33	162.57	37.40	818845	4513746	35	0.2021	2146	0.60
Bangladesh	3.43	7467.62	64.02	143946614	105294580	914	0.0550	1014	0.41
Solomon Islands	0.19	5.00	17.39	119899	345728	12	0.0547	1730	---
El Salvador	0.19	23.43	3.90	800806	5588607	270	0.0276	3159	0.64
Saint Lucia	0.33	2.76	21.74	115820	148868	233	0.0262	3904	---
Comoros	0.19	2.81	5.97	178171	520970	301	0.0204	1215	0.50
Vanuatu	0.57	4.52	29.52	312062	160465	13	0.0163	2798	---
Haiti	0.29	81.24	11.63	6752914	7413061	271	0.0130	1449	0.45
South Africa	0.43	6.05	0.16	513245	8206874	55	0.0126	7699	0.70
Pakistan	0.62	53.90	0.46	4997076	36819713	86	0.0115	1308	0.44
Saint Kitts and Nevis	0.29	0.29	6.96	37262	29881	101	0.0075	6753	---

Table 15: Main casualties in the last 21 years (Killed per year as in CRED) for cyclones

Countries	Events /year	Killed /year	Killed /mio	Physical Exposure	Local Population	Local Density	Vul.	GDP cap	HDI
Bangladesh	3.43	7467.62	64.02	143946614	105294580	914	0.0550	1014	0.41
India	2.76	1022.52	1.24	396374185	507634334	297	0.0029	1424	0.51
Philippines	5.57	863.19	14.35	294510768	72644008	246	0.0033	3191	0.71
Honduras	0.19	702.29	139.65	2444037	5185852	46	0.3214	2043	0.61
Viet Nam	2.24	435.24	6.40	83045674	73034173	224	0.0056	1427	0.63
China	6.90	428.38	0.37	606788434	727892455	292	0.0007	1741	0.63
USA	12.14	222.86	0.86	92481610	186302424	60	0.0025	22494	0.91
Nicaragua	0.33	162.57	37.40	818845	4513746	35	0.2021	2146	0.60
Haiti	0.29	81.24	11.63	6752914	7413061	271	0.0130	1449	0.45
Mexico	1.57	80.76	0.93	68154551	88704629	47	0.0012	6453	0.76
Republic of Korea	1.00	71.52	1.67	39490682	44498774	454	0.0019	9243	0.81
Pakistan	0.62	53.90	0.46	4997076	36819713	86	0.0115	1308	0.44

Table 16: Main casualties in the last 21 years (Killed per million as in CRED) for Cyclones

Countries	Events /year	Killed /year	Killed /mio	Physical Exposure	Local Population	Local Density	Vul.	GDP cap	HDI
Honduras	0.19	702.29	139.65	2444037	5185852	46	0.3214	2043	0.61
Cook Islands	0.19	1.19	65.09	---	---	---	---	---	---
Bangladesh	3.43	7467.62	64.02	143946614	105294580	914	0.0550	1014	0.41
Montserrat	0.10	0.52	48.73	13013	10435	90	0.0383	---	---
Nicaragua	0.33	162.57	37.40	818845	4513746	35	0.2021	2146	0.60
Vanuatu	0.57	4.52	29.52	312062	160465	13	0.0163	2798	---
American Samoa	0.14	1.19	25.21	---	---	---	---	---	---
Saint Lucia	0.33	2.76	21.74	115820	148868	233	0.0262	3904	---
Solomon Islands	0.19	5.00	17.39	119899	345728	12	0.0547	1730	---
Philippines	5.57	863.19	14.35	294510768	72644008	246	0.0033	3191	0.71
Haiti	0.29	81.24	11.63	6752914	7413061	271	0.0130	1449	0.45
Fiji	0.67	5.71	7.99	1087136	728643	38	0.0056	3721	0.72

Where:

*Killed /mio is the number of killed per million of inhabitant, Vul. is the vulnerability proxy (1000*killed/physical exposure), GDPcap is the Gross Domestic product per cap, at purchasing power parity, HDI is the Human Development Index, --- is indicated when no data are available.*

Floods

Table 17: Physical exposure to floods (12 first countries)

Countries	Events / year	Killed / year	Killed per mio	Physical Exp.	Local dens.	Vul.	GDP cap	HDI
India	3.86	1313	1.55	172196062	0.58	0.0083	1424	0.51
China	5.57	1491	1.32	160016017	0.14	0.0101	1741	0.63
Bangladesh	2.00	462	4.11	57098623	19.93	0.0089	1014	0.41
Indonesia	2.48	120	0.67	54120818	0.55	0.0024	1964	0.62
Pakistan	0.95	200	1.77	53129603	1.86	0.0041	1308	0.44
Afghanistan	0.76	421	24.63	43114583	9.02	0.0109	---	---
Iran	1.90	131	2.20	42363026	0.26	0.0034	3932	0.64
Myanmar	0.29	9	0.20	39762558	2.12	0.0002	---	0.55
Brazil	2.19	99	0.67	31560587	0.06	0.0034	5623	0.71
Nepal	0.90	199	10.92	19207890	13.00	0.0116	927	0.41
Peru	1.10	98	4.56	14375859	0.49	0.0075	3843	0.71
USA	3.48	24.19	0.09	12266267	0.03	0.0020	22494	0.91

Table 18: Vulnerability to floods (12 first countries)

Countries	Event / year	Killed / year	Killed per mio	Physic. Exp.	Loc Density	Vul.	GDP cap	HDI
Venezuela	0.67	1439.62	68.30	3250723	0.26	0.46	5082	0.75
Mongolia	0.10	1.38	0.57	4498	0.01	0.31	1461	0.55
Somalia	0.52	117.62	15.38	666024	0.11	0.17	---	---
Morocco	0.33	39.62	1.40	381432	0.95	0.10	2650	0.54
Djibouti	0.19	8.57	18.26	105675	6.01	0.09	---	0.45
PNG*	0.24	2.76	0.73	41801	0.04	0.07	1898	0.49
Egypt	0.14	28.95	0.48	419136	1.44	0.07	2287	0.57
Botswana	0.14	1.48	1.07	24102	0.06	0.06	4734	0.61
Yemen	0.52	46.71	3.65	1093607	0.48	0.05	746	0.44
Puerto Rico	0.10	24.67	7.07	588558	444	0.05	---	---
Zimbabwe	0.10	5.05	0.41	138965	0.3	0.03	2158	0.58
Fiji	0.14	1.57	2.10	51256	17	0.03	3721	0.72

*PNG: Papua New Guinea

Table 19: Main casualties in the last 21 years (Killed per year as in CRED) for floods

Countries	Events / year	killed / year	Killed / mio	Physical Exposure	Local dens.	Vul.	GDP cap	HDI
China	5.57	1491	1.32	160016017	0.14	0.01	1741	0.63
Venezuela	0.67	1440	68.30	3250723	0.26	0.46	5082	0.75
India	3.86	1313	1.55	172196062	0.58	0.01	1424	0.51
Bangladesh	2.00	462	4.11	57098623	19.93	0.01	1014	0.41
Afghanistan	0.76	421	24.63	43114583	9.02	0.01	---	---
Pakistan	0.95	200	1.77	53129603	1.86	0.00	1308	0.44
Nepal	0.90	199	10.92	19207890	13.00	0.01	927	0.41
Viet Nam	1.00	138	1.98	11392179	2.63	0.01	1427	0.63
Iran	1.90	131	2.20	42363026	0.26	0.00	3932	0.64
Mexico	1.10	121	1.41	5239974	0.17	0.02	6453	0.76
Indonesia	2.48	120	0.67	54120818	0.55	0.00	1964	0.62
Somalia	0.52	118	15.38	666024	0.11	0.17	---	---

Table 20: Main casualties in the last 21 years (Killed per million as in CRED) for floods

Countries	Events / year	killed / year	Killed / mio	Physical Exposure	Local dens.	Vul.	GDP cap	HDI
Venezuela	0.67	1439.62	68.30	3250723	0.26	0.46	5082	0.75
Afghanistan	0.76	420.57	24.63	43114583	9.02	0.01	---	---
Djibouti	0.19	8.57	18.26	105675	6.01	0.09	---	0.45
Somalia	0.52	117.62	15.38	666024	0.11	0.17	---	---
Tajikistan	0.33	68.33	11.80	44585800	166.05	0.00	---	0.66
Nepal	0.90	199.38	10.92	19207890	13.00	0.01	927	0.41
Puerto Rico	0.10	24.67	7.07	588558	444.02	0.04	---	---
Honduras	0.62	30.62	6.09	1972746	2.50	0.02	2043	0.61
Bhutan	0.10	10.57	5.44	8043383	63.42	0.00	336	0.48
El Salvador	0.33	26.76	4.92	1292771	29.00	0.02	3159	0.64
Peru	1.10	97.62	4.56	14375859	0.49	0.01	3843	0.71
Bangladesh	2.00	461.95	4.11	57098623	19.93	0.01	1014	0.41

Earthquakes

Table 21: Physical exposure to earthquakes (12 first countries)

Countries	Ph.Exp Norm.	Events / year	Killed / year	Local Population	Loc. Dens.	Vul.	GDP cap	HDI	Urb_Pc	Urban growth
Japan	30855862	1.14	281	116163536	344	0.009	18629	0.90	77.4	0.02
Indonesia	16301764	1.62	193	129011824	144	0.012	1964	0.62	30.4	0.15
Philippines	16228511	0.57	121	64754752	261	0.007	3191	0.71	49.4	0.14
Taiwan	9838800	0.14	108	20744528	572	0.011	---	N.D	N.D	N.D
USA	6745799	0.48	7	31235092	34	0.001	22494	0.91	74.1	0.04
Chile	4465047	0.24	9	13055402	29	0.002	5512	0.78	83.4	0.06
Mexico	4145529	0.76	427	28866146	65	0.103	6453	0.76	71.4	0.08
China	3493705	2.10	92	49157624	34	0.026	1741	0.63	26.3	0.13
Turkey	2745757	0.76	950	35375608	108	0.346	4681	0.68	60.2	0.15
India	2730309	0.67	577	55151316	176	0.211	1424	0.51	25.5	0.09
Guatemala	2671752	0.24	2	7747307	131	0.001	2885	0.58	38.3	0.10
Colombia	2663322	0.48	85	17799402	56	0.032	4625	0.72	69.3	0.09

Table 22: Vulnerability to Earthquakes (Armenia + 12 first countries)

Countries	Vul.	Events / year	Killed /year	PhExp Norm.	Local Pop.	Local Dens.	GDP cap	HDI	%age Urban	Urban Growth
(Armenia)	7.65	0.05	1190	155560	1674592	152	1822	0.75	69.4	0.03
Iran	1.07	1.43	2251	2094097	22731674	38	3932	0.64	54.1	0.15
Yemen	0.76	0.10	72	95423	2850740	161	746	0.44	23.2	0.24
Turkey	0.35	0.76	950	2745757	35375608	108	4681	0.68	60.2	0.15
Afghanistan	0.23	0.81	399	1749097	10468002	59	---	---	20.9	0.13
India	0.21	0.67	577	2730309	55151316	176	1424	0.51	25.5	0.09
Italy	0.18	0.52	226	1288265	18614814	182	16619	0.88	66.6	0.00
Russian Fed.	0.14	0.29	95	658876	5101117	10	8179	0.80	73.9	0.03
Algeria	0.11	0.38	137	1252109	15727568	159	4394	0.63	52.1	0.14
Mexico	0.10	0.76	427	4145529	28866146	65	6453	0.76	71.4	0.08
Nepal	0.08	0.10	39	512716	10146623	132	927	0.41	9.1	0.19
Georgia	0.05	0.14	13	286210	2453636	75	2353	0.74	57.4	0.04
El Salvador	0.04	0.10	53	1272919	5588607	270	3159	0.64	44.0	0.07

Table 23: Main casualties in the last 21 years (Killed per year as in CRED) for Earthquakes

Countries	Killed / year	Events /year	Physical Exp.	Pop. Loc	Density Loc.	Vul.	GDP cap	HDI	Urban Growth
Iran	2251	1.43	2094097	22731674	37.81	1.07	3932	0.6	0.15
Armenia	1190	0.05	155560	1674592	152.35	7.65	1822	0.7	0.03
Turkey	950	0.76	2745757	35375608	108.18	0.35	4681	0.6	0.15
India	577	0.67	2730309	55151316	175.88	0.21	1424	0.5	0.09
Mexico	427	0.76	4145529	28866146	64.69	0.10	6453	0.7	0.08
Afghanistan	399	0.81	1749097	10468002	59.29	0.23	---	--	0.13
Japan	281	1.14	30855862	116163536	343.82	0.01	18629	0.9	0.02
Italy	226	0.52	1288265	18614814	181.52	0.18	16619	0.8	0.00
Indonesia	193	1.62	16301764	129011824	143.92	0.01	1964	0.6	0.15
Algeria	137	0.38	1252109	15727568	159.47	0.11	4394	0.6	0.14
Philippines	121	0.57	16228511	64754752	260.78	0.01	3191	0.7	0.14
Taiwan	108	0.14	9838800	20744528	572.30	0.01	---	--	---

Table 24: Main casualties in the last 21 years (Killed per million per year) for Earthquakes

Country	Event /year	Killed /year	Killed /mio	Physical Exp.	Pop. loc	Local Dens.	Vul.	GDP cap	HDI	Urban Gr.
(Armenia)	0.05	1190	343.96	168993	1674592	152	7.6528	1822	0.75	0.03
Iran	1.43	2251	38.68	2326029	22731674	38	1.0748	3932	0.64	0.15
Afghanistan	0.81	399	24.82	2075759	10468002	59	0.2281	---	---	0.13
Turkey	0.76	950	15.58	2769410	35375608	108	0.3459	4681	0.68	0.15
El Salvador	0.10	53	11.23	1520363	5588607	270	0.0419	3159	0.64	0.07
Yemen	0.10	72	6.90	135750	2850740	161	0.7575	746	0.44	0.24
Algeria	0.38	137	5.79	1460969	15727568	159	0.1096	4394	0.63	0.14
Mexico	0.76	427	5.05	4468647	28866146	65	0.1031	6453	0.76	0.08
Taiwan	0.14	108	5.03	9853074	20744528	572	0.0110	---	---	---
Italy	0.52	226	3.98	1302702	18614814	182	0.1752	16619	0.88	0.00
Vanuatu	0.33	1	3.74	267395	160465	13	0.0024	2798	---	0.10
Ecuador	0.43	28	2.75	1715161	10999371	48	0.0184	2695	0.70	0.12
Tajikistan	0.24	15	2.74	176643	2151935	25	0.0891	---	0.66	0.04

5.7 *Maps*

Method of classification

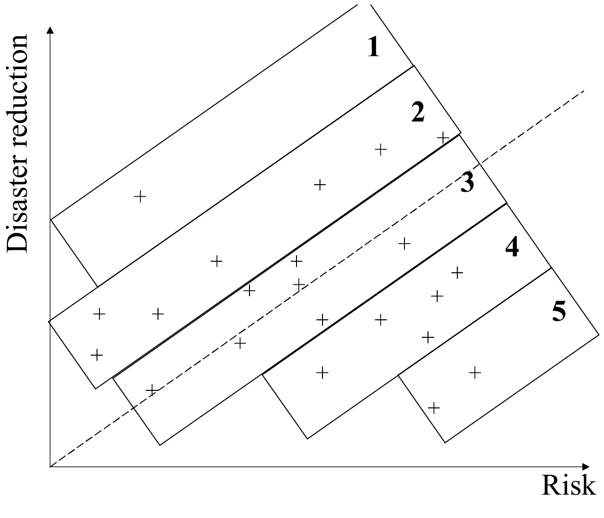
The number of classes and method for classifying the maps were chosen according to several criteria such as the precision of the data, the number and weight of error the correlation between model and observed values. According to this tests the number of five classes based on an equal interval subdivision method, was minimising the error weights and optimising the representation.

Categories

The precision and quality of the data does not allow the ranking of countries. However, for the risk component, results indicate a possibility to provide five classes of countries. A subjective – political – choice has to be made in order to choose from the different possibilities of computing risk (i.e. killed, killed per million inhabitant,…) such decision belongs to UNDP. The UNDP aims to provide categories of countries taking into account both risk and disaster reduction measures. A research conducted in parallel from GRAVITY is assessing how disaster reduction (prevention and mitigation) can be measured for the different countries. When such component will be provided, various method of classification can be tested to reflect both risk and disaster reduction at country level.

The method including minimum intern distance and maximum group distance is one of them. This requires that the number of classes to be chosen. This decision should also be taken by UNDP according to the precision of the two components. The Figure 9 provides an example on how countries could be categorised. It is relevant for countries facing less risk to take fewer measures for disaster reduction, however the level of measures should rise according with the level of risk.

Figure 9 Example of categories between disaster reduction and risk



Categories of ratio between disaster reduction and risk level.

Class 1: Good

Class 2: sufficient

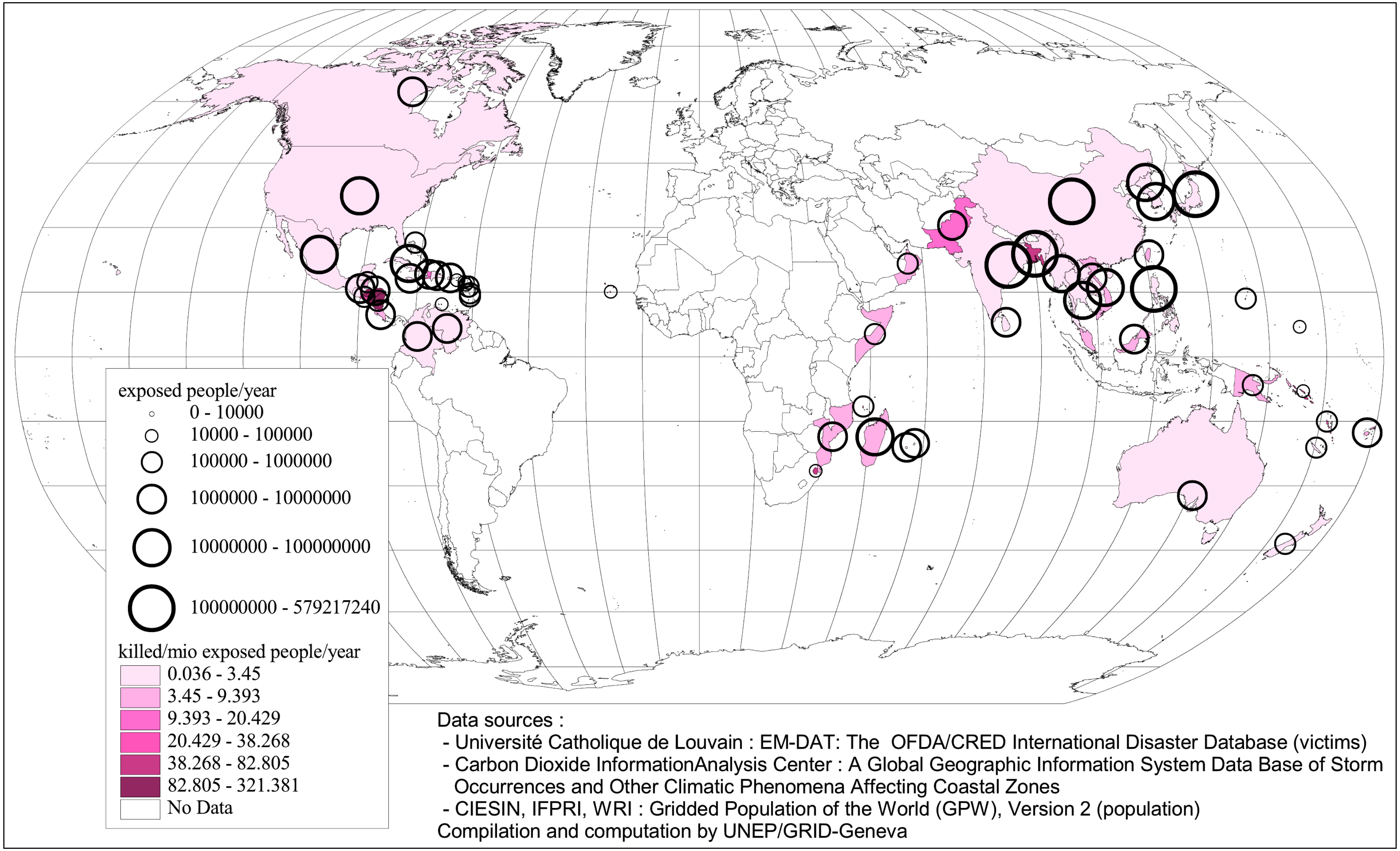
Class 3: at the limit

Class 4: insufficient

Class 5: bad

The following maps depict distribution of physical exposure, vulnerability (computed as killed divided by physical exposure) and risk. A map resuming the three types of risks is also provided.

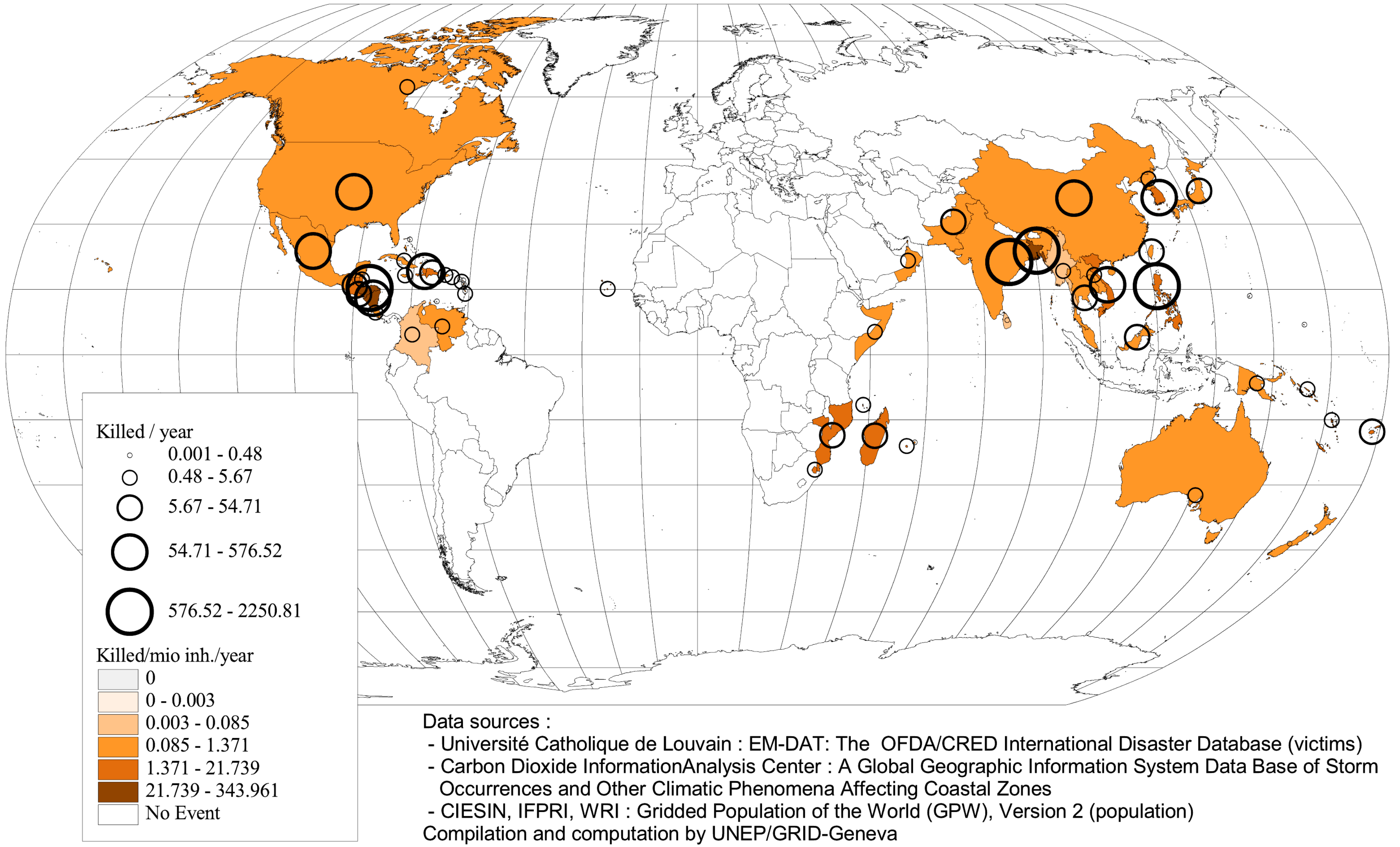
Figure 10: Map of Vulnerability and Physical Exposure to Cyclones



Data sources :
- Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (victims)
- Carbon Dioxide InformationAnalysis Center : A Global Geographic Information System Data Base of Storm Occurrences and Other Climatic Phenomena Affecting Coastal Zones
- CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2 (population)

Compilation and computation by UNEP/GRID-Geneva

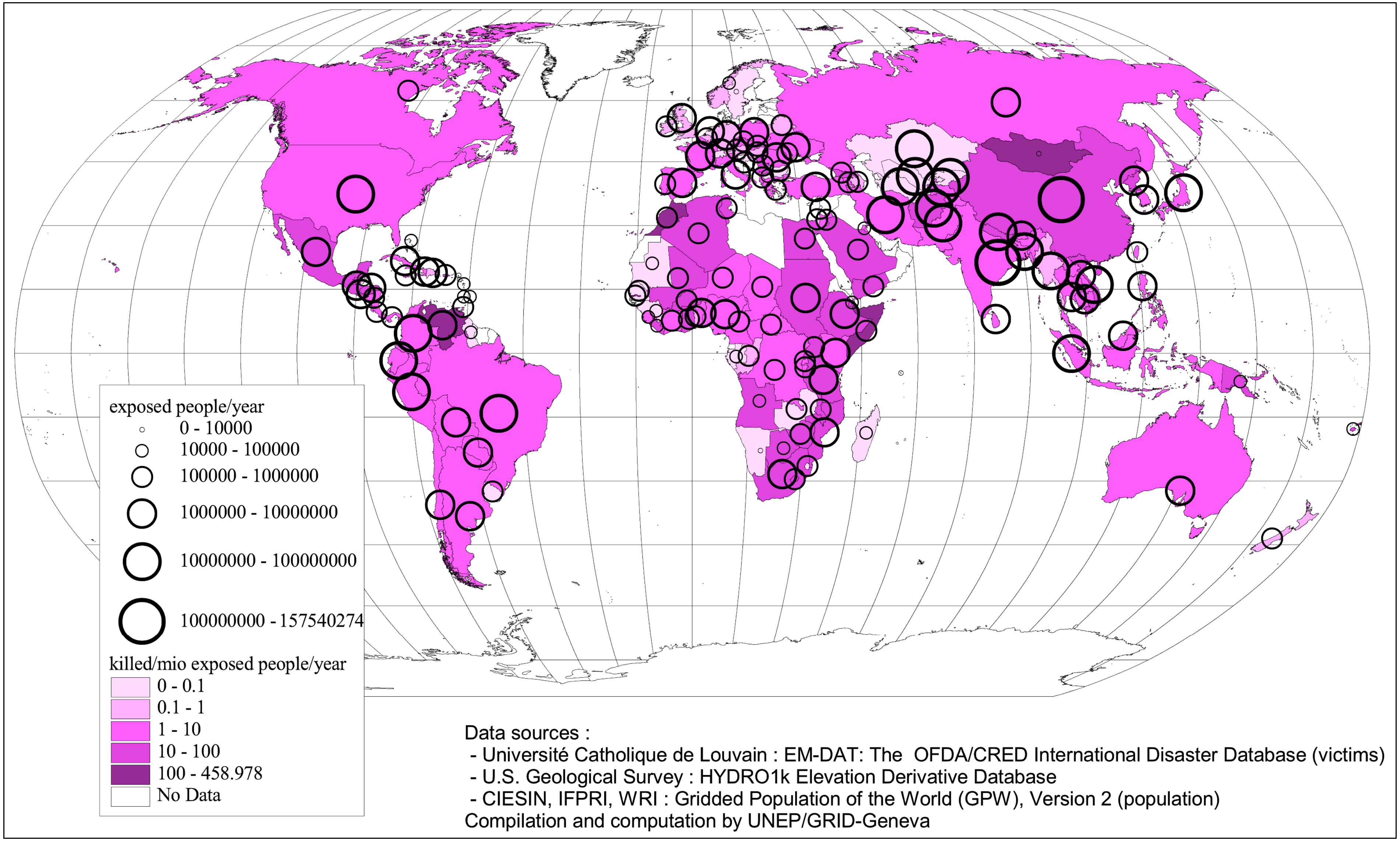
Figure 11: Map of Risk to Cyclones



Data sources :
- Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (victims)
- Carbon Dioxide InformationAnalysis Center : A Global Geographic Information System Data Base of Storm Occurrences and Other Climatic Phenomena Affecting Coastal Zones
- CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2 (population)

Compilation and computation by UNEP/GRID-Geneva

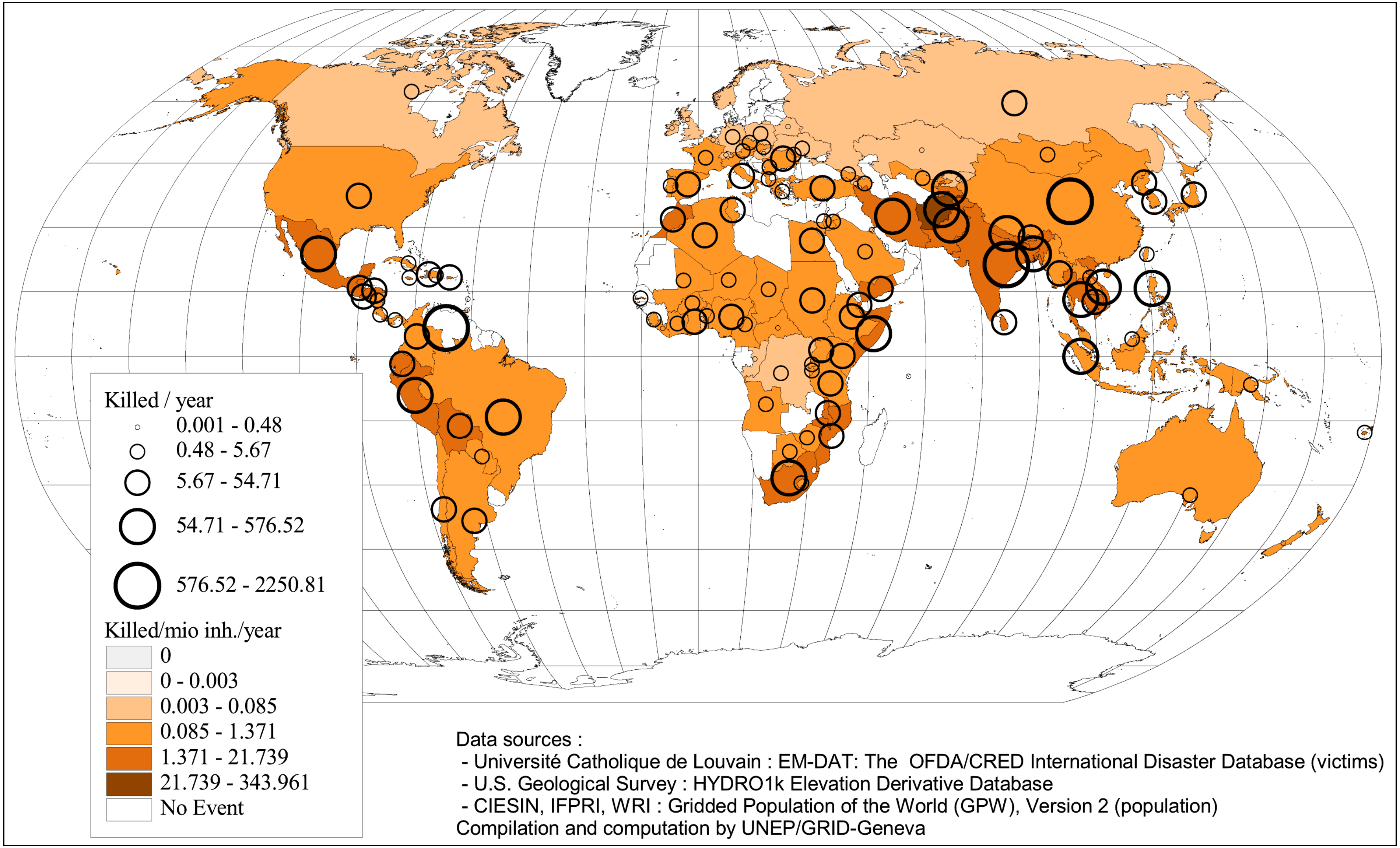
Figure 12: Map of Vulnerability and Physical Exposure to Floods



Data sources :
- Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (victims)
- U.S. Geological Survey : HYDRO1k Elevation Derivative Database
- CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2 (population)

Compilation and computation by UNEP/GRID-Geneva

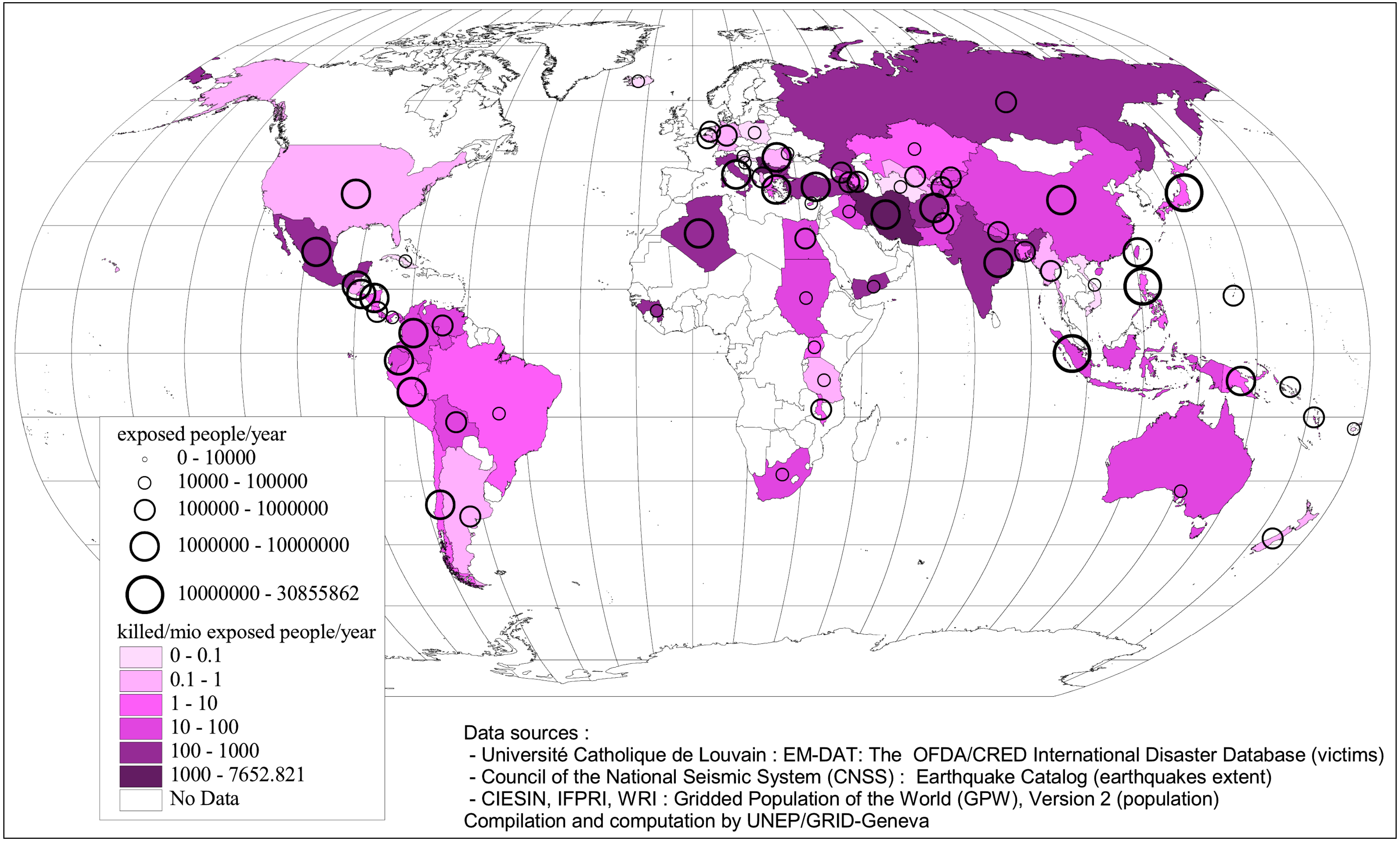
Figure 13: Map of Risk to Floods



Data sources :
- Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (victims)
- U.S. Geological Survey : HYDRO1k Elevation Derivative Database
- CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2 (population)

Compilation and computation by UNEP/GRID-Geneva

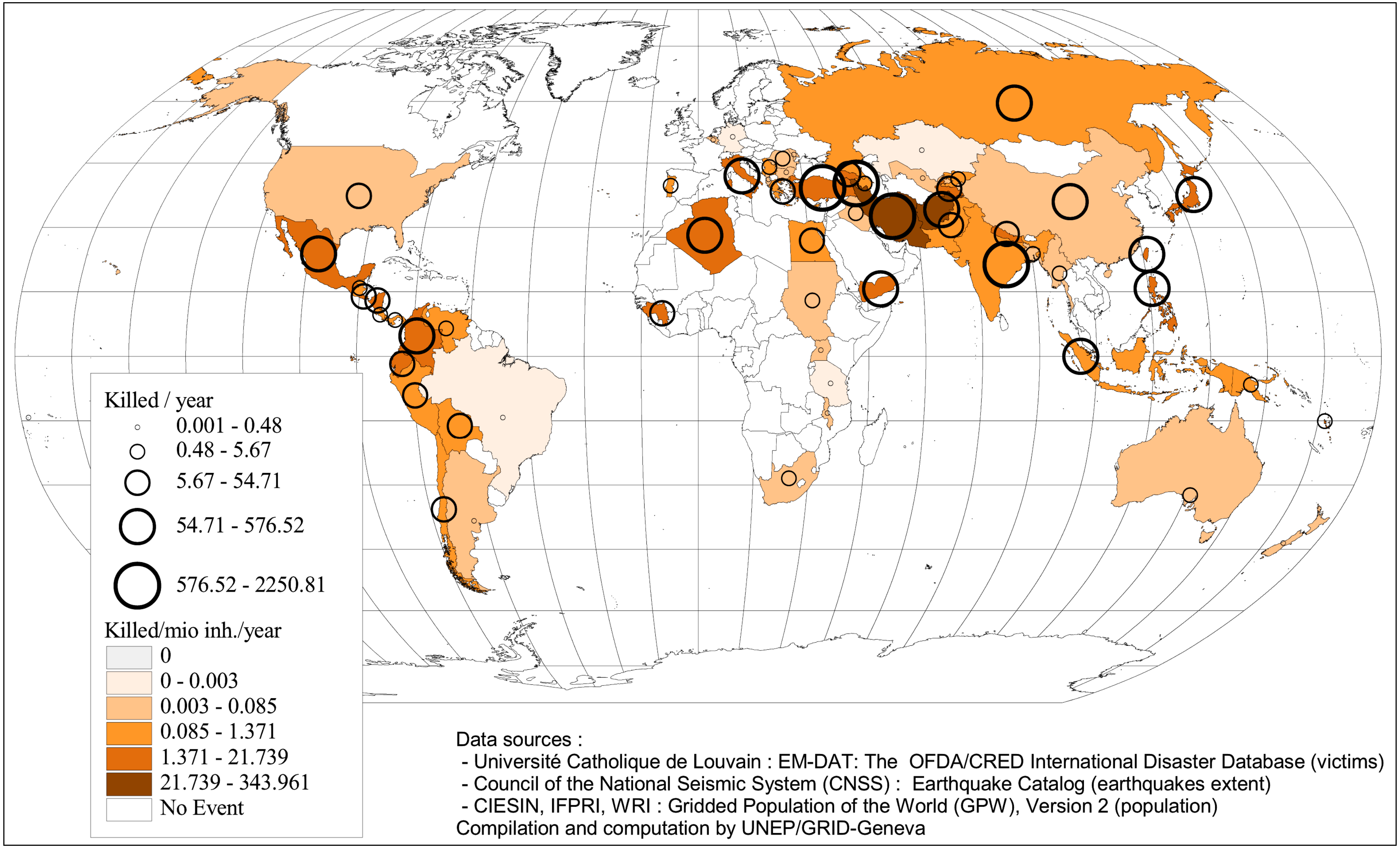
Figure 14: Map of Vulnerability and Physical Exposure to Earthquakes



Data sources :
- Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (victims)
- Council of the National Seismic System (CNSS) : Earthquake Catalog (earthquakes extent)
- CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2 (population)

Compilation and computation by UNEP/GRID-Geneva

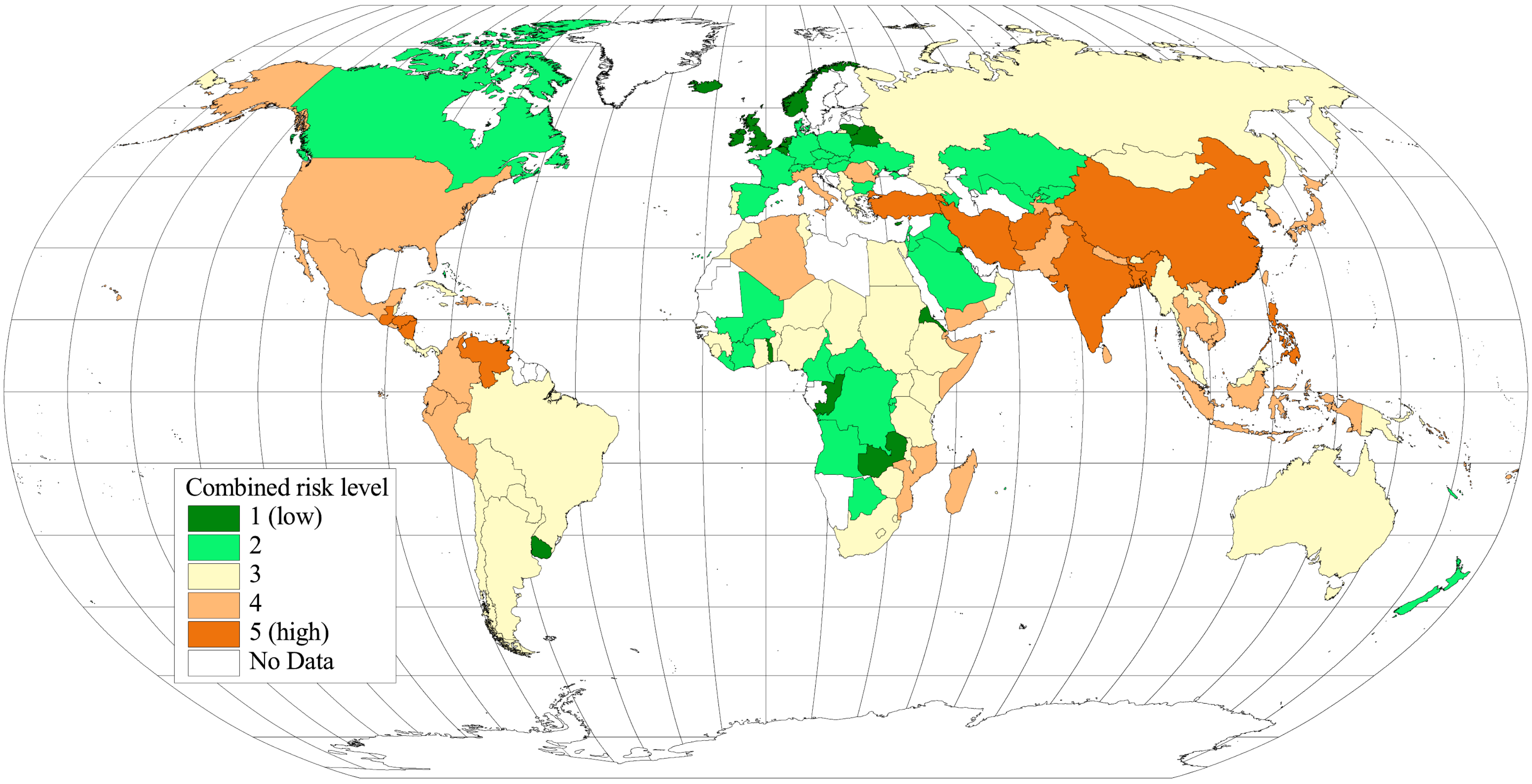
Figure 15: Map of Risk to Earthquakes



Data sources :
- Université Catholique de Louvain : EM-DAT: The OFDA/CRED International Disaster Database (victims)
- Council of the National Seismic System (CNSS) : Earthquake Catalog (earthquakes extent)
- CIESIN, IFPRI, WRI : Gridded Population of the World (GPW), Version 2 (population)

Compilation and computation by UNEP/GRID-Geneva

Figure 16: Multi-Hazard Risk Map (Cyclones, Floods and Earthquakes)



Method :
Combined risk levels are obtained by averaging the absolute risk levels (nb of killed people per year) and the relative risk levels (nb of killed per mio of inh. per year) of all disaster types

Figure 17: Graphic of risk for cyclones, floods and earthquakes

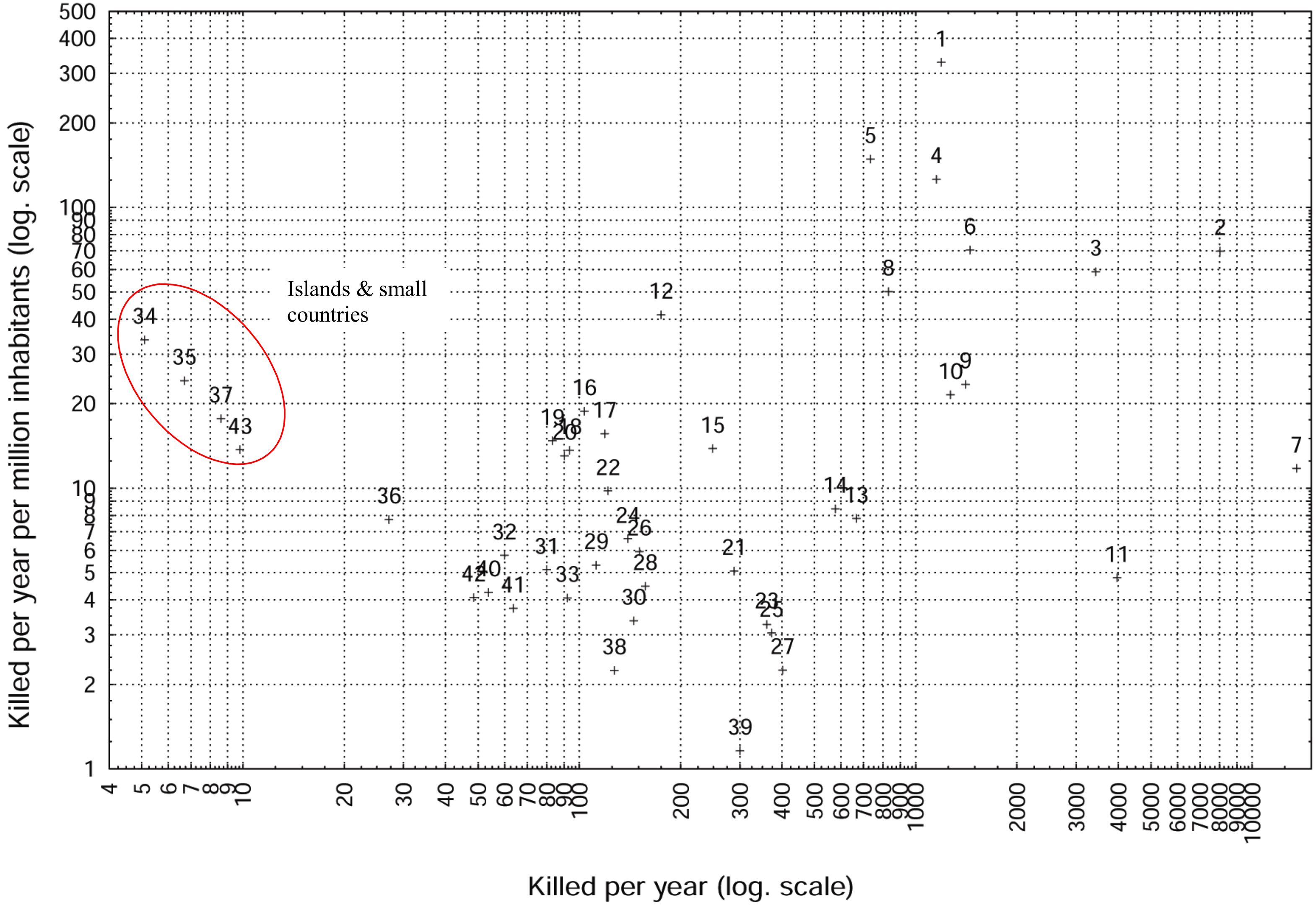


Table 25: Legend for the graphic in Figure 17

Name	Code	Killed /year	Killed /mio	class	Name	Code	Killed /year	Killed /mio	class
Armenia	1	1190.7	328.53	5	Algeria	26	150.7	5.95	4
Bangladesh	2	8024.4	69.81	5	Indonesia	27	402	2.25	4
Iran	3	3430.5	59	5	Colombia	28	156.8	4.48	4
Guatemala	4	1153.5	126.01	5	Peru	29	112.3	5.32	4
Honduras	5	733.9	148.6	5	Republic of Korea	30	145.2	3.37	4
Venezuela	6	1449.4	70.54	5	Mozambique	31	80	5.12	4
China	7	13556.6	11.75	5	Ecuador	32	59.9	5.76	4
Afghanistan	8	830.5	50.13	5	Romania	33	92.1	4.06	4
Philippines	9	1407.3	23.42	5	Vanuatu	34	5.1	33.73	4
Turkey	10	1269.3	21.49	5	Solomon Islands	35	6.7	24.12	4
India	11	3969.5	4.79	5	Puerto Rico	36	27.2	7.74	4
Nicaragua	12	174.7	41.49	5	Djibouti	39	8.6	17.69	4
Mexico	13	666.3	7.79	4	Thailand	37	127.1	2.24	4
Viet Nam	14	576.7	8.44	4	United States of America	38	300.2	1.16	4
Nepal	15	248.7	13.83	4	Madagascar	40	53.7	4.25	4
El Salvador	16	103.5	18.8	4	Sri Lanka	41	63.6	3.73	4
Somalia	17	119	15.64	4	Cambodia	42	48.5	4.08	4
Haiti	18	93.5	13.63	4	Fiji	43	9.8	13.7	4
Tajikistan	19	83	14.73	4	Dominica	44	2	28.37	3
Dominican Republic	20	90.4	13.04	4	Saint Lucia	45	2.8	21.74	3
Italy	21	288.4	5.07	4	Bolivia	46	22.8	3.46	3
Yemen	22	121.5	9.77	4	Chile	47	33.9	2.54	3
Pakistan	23	361	3.27	4	Brazil	48	123.5	0.84	3
Taiwan	24	139.4	6.6	4	South Africa	49	63.8	1.67	3
Japan	25	373.3	3.05	4	Bhutan	50	10.6	5.44	3

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Comments

The purposes of the GRAVITY research was to identify whether global data sets could be used for identifying population living in exposed areas and demonstrate the link between socio-economical parameters and vulnerability. The level of correlation achieved delineates that both physical exposure and variables tested are significant and could be identified. The correlation found is even much higher than initially thought. This is particularly true for climatic events. Smaller correlation was achieved with earthquakes, this is believed to be due to the long returning period, which is less compatible with the twenty one years period observed. The case of volcanic eruption was proved not too be relevant according to this method. According to the results, global approach can not be applied to volcanic eruption at least not with the data available for this study. The larger impacts are resulting from volcanoes with low (or unknown) historical activity.

For the three hazards remaining, the role of physical exposure appeared to be the most significant, however socio-economical parameters such as GDP, HDI, urban growth, percentage of arable land and local population density, were also selected depending on type of hazards. The sign of the exponents was always following what the common sense and specialists would have recommend with the notable exception of local density for flood.

All in all, the method used in this statistical analysis proved to be appropriate and allows the identification of the parameters leading to a higher risk and vulnerability. Such model should not, however, be used as a predictive model. Firstly because the level of data precision can not reach such precision. Secondly, because a significant discrepancy of losses between two events in the same country can be found. This shows the variability due to micro spatio-temporal context. For earthquakes the number of killed is probably different if it happened during the night or during the day; on a day off or when people are at work or school. It mostly depends on the type of habitat, type of soils direction of faults lines, depth of epicentre origin… access to most of these variables was not available at a global scale. The risk maps provided in this research are not to be confused with danger maps. At a local scale predictive model can and should be made allowing better urban planning and improved evaluation of risk. Maps at global scale are only produced in the aims of identifying the countries with the highest needs corresponding to the request from UNDP.

Extraordinary events – also called century disasters – do not follow the normal trend. Hurricane Mitch (Central America, 1998), or the flood in Caracas (Venezuela, 1999), earthquake in Armenia (1988), were clearly off the regression line. This is due to the abnormal intensity of such events which do not correspond with the average intensity. These events are (hopefully) too rare to be approached by a two decades period. Incorporating the intensity was performed, however this can only be done on an event per event approach. When entering an average intensity, the numerous low intensity events are biasing the average and finally the intensity was rejected as explicative variable.

6.2 Improvements

Socio-economical variables

Results delineate that global data sets can still be improved both in terms of precision and completeness, however they are already allowing the comparison of countries. Other indicators such as corruption index (transparencies) or political indicators would be interesting to test in the model, when all the countries will be available. It was surprising that indicators such as the number of physicians, the number of hospital beds or even the country dept service is not completed worldwide. Efforts on compilation are still needed to be deployed.

Tremendous amount of work was involved (by GEO3 team) to verify and complete the data. Units are not always accurate.

Floods

The geophysical data can also be improved. The watershed for flood physical exposure is based on a 1 km cell resolution for elevation. A new global data set on elevation from radar measures taken from the NASA shuttle is expected in the next two years. It consists on a 30m-cell resolution for the US and 90m resolution for the global coverage. This would allow the refining of the estimated area flooded. This would be especially welcome for the central Asian countries where the watershed taken were of very poor resolution.

Earthquakes

Compilation of national soil maps and fault orientation would also be much appreciated in order to improve the earthquakes physical exposure. The use of the Global Seismic Hazard Map (1999) from the GSHAP was used but present the difficulty for estimating the physical exposure as the frequency could not be derived. The method used was based on events from the similar period 1980-2000 provided better results, but once again can not be used as a predicting model.

Windstorms

The use of Greg Holland formula and algorithms developed by GRID-Geneva to automate the transformation of coordinates, central pressure and sustainable winds into buffers, was relevant, now 11 years of data were processed and India, Bangladesh and Pakistan were missing. The dataset should be completed for the 21 years and for all the countries. In the mean time the use of CDIAC data instead of the missing data was performed. This was possible due to a very high correlation between the two datasets (r=0.90).

6.3 Recommendations

Further improvements in the model can be performed:

Possibilities for improving the geo-spatial methods

> The physical exposure could be improved, especially for floods, although the correlation is high, this hazard was the less modelled. For the earthquakes, additional data may be available, such as presence of faults and orientation, type of soil for the selected exposed areas.

Possibilities for improving data quality and completeness

> The elevation and watershed for floods is based on a low resolution. Much higher resolution (30 or 90m) will be available within two or three years. This should highly improve the detection of the flooded areas.
>
> For the socio-economical parameters, some data sets were disregarded, not because they were not relevant, but because they were incomplete. Although the GEO3 team has significantly improved the data sets completeness, more efforts are needed in order to complete the selection of indicators. The choice of infant mortality was suggested and should be tested as health indicators. Finally all socio-economical data were not available for Taiwan, this should be arranged.

The case of small islands and archipelagos

Small islands and archipelagos are causing problem. In some cases they were too small to be considered by the GIS automated algorithms. This was typically the case for the population. The raster information layer for the population can not be used to extract the population of small islands. For single island countries, the problem might be overcome by using the population of the country, but for the others this was not possible. Indeed, when superimposing cyclone tracks on top of archipelago, the population is needed for each island. A manual correction is needed, but could not be performed due to the time frame of the study. The compilation of socio-economical parameters was also not complete for the islands. This could probably be improved by contacting SOPAC.

For all these reasons, the case of small islands and archipelagos would need a separate study and intuitively, the vulnerability for isolated countries might be different than other connected countries as seen on Figure 17, p.47.

Extending to other hazards

a. Drought

As already often mentioned the case of drought (food insecurity) represent nearly half of the casualties (46.54%), it should be taken into account, not only because its significant role in the mortality but, because it would leave the African continent apart. Otherwise, Africa is nearly not affected by other natural hazard. Food insecurity is due to physical conditions (drought), biological conditions (locust), socio-economical parameters (wealth, corruption, health,…) but mostly from political situation (conflicts). Such complex situation may be very difficult to model.

b. Tsunamis and Landslides

Some countries are not well represented by the model, because they are affected by hazards which were not of global significance. This is the case of Papua New Guinea and Ecuador, which are affected by tsunamis (respectively 67.8 and 14.3% of national casualties); landslides are also causing significant impact in Indonesia (13,88%), Peru (33%) and Ecuador (10.2%). As a result, the global risk is under evaluated for these countries.

c. Epidemics

This is more a health angle and should probably be taken care of by the World Health Organisation (WHO). However, the appropriate sanitation, access to safe water, number of physicians per inhabitants and other health infrastructure are also significant parameters of development. Data on epidemics are now starting to be available. Epidemics is representing a significant amount of casualties and AIDS is definitely impacting developing societies especially (but not only) in Africa.

d. Conflicts

The case of conflicts although much more politically difficult to approach is probably also highly correlated to human vulnerability. Results from a statistical analysis would be extremely interesting.

6.4 Last word

These results delineate the relation between level of development and low casualties from these three types of hazards. Stating that there is a relation can be understood both way: low development may lead to high casualties, but high hazard occurrence may also lead to low economical development as it destroys infrastructures and crops as well as scares the investors away. If higher impacts from natural hazards in developing countries were depicted, the message should not be perceived as “developed countries should be taken as models”. Other figures such as death from suicides, drug abuses or excess of fat food, are also leading to numerous casualties and are highly and positively correlated with HDI!

This research underlines the usefulness of continuing the improvement of data collection for a better identification of populations at risk. This is, however, not a final result as such. Final results will be achieved when proper risk reduction measures will be implemented leading to an observed decrease of casualties.

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APPENDIXES

Since printed tables do not allows sorting by fields for obvious reasons, the tables are provided on-line in a dynamic way. On this website you will also find, the maps, project document for presentations as well as other documents used for this research.

These documents can be download or open from this location:

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