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Assessment of global landslide hazard and risk hotspots

Évaluation globale des dangers et risques associés aux glissements de terrain

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ABSTRACT
Allocating resources for natural hazard risk management is of high priority among the development banks and international agencies working in developing countries. The paper presents the results of a study on global landslide hazard and risk mapping. The main objective of the study was to identify the countries and areas that are most exposed to risk from landslides. This involved a first-order, databased identification of geographic areas that form the global landslide risk disaster hotspots, with main emphasis on developing countries. The probability of landslide occurrence was estimated from modelling of physical processes combined with statistics from past experience. The main input data used in the landslide hazard assessment were topography and slope angles, extreme monthly precipitation, seismic activity, soil type, and hydrological condition.

RÉSUMÉ
Selon les banques de développement et les agences internationales travaillant dans les pays en développement, il est de la plus haute importance d'allouer des ressources pour la gestion des risques naturels. L'article présente les résultats d'une étude globale sur les dangers de glissement de terrain. L'objectif principal de l'étude était d'identifier les pays et les zones les plus exposées à ces risques. L'on a procédé à une identification de premier ordre avec base de données des zones géographiques concernant les risques de glissement à une échelle globale, avec emphase sur les pays en développement. La probabilité qu'il se produise un glissement a été estimée par modélisation des phénomènes géologiques et physiques et en utilisant les statistiques et l'expérience disponibles. Les principales données d'entrée pour l'estimation des dangers liés aux glissements sont la topographie, les pentes, les précipitations mensuelles extrêmes, l'activité sismique, le type de sol et les conditions hydrologiques.

1 INTRODUCTION

Information on hazards, vulnerabilities and risks at an appropriate scale is of fundamental importance for design and implementation policies and programs for mitigation of disaster risk. In order to be focused, relevant and effective, contingency planning, disaster preparedness and early warning systems require the knowledge of what kind of losses could be expected from what type of hazard. Lack of such data on a global scale, led in 2001 to an initiative from the ProVention Consortium of the World Bank to launch a collaborative project on "Identification of Global Natural Disaster Hotspots" – the "Hotspots Project", for short.

The aim of the Hotspots Project was to perform a global assessment of the risk of mortality and economic losses for six major natural hazards: drought, floods, wind storms, earthquake, landslides and volcanoes. Results of the project, which was lead by Columbia University and the World Bank, with Norwegian Geotechnical Institute (NGI) and UN Environmental Program (UNEP) as collaborators, are available in a World Bank publication in 2005.

NGI's role in this collaborative project was to assess the global distribution of landslide hazard and risk. In many parts of the world landslides pose a major threat. They occur more frequently than for the other hazards. However, in terms of the number of fatalities from different hazards, landslides rank rather low as seen from Table 1.

There is however, reason to believe that the number of causalities due to landslides shown in this table is grossly underestimated. This is because the loss figures in the international data bases are normally recorded by the primary triggering factor, and not by the hazard that causes the fatalities. For instance the 1999 Venezuela Disaster with more that 20 000 deaths is recorded as a flood, while most fatalities were caused by landslides in form of debris flows and mud flows.

Table 1. Ranking of Major Natural Hazards by Number of Deaths Reported in EM-DAT.

Rank	Disaster type	All Deaths	Deaths 1992-2001*
1	Drought	563,701	277,574
2	Storms	251,384	60,447
3	Floods	170,010	96,507
4	Earthquakes	158,551	77,756
5	Volcanos	25,050	259
6	Extreme temperature	19,249	10,130
7	Landslides	18,200	9,461
8	Wave/surge	3,068	2,708
9	Wild fires	1,046	574
	Total	**1,211,159**	**535,416**

* *2002 IFRC World Disaster Report*
(http://www.cred.be/emdat/intro.htm)

2 MODEL DESCRIPTION

The general approach adopted in the present study for the evaluation of global landslide hazard prone areas and risk hotspots is depicted in Figure 1.

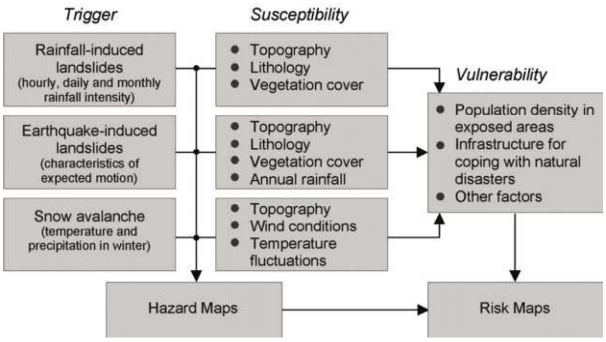


Figure 1. General approach for landslide hazard and risk evaluation.

The study focused on slides with **rapid mass movement**, like rockslides, debris flows, snow avalanches, and rainfall- and earthquake-induced slides; which pose a threat to human life. Slow moving slides have significant economic consequences for constructions and infrastructure, but rarely cause any fatalities.

2.1 *Approach for landslide hazard evaluation*

Landslide hazard level depends on the combination of trigger and susceptibility (Figure 1). In the first-pass estimate of landslide hazard, five parameters are used:

(i) slope factor within a selected grid (S_r), range of index: 0 – 4;
(ii) lithological (or geological) conditions (S_l), range of index: 1-5;
(iii) soil moisture condition (S_h), range of index: 1-5;
(iv) precipitation factor (T_p), range of index: 1-5; and,
(v) seismic conditions (T_s), range of index: 1-10.

The relative landslide hazard level was estimated using a model similar to that suggested by Mora and Vahrson (1994) for regional analyses. For each factor, an index of influence was determined (range of values are given above) and the relative landslide hazard level $H_{landslide}$ was obtained by multiplying and summing the indices using the following equation:

$$H_{landslide} = (S_r * S_l * S_h) * (T_s + T_p)$$

With respect to landslide hazard, the following classification was used:

Values for $H_{landslide}$	Class	Classification of land slide hazard potentia	Approximate annual frequency in 1 km^2 grid
< 14	1	Negligible	Virtually zero
15 – 50	2	Very low	Negligible
51 – 100	3	Low	Very small
101 – 168	4	Low to moderate	small
169 – 256	5	Moderate	0.0025 - 0.01%
257 – 360	6	Medium	0.0063 - 0.025%
360 – 512	7	Medium to high	0.0125 - 0.05%
513 – 720	8	High	0.025 - 0.1%
> 720	9	Very high	0.05 - 0.2%

The snow avalanche hazard was evaluated using a similar model, but with only 3 parameters:

(i) slope factor within a selected grid (S_r);
(ii) precipitation values for four winter months (T_p); and,
(iii) average temperature in winter months (T_t).

Further details of the models are provided in NGI (2004).

The estimation of expected losses was achieved by first combining the frequency of landslides and the exposed population in order to assess the physical exposure, and then performing a regression analysis using different sets of uncorrelated socio-economical parameters in order to identify the best indicators of human vulnerability for a selected hazard in a given country. The following formula for estimating the risk was used:

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

where:

R = risk proxy: number of expected human fatalities in landslides
H = annual hazard occurrence probability
Pop = population living in a given exposed area
Vul = vulnerability, depends on socio-politico-economical parameters

Defining physical exposure (*PhExp*) as the annual frequency of a hazard with specified severity multiplied by the number of persons exposed ($PhExp = H \cdot Pop$), the risk can be evaluated by logarithmic regression using the following formula:

$$\ln(R) = \ln(PhExp) + \ln(Vul)$$

In the case of landslides, once the average physical exposure was estimated from the hazard model(s) described above and population density data, an estimate of risk was made using a proxy of vulnerability. This included a multivariate regression analysis to correlate the number of expected fatalities to socio-economic parameters.

3 RESULTS

3.1 *Global hotspots for landslide hazard*

The main regions of the world with moderate to very high landslide hazards are found to include:

Central America, Northwestern South America, Northwestern USA and Canada, the Caucasus region, the Alborz and Zagros mountain ranges in Iran, Turkey, Tajikistan, Kyrgyzstan, the Himalayan belt, Taiwan, Philippines , Indonesia, New Guinea, New Zealand, Italy and Japan, The locations are marked on the attached world map on Figure 2.

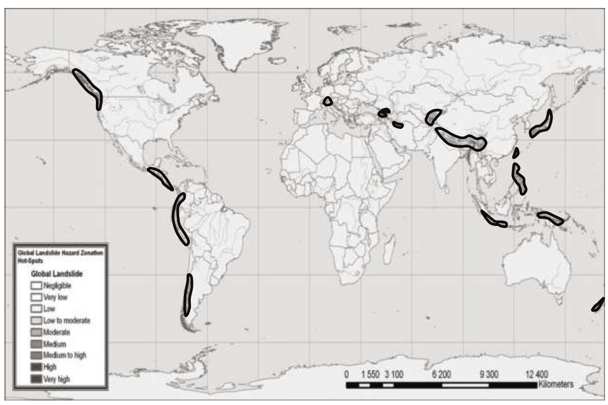


Figure 2. Global landslide hazard hotspots marked

A more detailed mapping for Central Asia and the Middle East is shown on Figure 3, see also C. Pusch (2004). Countries with medium to high, high, and very high landslide scores include: Georgia, Armenia, Turkey, Iran, a small part of Southern Russia, Tajikistan, Kyrgyzstan, Afghanistan, Nepal, India and Southern China.

Similar mapping is available for the Central American and Caribbean countries, where the most exposed countries include Guatemala, Mexico, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Columbia, Ecuador and Peru.

3.2 *Comparison of model prediction with actual inventories for slide events*

The hotspots project included validation of predicted landslide hazard zones in a number of countries where data on geographical distribution of historical landslides were available. The countries where calibration was performed were Norway, Armenia, Georgia, Nepal, Sri Lanka and Jamaica. In general the prediction model was found to yield a good first-pass approximation.

An example for Armenia is shown below. Armenia (Fig. 4a) is one of the most disaster-prone countries in the world (earthquake, landslides, hailstorm, droughts, strong winds, and floods). The average value of direct damages that landslide processes cause to the social and economic infrastructure approaches US$ 10 mill/year (Ref.: Emergency Management Administration). More than 3 000 large landslides have been reported for Armenia in the 20th century, and one-third of the country is exposed to high landslide hazard. Nearly 470,000 people (about 15% of the total population) live in the exposed areas. In the past five years, more than 2000 families have been left homeless as a result of landslides.

Several landslide prone areas in Armenia have been identified as being dangerous for the population. Nearly 300 of the largest landslides are in an active stage of development. They include an area of about 700 km^2, involving 100 settlements, where nearly 400 000 people live. About 1 500 km, of a total of 8 000 km of transport corridors in Armenia, are located in landslide-prone terrain. A typical huge landslide area covers a few km^2. In some instances, a village with a population from a few hundred to a few thousand inhabitants is situated in an active landslide area. A typical landslide exhibits a slow, creeping movement, with a thickness between 10 m – 100 m, and several, smaller, active creeping zones inside the area. The ground movements are horizontal and rotational, causing tension cracks in the ground, settlements and rotational slip surfaces.

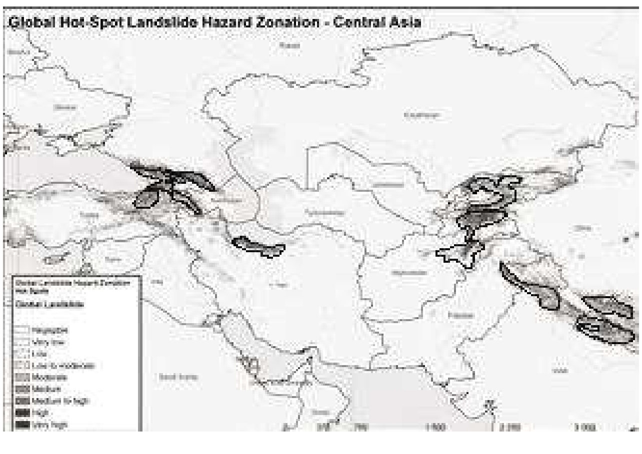


Figure 3. Predicted landslide hazard hotspots areas in Central Asia and Middle East are marked.

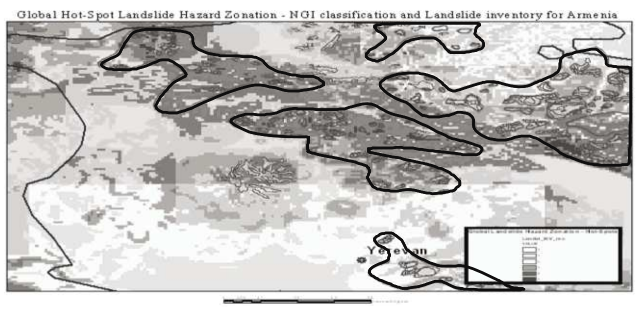
NGI produced a landslide hazard map for Armenia with support from the Armenian Scientific Research Company, GEORISK. Computations were based on several datasets available. GEORISK provided NGI with information on historical landslides as well as their interpretation of landslide-prone zones: regions where landslide processes develop, regions of creep motion of the ground, regions of intense landslide processes and regions of large seismic activity which involve the most hazardous landslides.

Figure 4b presents the superposition of the GEORISK landslide inventory (solid line contours) on the global landslide hazard map obtained with the first-pass NGI model in this study. Especially for the areas in the centre of the region mapped, the agreement between the NGI prediction and the GEORISK inventory is very good. The NGI prediction model assigns landslide values between 6 and 9 to all the landslide zones identified by GEORISK. The higher hazard zones correspond well to the areas characterized as most susceptible (values of 8 and 9). However the NGI prediction model does not show the hazard area close to Yerevan, and can only indicate the southern periphery of the hazard zone close to Azerbaijan identified by GEORISK.

3.3 *Hotspots for landslide risk*

A major part of the hotspots project included prediction of the geographical distribution of landslide risk expressed as the number of people predicted killed pr year pr km^2.

(a)



(b)

Figure 4. (a) Map of Armenia. (b) Comparison of global landslide hazard mapping in Armenia using the NGI model with the GEORISK landslide inventory.

In these predictions the distribution of hazard, frequency of occurrence, population density as well as loss figures from historical events were the major input parameters. Some the major findings were:

- The annual number of expected fatalities due to major landslides worldwide, as predicted by the model, was found to be in excess of 4300. This number is of the same order of magnitude as the reported average number of people killed per year (ca. 1700) in the past 30 years.
- 98 % of the recorded victims lived within areas predicted by the NGI model to fall in landslide hazard zones 5 and above.
- Localized areas of pixel size 1 km^2, with highest mortality risk, were found to be in Colombia, Tajikistan, India and Nepal where the predicted risk for number of people killed pr year pr 1 km^2 was found to be greater that 0.01.
- In countries like Guatemala, El Salvador, Honduras, Panama, Costa Rica, Mexico, Columbia, Afghanistan and Iran, the model predicted large areas with risk for number of people killed pr year pr 1 km^2 between 0.001 and 0.01.

The results showed strong correlation between high risk and physical exposure, and strong correlation between high risk and low Human Development Index (HDI) as determined by United Nation Development Program (UNDP). The analysis also showed high correlation between high risk and high percentage of forest cover, which is somewhat surprising. This might reflect the fact that the countries with highest forest coverage might also be the ones with the highest degree of deforestation. Deforestation is an important factor that needs to be addresses in more detail (Ref: World Disaster Report 2004), but the parameter is difficult to determine on the global basis with the existing data sets. The percentage “arable land” also showed a strong correlation with landslide risk, which indicates that rural population are more vulnerable to landslides than urban population.

The result of the regression analysis for landslide risk is shown on Fig. 5. It should be mentioned that out of the 249 countries that were included in the analysis, the model failed to explain landslide risk in nine of the countries. This demonstrates the need for better data sets, especially on deforestation.

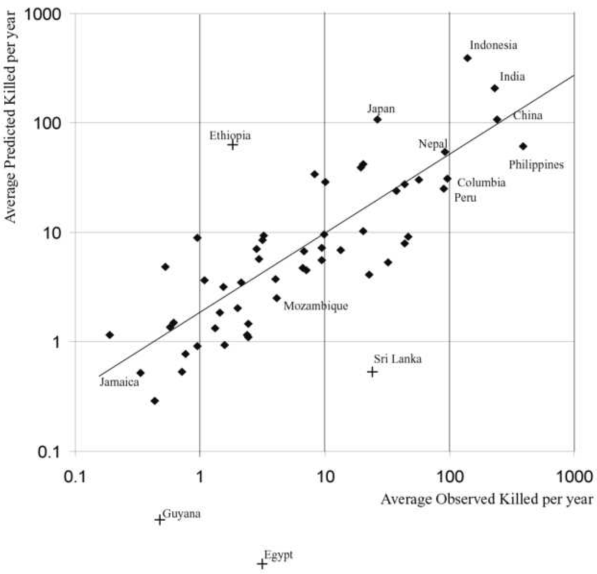


Figure 5. Predicted killed versus observed landslide fatalities

4 CONCLUSIONS

The analysis confirmed that a fairly good first-pass estimate of landslide hazard can be made by using the data sets on slopes, lithology, soil moisture, level of precipitation and seismicity.

Validation of the global hazard prediction, which was carried out for 6 selected countries, showed fair agreement between the boundaries of the historical slides and the hazard zones predicted by the global model. However, the analyses suffer from significant shortcomings in the quality and resolution of the available global data sets. Use or interpretation of the results for specific national conditions is not recommended without further investigations.

Working on a smaller scale, it should be possible to refine the analyses using better resolution in the input data, as well as adding supplementary parameters such as land cover, deforestation and effects of long-term climatic change. With use of a more comprehensive set of site-specific data, it should also be possible to make a prediction of economic losses with the model (and not only fatalities, as was done in the present study).

Improved data quality, adding new type of data sets to the model, and having loss data from the landslide prone countries that are presently missing, are also important for better understanding and identification of the most relevant socio-economic parameters for predicting landslide risk.

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REFERENCES

OFDA/CRED, 2001, EM-DAT: The OFDA/CRED International Disaster Database, http://www.cred.be/emdat.

Chen, R.S., Dilley, M., Deichmann, U. and Lerner-Lam, A. et al. (2004). Global Natural Disaster Risk Hotspots, Report International Bank for Reconstruction and Development/The World Bank and Columbia University. August 2004. review Draft.

Norwegian Geotechnical Institute (2004). First-order identification of global slide and avalanche hotspots. NGI report 20021613-1, 31 March 2004.

Mora, S. and Vahrson, W., 1994. Macrozonation methodology for landslide hazard determination, Bulletin of the Association of Engineering Geologists, vol 31, nº1, 49-58.

World Disaster Report 2004, International Federation of Red Cross and Red Crescent Societies, IFRC, Geneva; http://ifrc.org

GEORISK, 2004, Communications through. The World Bank study.

Pusch, C. 2004, A comprehensive risk management framework for Europe and Central Asia. Disaster Risk Management Working Paper Series no 9. The World Bank, October 2004.