Natural Hazards and Risk Assessment: the FOSS4G capabilities

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Abstract

In recent years, there has been a shift from reactive measures to protect the environment to more proactive approaches aimed at preventing or minimizing (rather than remediating) damages and losses. This change in emphasis has been reflected in the use of risk assessment at the outset as part of the package of tools for making decisions about land management, particularly in the context of sustainable development. Risk assessment has therefore been recognized as a key element in the appraisal of land management complex problems, and for formulating and communicating issues so that transparent and equitable policy, regulatory or other decisions can be taken.

In order to develop risk assessment studies that can support risk management strategies a large number of data, tools and expertise are required. However in developing countries these conditions are seldom met. In fact, small budgets availability restrict the acquisition of basic datasets, the purchase of specialized techniques and models, and the employment of staff with high technical skills. For this reason the Institute of Earth Sciences is conducting researches on the development of an accessible risk management system (named RiskBox). These studies include the investigation and development of hazard assessment models, risk assessment methodologies, software interfaces and distribution technologies. At present time, the RiskBox system is not a complete product with all necessary parts or elements assembled and defined. Therefore the objective of this paper is not to present the system itself but to present several studies conducted within the GRASS GIS and a first system design to show the FOSS4G capabilities in risk studies. This paper presents the approach, the general idea of the system design, and several case studies.

1 Introduction

The RiskBox project aims to investigate, design and develop a Web-based easily accessible system with risk assessment capabilities. This kind of system shall fill the technological gap found in many developing countries in order to permit the conduction of studies at local level on natural hazards and mitigation planning. This system shall enable users to run risk assessment via Internet without the following requirements: specific program installation; high computational power; large hard disks for data storage; and users with high computer skills level.

The objective of this project is to conduct research studies functional for developing an "accessible" system, so that communities can reduce impacts due to natural hazards. The word

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accessible is here referred to four different level of accessibility: (i) accessibility to the code, to let researchers understand, improve, expand, and optionally adapt implemented algorithms and methods. This accessibility leads to the extendibility of the system. (ii) accessibility to the users, to let the system be easily applied by means of an easy to use interface. This leads to the usability of the system. (iii) accessibility to the data, to let the researchers access and use the available data from different existing databases and allow decision makers to access the results of the studies. (iv) accessibility in term of costs, to enable poorest countries to use the system.

In order to reach those accessibilities the selected RiskBox developing environment is based on geo-information, Web-based, open source technology with particular emphasis on the FOSS4G softwares.

2 Risk assessment methodology

The RiskBox system will implement a multi level approach for an integrated risk management of natural hazards, able to take varying situations of quality and density of base data into account. This kind of approach, that has been successfully applied in the last decades in Switzerland (BUWAL, 1997), is composed of the following three consecutive steps: hazard assessment; vulnerability assessment; and risk analysis.

2.1 Risk assessment procedures

This first step of hazard assessment is subdivided in two phases. First the threatening processes (volcanoes, tsunamis, landslides, rock falls, debris flows, etc.) are identified and then their level of hazard is assessed.

The first phase of threatening phenomena identification is generally based on the analysis of previous studies and can be completed by regional studies, aerial photo imagery, field surveys and historical analysis. Whenever these data are not available, susceptibility models can be used to evaluate the exposition of the area to different hazards. The results are maps of natural hazard phenomena, identifying zones prone to various natural hazards.

In a next phase, the identified natural hazards can be attributed according their degree of hazard. Two main aspects describe the level of hazard: how often a hazard occurs (return period) and with what severity. The intensity represents the magnitude of an event and is divided into three classes: high medium and low. For each hazard type a characteristic parameter (or set of parameters) and relative boundaries values are identified to classify the intensity map accordingly. The magnitude of the hazard criteria (class boundaries) can be adapted to local needs. The return period, or probability, is also divided into three classes: low, medium and high. The classes are typically set at 30, 100 and 300 years, but can vary depending on the considered hazard.

In the second step of vulnerability assessment the elements directly exposed to risk (immediate affected people, goods, infrastructures) as well as indirectly exposed (socio-economic consequences) are identified and their vulnerability is assessed, according to the degree of hazard. This is generally accomplished through geographical analyses and the usage of vulnerability models, in the form of tabular data or vulnerability functions. The indirect, socio-economic, consequences of natural hazards can be derived from historical analyses and modelling.

In the final step of risk analysis, the both previously determined elements, hazard and vulnerable objects, are overlain, resulting in a risk evaluation of variable accuracy, depending on the quality of the available data.

2.2 Levels of analyses

According to Swiss recommendation, risk assessment can be conducted at three increasing levels of analytical depth, depending on the scope of analysis and the quality and availability of data. The three levels are complementary, and a risk can be evaluated at different levels.

Level 1 – On this level, the risk analysis leads to qualitative results that identify the the deficit of protection of the exposed elements. Here, the hazard map is superimposed on the land use map where protection objectives in the form of maximum allowable hazard level is assigned to different classes. Protection deficits are present where the hazard exceeds the permitted level.

Level 2 – On level 2, the risks for the elements studied on level 1 are quantified. level 2 is based on global assumptions and is carried out without the need of field surveys. Exposed elements are analysed by means of classes. Risks are evaluated in terms of monetary values for direct and indirect material damage and in number of fatalities for damages to people.

Level 3 – On level 3, risks are analyzed by specific investigations on individual objects. This level is used to quantify the risk within spatial elements of level 2. Risks are evaluated in terms of monetary values for direct and indirect material damage and number of fatalities for persons.

3 Risk assessment within the GRASS GIS

GRASS (Geographic Resources Analysis Support System) is a powerful Geographical Information System with hundreds of modules enabling the management and analysis of vector and raster data models (http://grass.osgeo.org/index.php). GRASS is an official project of the Open Source Geospatial Foundation and has a long history of applications in the field of environmental modelling (Mitasova et al., 2001; Ciolli and Zatelli, 2002; Raghavan et al. 2005; Jolma et al., 2006; Fedrici and Cannata, 2007; Mergili and Fellin, 2007). It shows the typical flexibility and accessibility of Open Source Softwares that easily allows new development either on a C programming level, or on a scripting level (Phyton, Shell, Pearl, etc..). In this paragraph several examples are given to show the GRASS capabilities in risk analysis.

3.1 Rockfall hazard assessment

A main task in hazard mapping is the assessment of hazards in areas where very limited resources are available or where the extension is too large to be detailed investigated. Here the need of a simple model, with just a few input data requirements is desirable. For this reason a well known algorithms using an empirical methods to compute a susceptibility map to rockfall hazard has been implemented in GRASS. The new module (*r.rockcone*) is based on a simple concept delineating the maximum run-out distance of a falling rock mass trough the definition of a shadow angle from the source points (Evans and Hungr, 1993; Jaboyedoff and Labiouse, 2003; Wieczorek et al., 2003). The shadow is defined by the terrain that is below a cone with a certain inclination (α) from the horizontal plane and with the apex located at the source point; an aperture angle (β) with respect to the maximum slope direction is defined to limit the area of influence and to avoid unrealistic lateral hazard area expansion (see figure 1). These two angles, together with the terrain model and the aspect map, are inputs of the module. From an energetic point of view, assuming that the rock is sliding with a linear energy dissipation proportional to the cone slope, the kinematic energy and velocity in a given point P can be estimated as:

$$E_K = m \cdot g \cdot (h_c - h_t) \quad ; v_t = \sqrt{2 \cdot g \cdot \Delta h} \qquad [4]$$

where m is the rock block mass [kg], g the gravitational acceleration [m/s^2], and (h_c – h_t) the distance between the cone and the terrain [m].

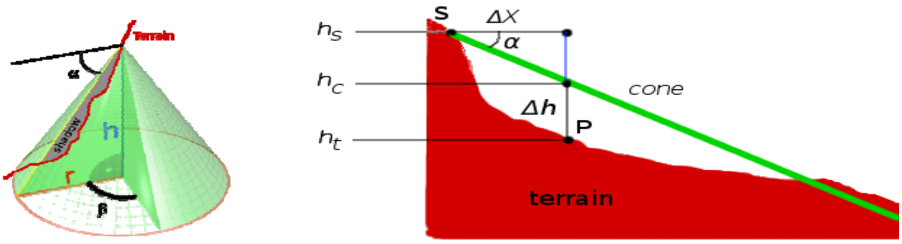


Figure1. Graphical representation of the implemented shadow methods.

In order to avoid overestimated velocity and energy values due to not considered rotational energy and energy losses due to bouncing, a reduction parameter f $(0 \leq f \leq 1)$ can be applied to calculate a corrected kinematic energy (E_{kc}) and a translational velocity (V_{tc}). A case study has been developed in the Southern Leventina valley (Canton Ticino, Switzerland). The rockfall source points have been defined by means of landuse and slope characteristics of the terrain selecting rock areas with slope greater than 45°. The cone inclination (35°) and aperture angle (45°) were selected after a calibration with aerial photo interpretation studies, while the reduction parameter was set to 0.21. The results (figure 2) show that mapped hazard areas (pink) has been verified.

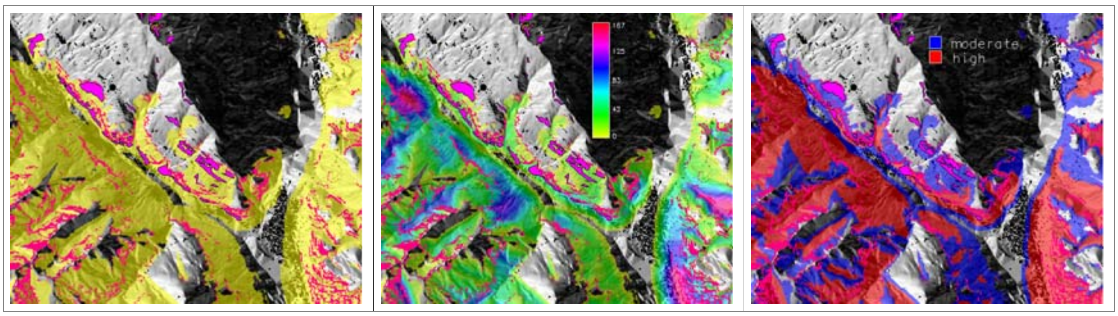


Figure 2. r.rockcone results. From left to right: hazardous area, kinematic energy [KJ], hazard levels

It must be noted that this method does not correctly simulate the energy losses of blocks moving down slopes (combination of free flight, bouncing, rolling and sliding) therefore it is essential to interpret those velocity and energy results with great caution.

3.2 Debris flow hazard assessment

Debris flow is a complex physical phenomenon, whose behaviour is driven by a number of parameters like meteorological data, elevation model, soil mechanical and hydrological parameters, and surface characteristics. Also for this type of hazard assessment the choice of a simplified approach not requiring a vast amount of data has been selected.

The *dfwalk* model applies an empirical-conceptual approach to determine depositional areas of debris flow. This approach originally developed by Gamma (1999) has been applied in different Swiss Cantons to create risk map. Within the European Interreg III programme in the scope of the CatchRisk project, this model was implemented and refined within the ArcGIS software, calibrated, and validated for several areas of the Canton Ticino region (German-Chiari, 2004). Last year this model has been ported to GRASS both to support the RiskBox project and to eliminate version incompatibility problems that often raised when ArcGIS is upgraded.

The model combines different approaches using physical motion description together with a deterministic/stochastic approach for the debris expansion and an empirical method for sedimentation. The new command *r.dfwalk* uses the total amount of debris material subdivided in the source cells and simulates the flow by means of *n* packages. Each package that represents the n^{th} portion of the debris detached from the source cell is processed to obtain the path, the velocities and the sedimentations. Sedimentations of each random walk modify the terrain elevation influencing the following packages flow. Table 1 lists the debris flow subprocesses and the respective approaches applied by the *r.dfwalk* command.

Table 1. Approaches applied by the *r.dfwalk* command

Sub-process	Approach	Approach type
Debris flow motion	Two parameters frictional model (Perla et al., 1980)	Physical
Flow expansion	Random walk (Monte Carlo simulation)	Deterministic / Stochastic
Sedimentation	Slope-velocity function	Empirical / Physical

The flow motion is calculated applying the Perla frictional model (Perla et al., 1980) that considers the flow as a mono dimensional motion on a curved surface. This model, based on the modification of the Voellmy (1955) formulation, combines the Columb frictional expression with the Chèzy formula assuming that the motion is mainly governed by two parameters: a sliding friction coefficient (μ) and a mass-to-drag ratio (*M/D*). This approach originally developed to describe the avalanche motion, has also shown his capability in the debris flow simulation.

The flow is propagated over the cells of a DEM depending on the local slope, a given slope threshold, and a given coefficient of expansion. If one of the slopes to the neighbour cells is bigger then the threshold, the flow direction is chosen in a deterministic manner selecting the cell with the maximum slope as the next cell. Otherwise the flow direction is chosen in a stochastic manner selecting the next cell by means of probabilistic sampling of a subset of the neighbour cells.

Sedimentation is governed by an empirical relationship linking it with velocity and slope. It is based on the following three assumptions:

- sedimentation begins when velocity (or slope) is lower than given thresholds;
- sedimented volume is inversely proportional to velocity or slope;
- sedimentation mechanism is the same inside and outside the river.

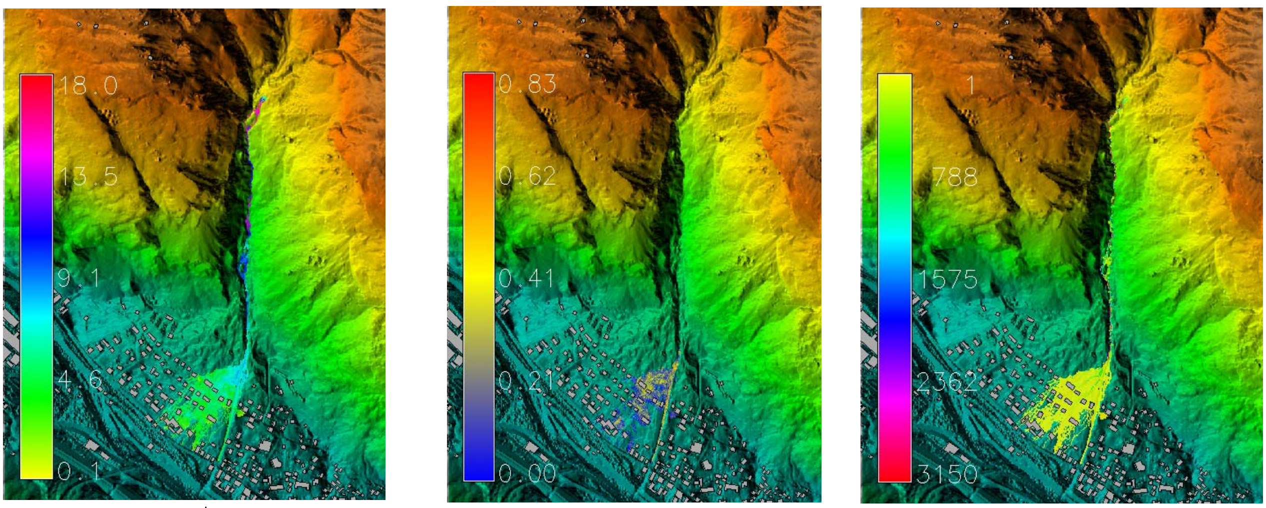
Given a volume available for sedimentation S_T [m^3], for each cell of the flow path the algorithm evaluates the sedimented volume S_i [m^3] as the minimum value between the sedimentation estimated with the velocity criteria $S_i(v)$ and the slope criteria $S_i(\beta)$. The resulting expressions are:

$$S_i = min[S_i(v), S_i(\beta)] \qquad [2]$$

where:

$$S_i(v) = \begin{cases} Sv_{max}\left(1 - \frac{v_i}{v_{ts}}\right) & if \quad v_i \leq v_{ts} \\ 0 & if \quad v_i > v_{ts} \end{cases} \qquad S_i(\beta) = \begin{cases} Ss_{max}\left(1 - \frac{\beta_i}{\beta_{ts}}\right) & if \quad \beta_i \leq \beta_{ts} \\ 0 & if \quad \beta_i > \beta_{ts} \end{cases} \qquad [3]$$

Sv_{max} and Ss_{max}[m^3] are the maximum values of sedimentation in a cell due to velocity and slope criteria, v_i is the velocity of the flow in the i^{th} cell [m/s], v_{ts} is a velocity limit threshold to sedimentation [m/s], β_i is the slope in the i^{th} cell [°], *and* β_{ts} is a slope limit threshold for sedimentation [°]. Figure 5 shows the command outputs. M/D has a higher influence on velocity in steeper parts of the track whereas the velocity in the run-out area is dominated by μ.



A B C

Figure 5. *r.dfwalk* outputs, A: velocity [m/s]; B: sedimentation [m]; C: number of random walk [-]

3.3 Tsunami risk assessment

This chapter illustrates e case study for tsunami risk assessment where the hazard was estimated by means of a GRASS script (*r.tsunami*) that implements the approach proposed in Federici et al. (2006) and validated in Cannata et al. (2007). The case study area is located in Olbia, a Mediterranean city on the Sardinia island's east coast.

Hazard assessment. According to the Swiss approach, hazard assessment requires the development, analysis, and integration of three intensity maps (inundation height in this case): one for each probability class (high, medium, low). The first step is therefore to identify the probability classes by mans of return period *T* and the associated event severity parameter and value. This can be done by means of statistical analysis of past events: on the basis of a previous study on the Mediterranean sea (Camilleri, 2006) the classes and values shown in table 2 are proposed.

Table 2. Hazard classes for the Mediterranean sea after Camilleri (2006)

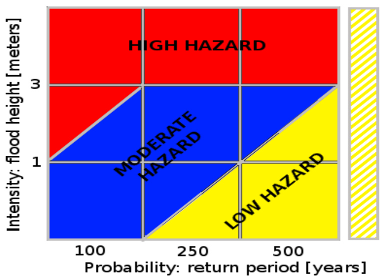
Probability class	Return period boundaries	Mean value	Event severity parameter: run-up wave height for the mean value
High	0< T < 200	T = 100	1.5 m
Medium	200 ≤ T < 300	T = 250	2.8 m
Low	300 ≤ T	T = 500	4 m

The second step is the delineation of the intensity parameter and classes boundaries that were identified according to the Indian prevention programme (NDMD, 2005) as listed in table 3.

Table 3. Intensity classes for tsunami events.

Intensity class	Inundation height (h) boundaries
High	h ≤ 1 m
Medium	1 m < h ≤ 3 m
Low	3 m < h

The final step of the hazard assessment involves: (i) the running of the *r.tsunami* command for each probability event class to extract the intensity maps (flood height); (ii) the classification of the intensity maps in hazard levels; (iii) and their integration according to the hazard matrix represented in figure 6 together with the hazard analysis resulting map.



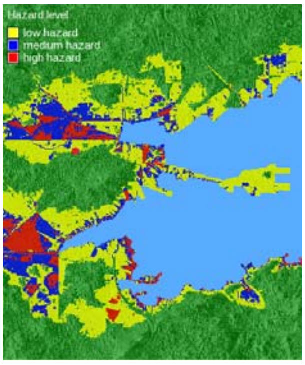


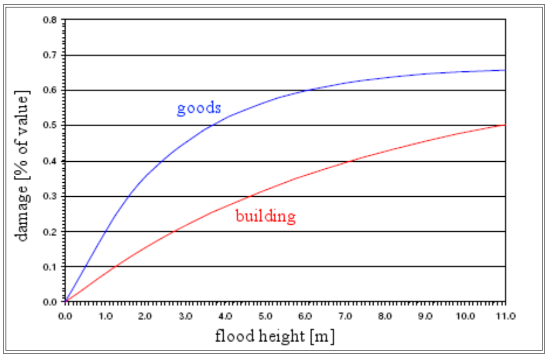
Figure 6. Hazard classification matrix (left) and tsunami hazard map (right).

<u>Vulnerability assessment</u>. The second step of vulnerability assessment requires: (i) to identify the object exposed to risk and (ii) to associate the expected damage for each object as a function of the intensity. The analysis in this case study is limited to the building objects. Once the exposed elements are extracted by overlaying the buildings with the total risk, according to the landuse map the selected objects are classified in three main classes: residential, industrial, and rural buildings. For each class a vulnerability function (U.S. Army Corps of Engineers, 1988) is then applied to the intensity maps to derive the percentage of damage and consequently the vulnerability maps of the

building structure and the goods.

Risk assessment. For each building class the unit value of the buildings [€/m^2] is derived from the database of the building quotation – available on the site of the Italian Territory Agency (www.agenziaterritorio.it) – while the values of goods are estimated according to De Lotto and Testa (1999) as a fraction of the total value. It is now possible to derive the monetary risk associated to each return period T (the damage expected every T years) by multiplying vulnerability maps and value maps. The total risk can then be calculated as Expected Annual Damage (EAD) according to:

$$EAD = \sum_i (R_i / T_i) \qquad [4]$$



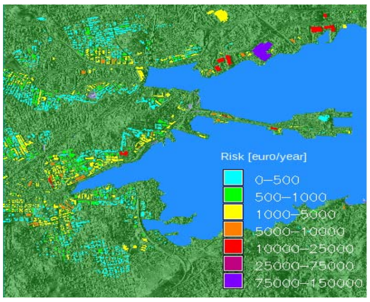


Figure 4. Example of vulnerability function (left) and estimated tsunami risk (right).

4 Future developments

The RiskBox project aims to develop geospatial tools to foster the risk assessment as an invaluable risk management tool. For this reason, next to the development of hazard models and procedures, is very important to develop clear and accessible interfaces. This objective can be met by implementing a framework that integrates different tools and data communication standards. In general this framework, whose developing is ongoing, will combine OGC standards (Open Geospatial Consortium, www.opengeospatial.org) like WFS, WCS, WMS, SOS, and WPS to execute models and procedures on the server side. The resulting risk management system will address three different domains: (i) data domain: to collect, store and serve updated information; (ii) modelling domain: to model natural hazards and vulnerabilities; (iii) operational domain: to access information, make analysis, evaluate options, and take decisions.

Up to now the *RiskBox* developments and researches have been mainly focused on the modelling domain, but more researches in the areas of the operational domain (to develop interfaces and methods) and of data domain (to address the temporal series data models) are needed. The RiskBox framework currently under development is implementing new libraries that enable the necessary interactions within the framework, new hazard processing services and risk assessment analysis.

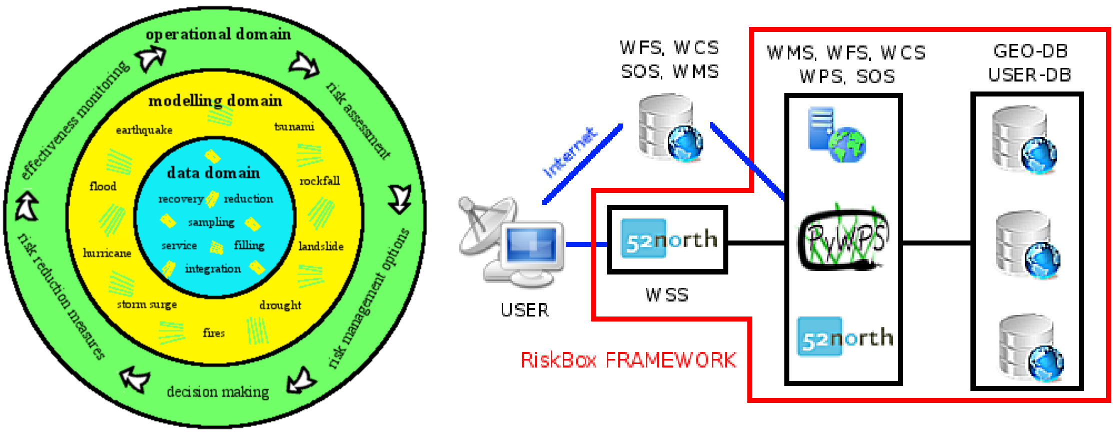


Figure 5. RiskBox Risk Management System: domains (left) and framework (right).

5 Conclusions

This paper illustrates the importance of GISs as a tool for risk assessment. It has been shown that the GRASS project is a flexible, feature rich, and accessible environment to develop new modules helping to conduct risk assessment studies. Together with the new and fast development of Web tools (Geoserver, OpenLayers, PyWPS, etc.) and other Open Source Software (R-stat, PostGIS, GRASS, etc.) the FOSS4G is an ideal environment for a new accessible service developments, substantially contributing to the sustainable development within societies and in particular within developing countries.

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7 References

BUWAL 1997, 'Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten', Empfehlungen, pp 42, viewed 14 August 2008, <www.bafu.admin.ch>

Camilleri, HD 2006, 'Tsunami construction risks in the Mediterranean - outlining Malta’s scenario', *Disaster Prevention and Management*, vol.15, no. 1., pp 146-162

Cannata, M, Federici, B, Molinari, M, 2007, 'Mappe di inondazione dovute a tsunami mediante il gis grass: applicazione all'isola di St. Lucia, Caraibi', *proceedings of VIII Italian GRASS user meeting*, Palermo, Italy, viewed 13 August 2008, <http://gislab.dirap.unipa.it/grass_meeting/index.htm>

Ciolli, M & Zatelli, P, 2002, 'Avalanche risk management using GRASS GIS', *Geomatic Workbooks*, no. 1, viewed 12 August 2008, <http://geomatica.como.polimi.it/workbooks>

De Lotto P & Testa G 1999, 'Dambreak risk management and social economic impacts: a simplified method of flood damage estimation', *proceedings of the 3rd CADAM workshop*, Milan, May 1999

Evans, SG & Hungr, O, 1993, 'The assessment of rockfall hazard at the base of talus slopes', *Canadian Geotechnical Journal*, v. 30, pp. 620-636.

Federici, B & Cosso, T, 2006, 'Tsunami inundation maps and damage sceneries through the GIS GRASS', *proceedings of FOSS4G2006*, Lausanne, Switzerland, viewed 13 August 2008, <www.foss4g2006.org>

Gamma, P 1999, 'dfwalk – Ein Murgang-Simulationsprogramm zur Gefahrezonierung', *PhD thesis*, Faculty of Natural Science and Phylosiophy, Bern University, Switzerland.

Germann-Chiari, C 2004, 'Colate detritiche', in *CatchRisk project report* 'Rapporto tecnico-scientifico finale', project mandate no. 2004-01. (in Italian)

Jaboyedoff, M & Labiouse V 2003, 'Preliminary assessment of rockfall hazard based on GIS data', *proceedings of the 10th ISRM conference*, South Africa, viewed 13 August 2008, <www.quanterra.org>

Jolma, A, Ames, DP, Horning, N, Mitasova, H, Neteler, M, Racicot, A, & Sutton, T 2006, 'Free and Open Source Geospatial Tools for Environmental Modeling and Management', in: Voinov, A., Jakeman, A., Rizzoli, A. (eds), *Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software",* Int. Environmental Modelling and Software Society, Burlington, USA.

Mergili, M & Fellin, W 2007, 'GRASS GIS and modelling of natural hazards: an integrated approach for debris flow simulation', *OSGeo Journal*, no. 3, pp 53-59, viewed 12 August 2008, <www.osgeo.org/journal/volume3>.

Mitasova, H & Mitas, L, 2001, 'Modeling Physical Systems', in Parks B., Crane M. and Clarke, K (eds.), *Geographic Information Systems and Environmental Modeling*, Prentice Hall, pp. 189-210.

Mitasova, H, n.d., 'Erosion/deposition modeling in complex terrain using GIS', *Tutorial*, viewed 12 August 2008, <http://skagit.meas.ncsu.edu/~helena/gmslab/index.html>

National Disaster management Division, Government of India 2005, 'Prevention/Protection and Mitigation from risk of Tsunami Disaster', s*trategy pape*r, viewed 14 August 2008, <www.ndmindia.nic.in>

Perla, R, Cheng, TT, McClung, DM 1980, 'A Two-Parameter Model of Snow Avalanche Motion', *Journal of Glaciology*, vol. 26, no. 94, pp 197-207

Raghavan, V, Masumoto, S, Kajiyama, A, Nemoto, T 2005, 'Landslide hazard zonation using the GRASS GIS: A case study in the Ojiya District, Niigata Prefecture, Japan.', *proceedings of the gisideas04*, Hanoi, Vietnam, viewed 13 August 2008, <http://gisws.media.osaka-cu.ac.jp/gisideas04>

U.S. Army Corps of Engineers, The Hydrologic Engineering Center 1988, 'Incorporating the Effects of Mudflows into Flood Insurance Studies on Alluvial Fans', Special Projects Report 86-4, August 1988

Voellmy, A 1955, 'Uber die Zerstorungskraft von Lawinen', *Schweizerische Bauzeitung*, 73rd year, vol. 12, 15, 17 & 37, pp 159–162, 212–217, 246–249, 280–285 (in German).

Wieczorek, GF, Morrissey, MM, Iovine, G, Godt, J 1998, 'Rock-fall Hazards in the Yosemite Valley', *USGS Open-File Reports*, no. 98-467, viewed 13 August 2008, <http://pubs.usgs.gov/>