Classification of warning systems for natural hazards

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Abstract: Intensified efforts are being made to establish warning systems as efficient components of an integrated risk management strategy for natural hazards. While testing and reliability analyses are well established procedures for active protection measures such as dams, rockfall nets and galleries, methods and conventions for evaluating the reliability of warning systems are lacking. To incorporate warning systems as standard measures of an integrated risk management strategy for natural hazards, their reliability must be quantifiable. The aim of this contribution is to establish appropriate reliability quantification methods for warning systems by classifying them according to characteristics relevant to assessing their reliability. Firstly, chief natural hazard processes in Switzerland in need of warning systems are selected and system relevant process characteristics such as the role of the geographical disposition of the event site, trigger events and dynamic process parameters are clarified. In three examples the influence of the process characteristics on the monitoring possibilities with respect to the system lead time is illustrated. A system classification is suggested, which classifies the systems in i) threshold systems, ii) expert systems and iii) model-based expert systems. The classification is applied to 52 warning systems in Switzerland and for each system class typical characteristics such as the lead time, the geographical range, the degree of human influence vs. technical influence and direct vs. indirect monitoring possibilities are identified. The classification allows a structured identification of reliability criteria for each class and is a first step towards development of a method for quantifying the reliability of warning systems for natural hazards.

1 Introduction

Integrated risk management aims to mitigate the risk caused by natural hazards to persons, animals, infrastructures and to achieve protection goals through the application of approved mitigation measures. Thereby, risk to an object i associated with a scenario j is a function of [3]:

p_j	probability of occurrence of scenario j,
pe_{ij}	presence probability of object i in scenario$j$,
V_{ij}	vulnerability of object i in scenario j,
A_i	value of object i.

Warning systems mitigate the overall risk level by reducing pe_{ij} and with sufficient warning time V_{ij} can be reduced [10]. One of the first automated warning system in Switzerland is the snow avalanche detection system in “Mahnkinn”, commissioned by a railway company in 1953 [20]. Since then, the use of viable warning systems has increased considerably, and warning systems have been established by a number of different institutions according to different needs specific to various natural hazard processes all over Switzerland. To date the systems are often installed as prototypes where technical developments are tailored to specific projects and there is little standardisation between systems [11]. In order to incorporate warning systems as standard measures in an integrated risk management strategy for natural hazards, their reliability must be quantifiable. Warning systems are complex technical systems and to efficiently access their reliability requires an holistic system approach considering the system design and the technical failures as well as the natural hazard process characteristics and the human influences. A system classification is the first step towards such a method, since it allows the identification of system reliability criteria in a structured manner. At present a recognized classification of this kind does not exist.

Glantz [8] discusses system types and classification criteria, but argues that even a simple definition for the term warning system is not practical and thus limits the system diversity, the space for interpretations and the opportunity for future system advancements. The Swiss Federal Office for Civil Protection distinguishes between warning, which is a notification to authorities, and alarm, which is issued directly to general public [6]. According to the United Nations Office for Disaster Risk Reduction [14], a warning system is “a set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss”. Monitoring is a part of warning, but it does not include automatic issued warning possibilities and is thus no warning system [8]. Bell et al. [2] classify warning systems in monitoring, expert and alarm systems, but emphasize that a sharp system classification is not convenient. These approaches and ideas are the starting point for the development of the classification proposed in this paper.

2 Hazard processes and warning systems in Switzerland

The geography of Switzerland implicates that natural hazards often involve water or mass movement processes. The landscape is characterised through rivers and more than 1500 lakes, and the Alps cover 60% of the country [22,23]. The most frequent events in Switzerland are forest fires, earthquakes, floods, (thunder) storms, rock and snow avalanches, debris flows, rock/ block and ice falls, permanent landslides, flash floods and glacier lake outburst floods (GLOF) [21]. Floods, hail and storm have been causing the highest property damages since 1990 [13], while the number of flood, debris flow, landslide and rockfall damages between 1972 and 2007 were dominated by six major flood events [12]. They caused over 50% of the total damages recorded and were mainly triggered through long-lasting rain fall [12]. Permanent landslides, debris flows and rockfalls caused 64 fatalities while floods caused 46 deaths between 1972 and 2007 (Rockfall events have only be recorded since 2002). Snow avalanches have the highest fatality rate with about 25 deaths each winter, of which a great number are self-inflicted by mountaineers and off-piste skiers [12].

The range of warning systems identified in four Cantons of Switzerland (Bernese Oberland, Grison, Ticino and Valais) mainly covers the variety of hazard processes identified (Figure 1). The documentation and analysis of these 52 active warning systems is the basis for the classification. Thereof are four systems operated by specialist departments on a national scale (Federal Office for the Environment (FOEN) - flood, MeteoSchweiz - meteo hazards, Swiss Seismological Service (SED) - earthquake, WSL Institute for Snow and Avalanche Research SLF - snow avalanches). The identified systems are installed for ten different hazards processes and classified following the suggestion from Dikau and Weichselgartner [4].

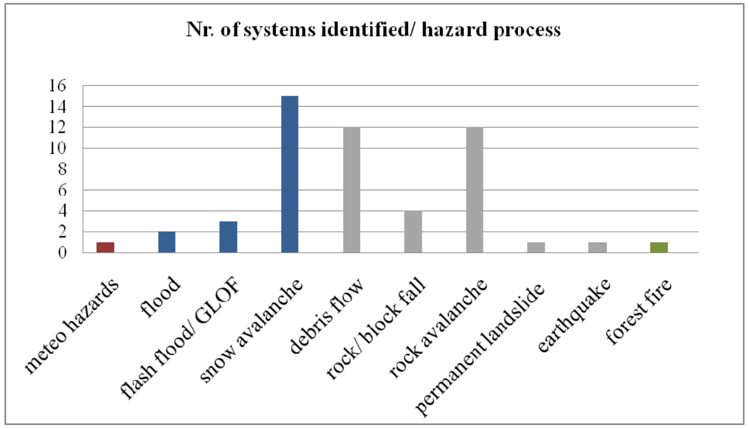

Figure 1. Number of systems identified for different hazard processes.

3 Hazard process characteristics and system monitoring possibilities

3.1 Hazard process characteristics

Natural hazard processes can be divided into an initiating *hazard event* and a resulting *damaging event* in the case that objects of value are hit. Each hazard event is characterised through its process characteristics. The *basic disposition* determines the general and long-term potential for a hazard process of a certain area. It is defined through parameters such as the topography, geology, geomorphology, hydrology and vegetation. The *variable disposition* is characterised by time dependent parameters such as state of vegetation, rain, snow and temperature changes. The basic disposition determines if an area is endangered and the variable disposition when and how often events take place[18]. Keefer [15] lists common *trigger events*, which are pre-events that activate main hazard events, such as precipitation, snow melt, frost actions, human-induced cutting of slopes, weathering processes, deposition of material on slopes, changing in ground water conditions, surface drainage, blasting, tectonic deformation and earthquakes. For an event to occur both triggers and the variable disposition must be critical and coincide [18]. Each hazard process itself is marked through specific *dynamic process parameters*.

For example, the basic disposition of a debris flow torrent could be characterised by the presence of a glacier, a terrain with steep slope and curvature, while the variable disposition depends on the availability of additional loose debris material. Trigger events can be short and intensive precipitation, long rainy periods, intense snow and ice melting, hail and outburst of sub-surface flows or a combination of them. For debris flows, characteristic dynamic process parameters are flow depth, velocity, volume and density [9].

3.2 System monitoring possibilities

Warning systems monitor different hazard process characteristics. The choice of the monitoring parameters depends on the hazard process and determines the system lead time (Figure 2). Two situations can be distinguished:

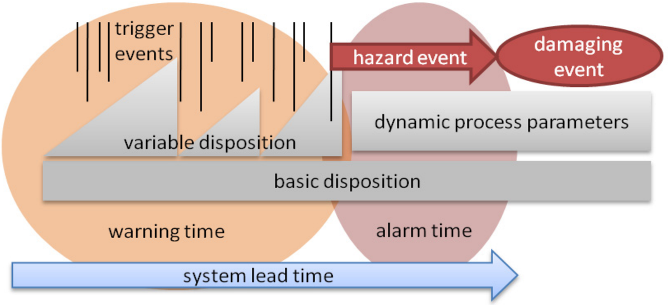

Figure 2. Reliability relevant hazard process characteristics and monitoring parameters. Figure aligned to [26].

1. System lead time = alarm time: the system directly monitors the dynamic process parameters during the ongoing hazard event. The alarm time is less or equal to the event time. Thus, the alarm time depends on the velocity of the process and the distance between the warning system and endangered objects.

2. System lead time = warning time + alarm time: the system monitors direct or indirect changes in the disposition or indirect trigger events. The potential warning time is the time between the appearances of the changes in disposition and triggers until the start of the damaging event. The lead time is the warning plus the alarm time.

The geographical coverage of a system is defined as the area covered by the monitoring system. The system coverage can be international, national, regional or local (catchment and endangered objects below). The geographical resolution is the minimum area that can be monitored.

Dikau and Weichselgartner [4], Felgentreff and Glade [5], Keller and Blodgett [16] and Lang et al. [19] discuss speed and duration, warning times as well as the geographical range of different hazard processes. We discuss the

influence of process characteristics on the system monitoring parameters in the following three examples.

The Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) operates a local debris flow warning system at Illgraben in Canton Valais. The system aims to detect ongoing events by monitoring specific dynamic process parameters. Geophones and radars are controlled by a logger, which initiates an alarm if certain thresholds for ground motion and water level are exceeded. This alarm automatically triggers acoustic and optic signals to warn the population in the catchment area. Additionally, authorities responsible for managing the hazard are informed directly and data of the event is stored in a database. Here the lead time is equal to the alarm time [1].

A local rock avalanche system was installed at Preonzo in Canton Ticino which was able to provide sufficient warning time of an event in May 2012. Prediction of the release time was possible through monitoring the variable disposition [7]. Rock avalanches, although spontaneous events [24], have typically long warning times, as they start with visible cracks, move slowly and accelerate over time [17]. In Preonzo extensometers and a theodolite were installed to directly measure pre-failure movements of the rock-mass at regular intervals. An alarm was sent to the authorities and geologists whenever a specific velocity threshold was exceeded. The decision about further actions was made by the experts after analysing the input data. The acceleration of the rock-mass was evaluated in simple models to predict critical failure. Final evacuation decisions were made based on these models and information drawn from indirect rain data. The lead time incorporated the warning time.

The national avalanche warning system operated by SLF issues information about the avalanche danger level for specific alpine regions and the Jura daily at 5pm as forecast for the following day during the winter. Avalanche forecasters use measurements of snow height, amount of fresh snow, air and snow temperature, solar radiation, wind direction and wind speed. This data inputs are crucial for judging the snowpack stability and the release of avalanches, because they affect the variable disposition. The data are collected from 180 automatic measuring stations and observers in the field. In addition, experts consult meteorological forecasts and complex snowpack models for generating two public and daily avalanche bulletins. The lead time incorporates the warning time [25].

4 System classification and application

We propose a generic classification that takes into account the monitoring possibilities and distinguishes between three system types i) threshold systems, ii) expert systems and iii) model-based expert systems. The classification has some similarities to the one given by Bell [2], but is more refined and does not incorporate monitoring systems. Expert and alarm systems are further differentiated according to certain system characteristics. The application of the classification on 52 systems identified in Switzerland revealed that each system class incorporates similar system characteristics (Table 1).

Table 1. Classification of the 52 systems identified in Switzerland. Individual system characteristics which derivate from the typical characteristic for a certain system class are illustrated in grey font.

Type **Characteristics**	**Threshold (34)**	**Expert (14)**	**Model-based expert (4)**
system lead time	alarm (34)	warning/ alarm (13) alarm (1)	warning/alarm (4)
geographical coverage	national (2) regional (1) local (31)	national (1) local (13)	national (3) regional (1)
geographical resolution	local (34)	local (14)	regional (4)
type of monitoring	direct (33)	direct (14) indirect (7)	indirect (4)
first decision instance	threshold (33)	threshold (14)	threshold (1) no (3)
final decision instance	threshold (33)	expert (14)	experts (4)
model-based decision	no (33) complex models (1)	simple model (14)	complex models (4)
automated actions	yes (34)	no (14)	no (4)
warning levels	one (21) multiple (13)	one (6) multiple (8)	multiple (4)
information receiver	endangered object (33) public (1) authorities (31) system operator (33)	endangered object (14) public (6)	interest groups (4) public (4) authorities (4)

Threshold systems are systems with small lead times on the order of minutes or seconds, installed for spontaneous natural hazard processes such as debris flows, snow avalanches, rock/ block and ice falls, GLOFs and flash flood. The geographical coverage and resolution is local. Dynamic process parameters are directly monitored in the field. A threshold determines if an alarm is issued e.g. in the form of colored or flashing lights or acoustic signals. Alarm signals are automatically provided in one or multiple states of alarm to the endangered objects, authorities and system operators.

Expert systems are installed for processes with longer lead times such as rock avalanches and permanent landslides and have lead times on the order of minutes to years. The systems installed are site specific and thus the geographical coverage and resolution of the systems is local. The parameters monitored in the variable disposition are direct changes similar to the real process parameters. The alarm is not issued automatically or with direct signals. Experts decide on necessary action plans by evaluating the monitored data and by using simple models. In addition, data is collected from parameters that are indirectly related to the process such as rain data. In most cases, systems include different alarm levels and the data is made available only to those responsible for managing natural hazards. For systems in Canton Ticino all data are collected on a server and provided to the general public on a website.

Model-based expert systems aim to make spontaneous hazard processes predictable. The alarm time is complemented with a warning time and hence a lead time in the range of hours and days is reached. Immense sensor networks offer national or regional system coverage. The input data are mainly gained through indirect monitoring parameters influencing the variable disposition and trigger data. They are further processed in complex models and resulting in final products (e.g. bulletins) published on a regular base for general public and affected institutions.

Each system class can be described though a typical system design which is influenced by the identified characteristics. The design describes the monitoring choice, the decision instances and their tresholds, expert and model dependencies, data management and alternatives for implementing measures of the integrated risk managment strategy (Figure 3).

Five out of 52 systems do not explicitly fit into one system class. The national SED earthquake detection system is a typical example of such a system. By counting the number of instances in which the system complies with the characteristics of any class, the appropriate class can be identified. Thus, the SED system is classified as a threshold system, which is based on complex models covering a national area. Another edge case system in the threshold system class is the CERTAS flood reporting system, which consists of a network of 38 local measuring stations that directly issue alarms to customers, if certain water level thresholds are exceeded. A similar threshold approach is employed in the BLS rockfall system with a regional coverage. A rockfall system operated by the Swiss Federal Railway Company has a short lead time similar to threshold systems, but complies in most characteristics with an expert system, because an expert is consulted and makes the final decision within seconds. The reason is that false alarms would cause high financial losses to the company. The FireLess system was recently installed by WSL, on a regional scale in Canton Ticino and Canton Valais, to predict forest fires and is classified as model-based expert system, even though it is issuing an alarm to the experts if a threshold is exceeded.

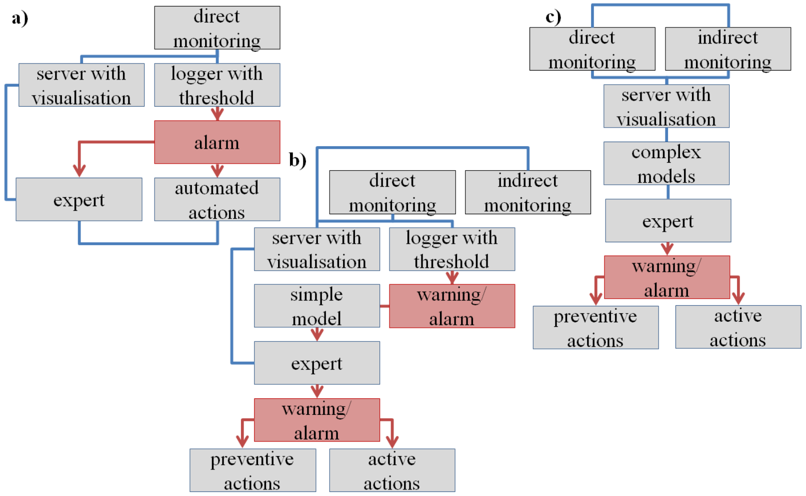

Figure 3. System designs: a) threshold, b) expert and c) model-based expert system.

5 Identification of reliability criteria

The overall reliability of a warning system is strongly related to the assigned system characteristics per class and the resulting design (Figure 4).

The reliability of threshold systems mainly depends on the threshold and the implementation of automated actions. The human influence and the technical complexity are low. Uncertain parameters are technical and data-related factors. The following reliability criteria can be derived for this class:

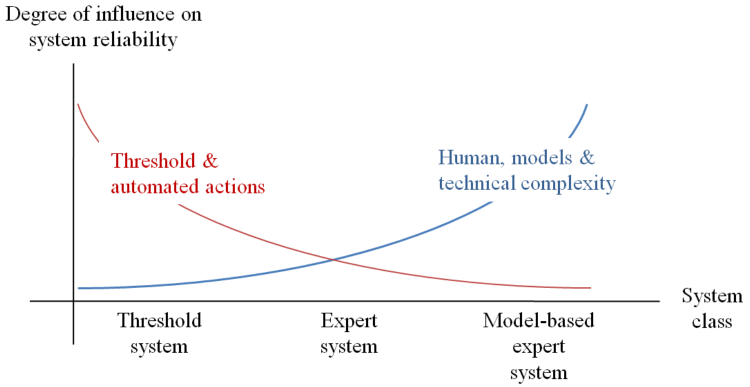

Figure 4. System types and the influence of reliability relevant characteristics on the system reliability.

- The monitoring of the correct dynamic process parameters is ensured through the right choice of sensor type, redundancies and their ideal position and fixation.
- A suitable threshold value should be chosen. A high threshold leads to missed events and a low leads to false alarms.
- The logger is functional. Power supply at remote sites is required, technical failure is reduced to a minimum and communicated automatically.
- The alarm transmission from the detection area to the endangered objectives is reliable, ideally redundant and controlled.
- The functionality of the alarm facilities/ equipment is ensured and controlled.
- The technical complexity and the number of interfaces between the system components are kept to a minimum.

The reliability of expert systems is mainly influenced by the predefined threshold and the decisions of the experts. Automated actions are not directly implemented and the technical complexity is moderate. Uncertain parameters are technical, human, data-related and organisational factors. The detection of an event depends on the same reliability criteria as for the threshold system, but is also dependent on the following criteria:

- The data is transmitted to a server and made available to the experts.
- The experts experience is high and their risk attitude neither too high nor too low.
- The quality of models used is high and the indirect data are interpreted correctly.
- Preventive and active actions are implemented in a timely manner.
- The endangered objects are reached in a timely manner.

The reliability of model-based expert systems is independent from thresholds and the implementation of automated actions, but incorporates high human influences, complex models and a high technical complexity. Uncertain parameters are technical, human, data-related, organisational- and standardisation-related factors. In addition to the factors illustrated above further criteria are relevant for the system reliability:

- Networks of several hundred sensors require a complex data management e.g. redundant servers and clear work and decision processes.
- The data format and measuring stations should be standardised, to minor the influence of measuring failures, because the same failures occur in each measurement and hence the data stay valid and comparable.

6 Conclusion

Warning systems for natural hazards can be classified as i) threshold systems, ii) expert systems and iii) model-based expert systems. The application of the classification has revealed that each system class can be described by typical system characteristics resulting in a typical system design. Systems that do not explicitly fit into one system class can be classified to the class with the highest compliance and variations can be described within the defined characteristics.

The classification does not limit the space for interpretation and further enhancement of warning systems, but allows a structured determination of reliability relevant criteria for each class. General influences on the overall system reliability could be identified for each class, before reliability criteria could be derived from the typical system characteristics. The characteristics of the monitored hazard process determines the system lead time and drastically influences the system characteristics, design and hence the system reliability criteria. The classification and the derived reliability criteria are essential inputs to develop a method for quantifying the overall reliability of warning systems. In the next step each system class will be further analysed on a subsystem level to identify appropriate reliability methods.

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8 References

[1] Badoux, A.; Graf, C.; Rhyner, J.; Kuntner, R.; McArdell, B.W.: A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. *Natural hazards* 49 (3), (2009), p. 517-539

[2] Bell, R.; Mayer, J.; Pohl, J.; Greiving, S.; Glade, T.: *Integrative Frühwarnsysteme für gravitative Massenbewegungen (ILEWS): Monitoring, Modellierung, Implemenierung*. Essen: Klartext Verlag, 2010

[3] Bründl, M.: *Risikokonzept für Naturgefahren - Leitfaden*. Bern: Nationale Plattform für Naturgefahren PLANAT, 2009

[4] Dikau, R.; Weichselgartner, J.: *Der unruhige Planet: Der Mensch und die Naturgewalten*. Darmstadt: Wissenschaftliche Buchgesellschaft, 2005

[5] Felgentreff, C.; Glade, T.: *Naturrisiken und Sozialkatastrophen*. Berlin: Springer Verlag, 2008

[6] Fuchs, C.: Warnen, alarmieren, informieren – eine Tour d'Horizon.
BEVÖLKERUNGSSCHUTZ, 3 (2009), p. 7-9

[7] GEOPRAEVENT: *Interferometrische Radarmessungen in Preonzo/TI.*
URL http://www.geopraevent.ch/?page_id=370. last retrieved: 07.08.2012

[8] Glantz, M.: *Unsable Science 8: Early warning systems: Do's and Don'ts*. Report of Workshop held 20-23 October 2003 in Shanghai, China. Boulder: National Center for Atmospheric Research, 2004

[9] Iverson, R.M.; Vallance, J.W.: New views of granular mass flows. *Geology* 29(2) (2001), p.115-118

[10] Gubler, HU.: Personal communication, 25.11.2011. Davos: Alpug GmbH

[11] Hattenberger, D.; Wöllik, A.: Naturgefahren- Mess-und Frühwarnsysteme: Einzelne rechtliche Aspekte. *Baurechtliche Blätter: bbl* 11(3) (2008), p. 89-101

[12] Hilker, N.; Badoux, A.; Hegg, C.: The Swiss flood and landslide damage database 1972–2007. *Natural Hazards Earth System Science* 9 (2009), p. 913–925

[13] IRV Interkantonaler Rückversicherungsverband: *Durchschnittlicher Anteil der Ursachen an der Schadenhöhe im Zeitraum 2002 - 2011*.
URL http://irv.ch/IRV/Services/Statistik/Elementar/Ursachen.aspx, last retrieved: 06.08.2012

[14] ISDR: *A terminology on disaster risk reduction*.
URL http://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf. last retrieved: 06.08.2012

[15] Keefer, D.K.: Earthquake-induced landslides and their effects on alluvial fans. *Journal of Sedimentary Research 69* (1999), p. 84-104

[16] Keller, E.; Blodgett. R.: *Natural Hazards - Earth`s Processes as Hazards, Disasters, and Catastrophes*. New York: Pearson Education, Inc., 2008

[17] Keusen, HR.: Warn-und Überwachungssysteme (Frühwarndienste). In: Rageth, T. (ed.)*: Frühwarndienste-Stand der Kenntnisse und Anwe*ndungen. Glarus: FAN Forstliche Arbeitsgruppe Naturgefahren, 1998, p.1-34

[18] Kienholz, H.: Early Warning systems related to Mountain Hazards. In: Zschau J.; Küppers, A.(ed.) *Early Warning Systems for Natural Disaster Reduction*. Potsdam: Springer, 2003, p. 555-564

[19] Lang, P.; Munier, H. Böhm, T.; Deutscher Wetter Dienst (ed.): *Anleitung zur Nutzung von Konrad: Das Verfahren zur schnellen Erkennung und Verfolgung sommerlicher Unwetter mittels Wetterradar*. ULR http://www.meteo.life-rostam.de/KonRad-Benutzerhandbuch.pdf. last retrieved: 08.08.2012

[20] Lehnherr, A.: Personal communication, 08.12.201. Bern: BLS AG

[21] PLANAT Nationale Plattform Naturgefahren: *Wissen.*
URL http://www.planat.ch/de/wissen/. last retrieved: 02.08.2012

[22] Russi, T.; Ammann, W.; Brabec, B.; Lehning, M.; Meister R.: Avalanche Warning Switzerland 2000. In: Zschau J. ; Küppers, A.(ed*.): Early Warning Systems for Natural Disaster Reduction*. Potsdam: Springer, 2003, p. 569-577

[23] Spreafico, M.; Weingartner, R.: *Hydrologie der Schweiz - Ausgewählte Aspekte und Resultate*. Berichte des BWG, Serie Wasser Nr. 7. Bern: Bundesamt für Wasser und Geologie BWG, 2005

[24] Varnes, D.J.: *Landslide Hazard Zonation: a review of principles and praxis*. Paris: Unesco, 1984

[25] WSL Institute for Snow and Avalanche Research SLF: *Avalanche Warning.* URL www.slf.ch/forschung_entwicklung/lawinen/lawinenwarnung/index_EN. last retrieved:22.08.2012

[26] Zimmermann, M.; Mani, P.; Gamma, P.; Gsteiger, P.; Heiniger, O.; Hunziker, G.: *Murganggefahr und Klimaänderung: ein GIS-basierter Ansatz: Projektschlussbericht im Rahmen des Nationalen Forschungsprogrammes" Klimaänderungen und Naturkatastrophen*. Schlussbericht NFP 31. Zürich: vdf Hochschulverlag AG an der ETH, 1997