UNDERSTANDING THE RISK: ESTABLISHING OF AN INTERACTIVE SYSTEM FOR THE VISUALIZATION AND EXPLORATION OF NATURAL HAZARDS AND ASSOCIATED UNCERTAINTIES

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Abstract

Gravitational natural hazards have always been part of the mountainous environment. However, during the last decades there has been a worldwide increase in damage potential while existing protection measures have often failed to prevent high damage costs.
Hazard maps are an important outcome of hazard assessments and provide for an alignment of land use with natural conditions. They are made to decrease damage potential, satisfy the safety requirements, and protect human lives and property. Yet the potential of hazard maps can only be fully exploited if all underlying data are presented to decision makers in an understandable and interpretable way.
The objective of this research is to incorporate the latest findings on hazard assessment into a concept for simultaneous representation of multivariate hazard data and their inherent uncertainties. For this purpose an interactive visualization system is being developed, providing new forms of high quality cartographic content. It aims at providing decision makers and involved experts with tools to intuitively explore and understand available natural hazard data. Combining and advancing new technologies and methods in an integrative approach will provide a guided exploration of hazard as well as uncertainty data and related visualizations. The implementation of this concept is expected to facilitate communication among experts just as it will support decision makers.

1. Introduction - Deficiencies, Needs and Goals

Although gravitational natural hazards (such as avalanches, debris flows, rock falls, and floods) are no new phenomenon in mountainous regions, characterized by a long history of protection strategies, damage costs are still increasing. In order to stop this trend holistic risk management approaches have been developed. An important element of this interdisciplinary environment is the hazard map that illustrates the results of the hazard assessment and shows where hazard-prone areas are located. However, these

maps have been designed for spatial planners and are not able to meet the requirements of every specialist involved in the complex risk management process.
A recent, very detailed analysis of the 2005 flood which occurred in Switzerland, illustrate the actual problems, deficiencies, and needs related to natural hazard assessment. According to Bezzola and Hegg (2007 & 2008), the following issues have to be addressed:

- For the definition of hazard assessment scenarios it has to be recognized that even the “unthinkable” is possible
- Uncertainties and fuzziness associated with hazard assessment and prediction have to be located and communicated
- Decision makers have to take into account uncertainties and fuzziness
- Hazard assessments have to be carried out without respect to a certain product (e.g. hazard maps or dimension of structures)
- New products (e.g. intervention/response maps, risk maps, intensity maps, etc.) have to be derived directly from hazard assessment and not via hazard maps
- Preconditions for a successful response are: emergency management and planning, early warning, alerting of the population, strengthening of local knowledge, and training of executives and response personnel

Considering these facts, the goal of this research is to provide a concept for the representation of multivariate hazard data as well as the inherent uncertainties. For this purpose an interactive system is being developed, allowing decision makers (e.g. spatial planners) and involved experts (e.g. geologists, engineers, etc.) to intuitively explore and visualize available data in order to get an overview of the hazard situation without any previous GIS knowledge or special skills. To do so, it needs to support the flow of information and facilitate the communication process during all phases of risk management.

In this context the current deficiencies of hazard representations are:

- Hazard maps often exist only in static, non-interactive form (paper-based or digital)
- Hazard maps do not include uncertainties
- Synoptic hazard maps contain a wealth of information and are difficult to read and understand by non-experts
- Communication among experts and decision makers is not well supported
- There is a loss of data through misinterpretation
- Existing knowledge on data visualization and user guidance are not combined

2. State of Research

Developing a concept to represent multivariate hazard data as well as inherent uncertainties in an interactive application requires an interdisciplinary approach, including a number of unique methods, technologies, and techniques. Since the management of natural hazards strongly depends on the situation and the legislation of a specific country, in this case the state of research concerning risk and hazard procedures was assessed for Switzerland.

2.1. Risk Management and Hazard Assessment Procedures

In the past, hazards were mostly assessed independently, often used to determine the dimension of protection measures. This point-wise approach was intended to control the course of an event in order to protect specific locations. However, with continuously increasing damage potentials, this approach has become too expensive and can no longer meet protection requirements.

Therefore, an integral approach had to be adopted, illustrated by the risk management circle (Fig. 1). It consists of three stages: prevention, event management, and regeneration. Hazard assessment is the core of this circle, providing a basis for the development of all other tasks.

Natural hazards comprise all natural events and impacts which can harm people or material assets. For the production of hazard maps, the Swiss law recognizes only the following, mostly gravitational, hazards which are spatially clearly identifiable:

- Floods (inundations, debris flows, sediment deposition, bank erosion)
- Mass movements/landslides (rock-, block-, and ice fall, rock- and block avalanches, spontaneous and continuous landslides, unconfined debris flows, subsidence, sinkholes)
- Snow avalanches (powder and dense flow avalanches, snow slabs)

The Swiss government provides guidelines for hazard assessment workflows, but the choice of methodology stands open as long as it takes into account the current state of knowledge.

There is a vast number of approaches, methods, and models for the analysis of natural hazards. The choice of methods and models largely depends on the level of detail (scale) of an assessment. On the local level where every property has to be assessed, deterministic process models based on physical laws and model parameters are frequently used in the assessment procedure. In some cases physical models in flume experiments also play an important role.

In practice, the usual procedure for hazard assessment on the local level is to form working groups comprising specialist from specific domains who assess each process. This makes hazard assessment a multidisciplinary task which involves numerous experts from different fields, where facilitation of knowledge transfer as well as communication can become a challenge.

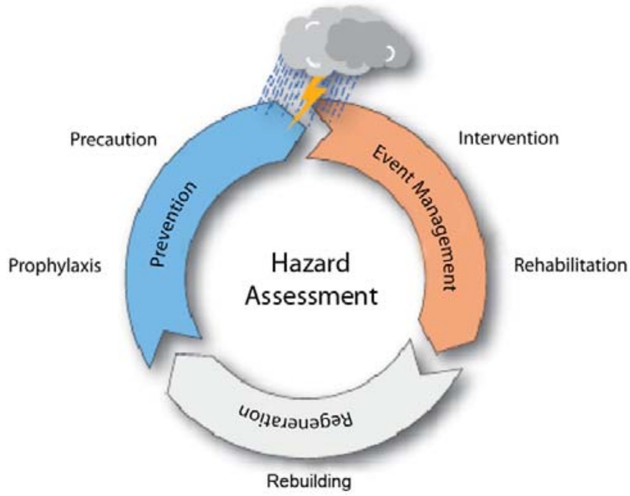

Figure 1: Risk Management Circle (Bezzola & Hegg, 2007, translated and modified)

2.2. Uncertainty in Hazard Assessment

Hazard assessment, by its very nature, is associated with uncertainty. No prediction of intensity or frequency will ever be entirely accurate (e.g. Kinzig, et al., 2000). Nevertheless, hazard assessments form the basis for decision making processes and associated uncertainty has to be addressed and communicated. Understanding the sources of these uncertainties will allow their classification and visualization.

Furthermore, updating hazard maps with respect to realized protection measures or altered climatic conditions (climate change) represents a great challenge for the future. Thus, there is a need to also consider the aspect of currency when dealing with uncertainty.

The issue of spatial data quality in general has received a lot of attention during the last two decades, especially when associated with GIS. Experts are still debating whether the inclusion of uncertainty information benefits the user or whether additional information can be confusing or misunderstood by the map reader. However, Evans (1997) investigated this issue and found that the graphic depiction of reliability information was accessible and comprehensible by all participants of her study; novice or specialist.

The definition of uncertainty in the broad sense encompasses statistical variation, errors and differences, minimum-maximum ranges, and noisy and missing data (Pang, et al., 1997). MacEachren (1992) expanded this definition by adding data variability, including spatial, temporal, and thematic issues.

2.3. Hazard and Uncertainty Visualization

In order to avoid any loss of information the hazard assessment information has to be presented in a clear and understandable way. In addition to technical reports, the results of these assessments are represented on maps of phenomena, risk maps, intervention/response maps, intensity maps, hazard index maps, and hazard maps. In Switzerland, hazard maps are derived from detailed local hazard assessments and usually range in scale from 1:2,000 to 1:10,000. They display frequency and magnitude of potential hazardous processes within the assessed perimeter, using three hazard classes (low, moderate, and high). There are maps for every single process as well as for their aggregation. The latter ones are called synoptic hazard maps and illustrate the highest possible expected hazard class for each location.

Results of assessments on a regional level are displayed on maps at scales smaller than 1:10,000. These hazard index maps delineate areas that are potentially affected by natural hazards, however, magnitudes and frequencies are not explicitly displayed.

Existing methods of cartographic uncertainty visualization include the application of visual variables, supplementing maps with added geometry (such as bars, diagrams, etc.) or adding interactive (e.g. toggling between data and uncertainty visualization) and animation (e.g. blinking areas or animated pictures) capabilities (Deitrick, 2007). Potential variables for uncertainty representation include: saturation, crispness, resolution, transparency (fog effect), color and texture. Geometry can be added by arrows, bars, dials or glyphs, which are compound point symbols used to summarize a wide array of data simultaneously (Pang, 2001). However, there is little consensus about the best technique for visualization. Furthermore, little effort has gone into assessing the use and effectiveness of the different methods, as stated by MacEachren et al. (2005).

The above mentioned methods can either be applied on separate maps (*maps compared approach*) or on a single map where data and uncertainty are combined (*maps combined approach)* (Slocum, et al., 2005). A third method is to use an interactive computer environment where users are able to manipulate the display of the data and the uncertainty (Howard & MacEachren, 1996).

Presently only a few hazard representations (e.g. US Geological Survey, 2002; National Hurricane Center, 2009) include information about uncertainty and the visualization tools and techniques are quite rudimentary (Pang, 2008). On that account, there is an obvious need for research in this field.

2.4. Representation of Multivariate Information

The representation of hazards is a classical problem for thematic cartography. However, with the aggregation of more than one hazardous process at a certain location and the introduction of uncertainty, it becomes a multivariate problem.

Andrienko and Andrienko (2007) conclude that the concept of multimedia cartography has appeared as a natural response to the new opportunities provided by computer technologies, over paper-based technologies of the past. Hereby, multimedia cartography not only aims at combining maps with images, sound elements, movies, etc., but also dynamic (animated) maps, interactive maps, linked maps (e.g. in electronic atlases), three-dimensional images and virtual reality.

It is generally believed that multimedia and interactive techniques can convey the multifaceted and dynamic character of the spatial environment much more effectively than static paper maps (Peterson, 2007).

The interaction capabilities included in multimedia cartography offer interaction between the user and the display media and aim at contributing to a better understanding of the data on display. It is recognized that exploration of non-trivial data-sets requires the data to be viewed from multiple perspectives. Support for this is found in application of several dynamically coordinated displays of various types (Andrienko & Andrienko, 2007).

As natural hazards have a highly dynamic nature and the associated data are multifaceted and obviously non-trivial, it is apparent that an interactive environment can improve the possibilities of adequately illustrating this field. Such systems provide a platform for the presentation of graphs, plots, diagrams, and maps. Digital maps must follow the same cartographic principles as paper maps, but in addition, the visualization has to be adapted to altered conditions.

However, the basic visual variables, as introduced by Bertin (1977) and extended by MacEachren (1992), remain equally applicable. Huber, et al. (2007) discuss these visual variables and present a new generic approach of multivariate mapping in high quality atlases.

2.5. Multimedia Atlas Information Systems

Multimedia Atlas Information Systems (MAIS) encompass numerous characteristics and functionality which facilitate the presentation of multivariate information.
In Hurni’s (2008) definition of MAIS, numerous advantages for the handling of the previously mentioned digital data can be found: MAIS are systematic, targeted collections of spatially related knowledge in electronic form, providing a user-oriented form of communication for information and decision-making purposes. The different maps have a common legend and symbolization and can be accessed through thematic or geographic indexes. MAIS dispose of special interactive functions for thematic or geographic navigation, querying, analysis and visualization. The data in MAIS is cartographically edited and the functionality is intentionally limited to provide a user-targeted set of data as well as adapted analysis and visualization functions. In multimedia atlases, additional related multimedia information (graphics, diagrams,

tables, text, images, videos, animations, and audio documents) are linked to geographic entities.

Most modern atlases comprise versatile navigation tools, sophisticated visualization techniques and analytical functionality. Zooming and panning, coloring, and interactive queries are standard features (Sieber, et al., 2005). The access to these functions is provided by the Graphical User Interface (GUI). In order to guarantee an unconfined and intuitive use of the system, the GUI has to be laid out clearly and the functions must be easily recognizable and manageable.

3. Methodology

3.1. Goals of the Project

The specific tasks of this project will be conducted in a theoretical and conceptual framework, which can be applied to diverse sets of multivariate hazard data. To support the practicability and the increased value of these developed concepts for hazard and uncertainty representations, they will be implemented in an interactive system prototype (Fig. 2). This prototype for natural hazard data representation and exploration will be developed by applying and extending existing methodology concerning GUI design, MAIS, interactive hazard maps and general rules for digital and multimedia cartography.

The targeted users are experts assessing hazards, specialists working with hazard assessments and decision makers with existing hazard knowledge. The proposed visualizations are intended to improve the communication among this heterogeneous user group. To support and encourage a better exchange of information, the available functionalities and representations will guide the user through the layers of data and facilitate better understanding of the issues.

The following chapters describe the specific tasks that must be carried out in order to develop a holistic concept for enhanced hazard data and uncertainty exploration and visualization.

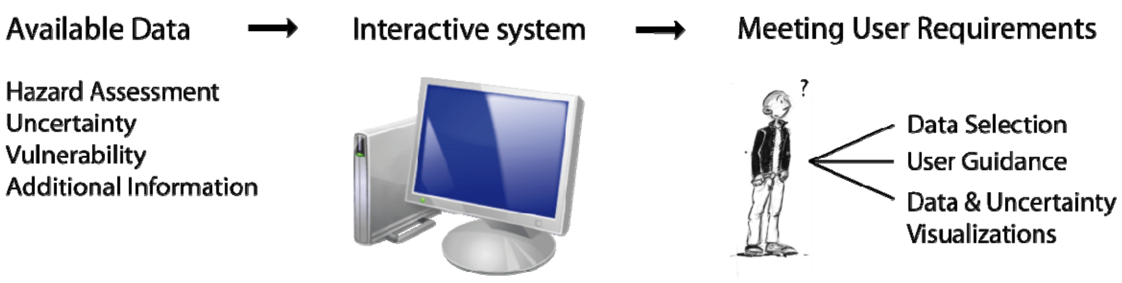

Figure 2: Interactive System

3.2. Development of Large-scale Multi-Hazard Representations

Synoptic hazard maps contain an enormous amount of information and the resulting visualizations are often overloaded and therefore difficult to understand and interpret. A disentanglement of the information with a subsequent reorganization into a layer structure (as applied in GIS) seems a plausible idea for decreasing the complexity of these maps. Combinations of Bertin's (1977) visual variables and MacEachren's (1992) extensions will be tested for their suitability to illustrate these layered hazard data.

The multivariate hazard representations will be developed at relatively large scales of 1:2,000 to 1:10,000. They have to be intuitively interpretable by the users, enabling them to indentify hazard-prone areas and the processes by which they are affected. To facilitate these tasks, several interactions will be implemented, including common ones like zooming and panning, more sophisticated ones like changing visualization parameters according to the user's needs, or experimental ones like multivariate representations or clustering. Different multivariate representation methods (e.g. layering, combination of variables, map-related representations, etc.) will be tested, assessed, developed further and finally implemented.

3.3. Design of Uncertainty Visualizations

Uncertainties arise during every step of the hazard assessment, and calculating the exact quantification for every map would be disproportionate to its cost (if at all feasible). However, recent events have made it clear that existing uncertainties and fuzziness inherent to hazard assessment must be addressed so that they become comprehensible and can easily be shared between experts and decision makers involved. Such statements of uncertainty, made by the responsible specialists, will have to be analyzed, quantified, classified and eventually visualized.

Probabilistic approaches such as Bayesian networks have been used for the introduction of uncertainties into the process of hazard assessment. In such networks, experts' knowledge about the input parameters can be incorporated into the risk or hazard analysis. A visualization of different outcomes resulting from varying confidence intervals of the input parameters will be the first attempt for hazard map uncertainty visualization.

There are several existing methods for uncertainty visualization in general. Effective visualizations (whether uncertainty is taken into account or not) must address the user needs (Pang, 2008) and the most suitable for hazard mapping will be determined through a review of different possible methods.

The use of an interactive environment for this purpose offers a number of advantages: users may identify the sources of different uncertainties and explore available data to

identify the issues most relevant to them. In addition, they may choose between various display methods, such as the maps compared approach, the maps combined approach, or an interactive version within which the data and uncertainty display is manipulable.
Since the users are carefully guided through visualization and exploration of selected data, misunderstandings and misinterpretations associated with uncertainty representations are expected to be minimized.

3.4. Introduction and Development of Additional Cartographic Depictions in the Field of Hazard Mapping

Cartographers have long adhered to the view that maps are primarily a medium of communication and only recently, many have started to recognize the role of maps as means of supporting visual thinking and decision making (Andrienko & Andrienko, 1999). In order to enhance visual data processing and to offer better methods for exploring and interpreting hazard data, additional visualization methods such as the display of cross sections, block diagrams, and statistical surfaces will be used for their representation. The implementation of such a variety of visual representations of hazard data will enhance interpretation of the data and lead to a better understanding of the available information. For best results, the existing methods need to be modified and adapted to the field of natural hazards.

3.5. Development of User Guidance

To facilitate the handling of hazard related data, the GUI of the prototype has to guarantee an easy and intuitive handling of the tool. In addition, users will be guided through the available pre-processed data and their visualizations in order to gather all relevant information.

By merging and enhancing existing knowledge and technologies, the GUI will be developed with a user-centered approach in order to fulfill the requirements of the users. The structure of the system will be tripartite; there will be a section for data exploration, a section for data visualization, and a section for data analysis.

In the exploration part, an overview of the available data is presented. From there, users can either determine which data is of importance by selecting the layers themselves or by choosing a standard set of data.

In the visualization part the chosen data (including uncertainty) can be displayed in manifold ways (as explained above), yet always according to the user’s choice. Different parameters such as color settings, patterns, transparency, etc. may easily be modified. However, there will also be a standard set of visualizations for users less keen to experiment.

The analysis part finally enables the user to create new layers and maps through overlaying, blending or by adding additional data.

4. Discussion and Expected Results

This innovative project combines and advances existing technologies and methods in an integrative approach to provide a guided exploration and visualization of hazard data and uncertainty. The users decide which data they want to explore and how they want them to be visualized. The use of an interactive environment offers the opportunity to guide experts and decision makers from different backgrounds and with different skills through the labyrinth of complex data. This is achieved by offering varying visualization methods, which has not been previously possible with printed maps. The usability of such a system is emphasized by incorporating the latest findings of GUI and MAIS technologies.

In addition, such a system carries the potential to offer a novel platform for uncertainty visualization so that uncertainty is eventually incorporated quantitatively in the decision making process.

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