Customized Visualization of Natural Hazards Assessment Results and Associated Uncertainties through Interactive Functionality

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ABSTRACT: Communication of natural hazard assessment results is crucial to protect people and infrastructure from devastating impacts of extreme events. While hazard maps provide important information on potential impacts, their interpretation and the general knowledge exchange between stakeholders is often difficult. Web-based information systems contain the potential to support hazard management tasks by fast distribution and customization of hazard visualizations through interactive functionality. Cartographic principles are, however, often ignored in existing web-based visualizations which leads to poor graphical results and consequently to an impairment of the information flow. While these issues need to be solved, a new task is already waiting: the integration of uncertainty information into hazard visualizations. Since many hazard management activities rely on hazard assessment results, communication of associated uncertainties among experts is vital.

The challenge of this research is to overcome these existing shortcomings by combining high quality cartographic visualizations of natural hazard data as well as associated uncertainties with interactive functionality. The resulting web-based cartographic information system will convene the needs of natural hazard specialists by offering a high level of customization: the suggested visualizations include various cartographic techniques such as the application of textures, bars, and interpolated surfaces. The possibility to interactively select particular data sets, customize colors, choose dimensions, query attribute data, and include uncertainty information facilitates the interpretation of complex data and finally the communication among natural hazard specialists.

In this paper we summarize requirements that have to be considered, suggest functionalities necessary to perform natural hazards management tasks, and present a prototype of an expert system for the visualization and exploration of natural hazards assessments results and associated uncertainties.

Keywords: Natural Hazards, Visualization Customization, Uncertainty Visualization, Cartographic Information System

Introduction

Natural disasters cause suffering through the harm of people and infrastructure as well as enormous economical damage. Natural hazard management aims at minimizing these impacts by the tasks of prevention, event management, and rebuilding (Bezzola and Hegg, 2008). Assessments of natural hazards form the basis for all management tasks and are therefore a crucial component of hazard management. This fact has become apparent during the last years and consequently funds for the advancement of hazard assessments as well as the enhancement of management strategies have been allocated (e.g. by the Swiss Government).

Cartographic representations have proved suitable for the communication of hazard assessment results which is reflected in the fact that the generation of hazard maps as basis for land-use-planning is standard procedure in many countries and in some places even regulated by law (e.g. Switzerland[1], Colorado[2], and many more).

Motivation

Recent analyses of past flood events (Bezzola and Hegg, 2008) showed that the requirements towards hazard maps have increased over the last years: not only spatial planners for whom these maps were designed work with these visual representations of natural hazard assessment results, but also many other specialists involved in different tasks of hazard management. Bezzola and Hegg (2008) therefore suggest that hazard assessments should not be performed for a particular application anymore but as a general basis for various future uses. Once these multifaceted results exist, they can be visualized for specific users according to their requirements. These visualizations, however, have to be generated following cartographic design principles in order to produce clear and well balanced maps that are effortlessly readable.

An additional issue which is often discussed in different hazard management phases and tasks is the question of uncertainty inherent to hazard assessment results. Many important decisions that can have severe consequences for third parties (e.g. initiation of evacuation, construction bans, etc.) are based on these results. Information about the accuracy of the presented assessment results is therefore very important. However, until now, most hazard maps pretended absolute certainty by solid borders of hazard zones even though experts agree that the definition of hazard zones is associated with uncertainty. Apart from the difficulties of quantifying existing uncertainties, this issue also poses a cartographic challenge: there are no guidelines about suitable methods for uncertainty visualization in natural hazard maps and most existing recommendations are only of theoretical nature (Pang, 2008).

Overview and References to Related Work

The Internet has evolved to one of the most relevant media to publish cartographic information, as it facilitates greater access to spatial information, increased levels of interactivity with maps, real-time locational information, and greater integration of multimedia content through pictures, sound, and video (Peterson, 2008). In recent years, web cartography shifted towards a distributed and service-oriented cartography, providing individual maps on-demand for specific purposes (Schnabel and Hurni, 2009). While early web maps were mostly raster-based and static, modern interactive applications allow for thematic as well as geographic navigation and offer visualization functionality to display available information according to the specific needs of the users. In addition, users can be guided through the map making process in order to avoid the violation of cartographic rules. Consequently, a web-based cartographic information system provides a well suited environment for the visualization and exploration of natural hazards assessment results as well as associated uncertainties.

Chesneau (2004) analyzed over two hundred hazard visualizations which were published in geographic journals and the Internet and observed that most maps are published in printed form; interactive or multimedia environments are rare. Her analysis also showed that most web-based maps offer little interactive functionality and consequently the implementation of animations and interactivity into natural hazard visualization environments is suggested. Research by Peterson (2007) confirms that 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.

The lack of interactive functionality in web-based applications can also be observed in tools for the presentation of spatial data in general. In Switzerland for example, such tools have become common during the past years and every canton (= state or province) maintains its own system. These so called geoportals are designed for the general public and the typical application offers little interactivity: thematic content is available in a layer structure so that users can select the topics they want to have visualized in 2D maps and sometimes the query of attribute information is possible. Further interactions are generally limited to zooming and panning.

However, the need for interactive expert tools has been identified in recent research. Lienert et al. (2009) developed a web-based application for the real-time visualization of hydrological data. This application offers functionality to interactively monitor, retrace, and compare the available information. Romang et al. (2010) built on the experiences of snow avalanche tools and established an interactive early warning and information system for floods and debris flows.

Research in the field of uncertainty visualization has been ongoing for the last 30 years; after Buttenfield and Ganter (1990) analyzed Bertin’s (1983) visual variables and suggested what characteristics of uncertainty can be illustrated by these variables, different studies have investigated and in some cases also evaluated potential visualization methods for the visualization of uncertainty in geospatial data sets (e.g. Buttenfield and Beard, 1991; MacEachren, 1992; McGranaghan, 1993; Goodchild et al., 1994; Van der Wel et al., 1994; Wittenbrink et al., 1996; Leitner and Buttenfield, 2000; Drecki, 2002; Aerts et al.2003; MacEachren et al., 2005; Zuk and Carpendale, 2006). More recent research analyzed general uncertainty visualization methods and assessed their suitability for applications in the field of natural hazards: Trau and Hurni (2007) give an overview on existing methods and suggest visualizations suitable for the depiction of uncertainty in hazard and hazard index maps, Bostrom et al. (2008) present a review of research about the visualization of seismic risk and uncertainty and Pang (2008) finally discusses the issue of uncertainty associated to natural hazards data in detail and presents potential methods for visualizing uncertainty in natural hazards such as the application of blurriness, transparency, or fuzziness, the use of color hue, saturation, or value, the superimposition of a grid that is modified according to uncertainty values, the drawing of contour lines, the variation of the thickness, brightness, or connectedness of symbolization, the use of glyphs, histograms, or box plots, or the creation of complex 3D surfaces.

Aims

The objective of this research is to facilitate the interpretation of natural hazard data by implementing natural hazard assessment results into a web-based cartographic information system. Since these systems provide collections of spatially related knowledge, they are also referred to as Multimedia Atlas Information Systems (MAIS). According to Hurni (2008), MAIS are defined as follows: they consist of a harmonized collection of maps with different topics and scales. The maps have a common legend and symbolization. MAIS dispose of interactive functions for geographic and thematic navigation, querying, analysis, and visualization in 2D and 3D mode. Unlike in many geographic information systems (GIS) applications, the data in MAIS is cartographically edited and the functionality is intentionally limited in order to provide a user-targeted set of data as well as adapted analysis and visualization functions. In multimedia atlases, additional related multimedia information, like graphics, diagrams, tables, text, images, videos, animations, and audio documents, are linked to the geographic entities.

All advantages of MAIS characteristics are integrated into our cartographic information system to ensure for a customized visualization that meets the requirements of natural hazard experts. In addition to high quality visualizations of thematic information about hazard assessment results, our system also allows for the visualization of uncertainty inherent to these results, which is needed to support users during their decision making tasks.

Requirements

According to Acevedo et al. (2008) evaluations of visualization methods by visual design experts are faster and more productive than quantitative user studies. We therefore decided to design a first version of our cartographic information system according to the opinions of specialists in the field of web-, multimedia-, and atlas-cartography. As a first step we collected general feedback from project leaders of ongoing and completed projects of the Institute of Cartography of ETH Zurich (IKA) in order to adopt the main findings about design of graphical user interfaces (GUI), interactive functionality, and visualization methods for our cartographic information system. These projects include the Atlas of Switzerland (AdS, 2004; Sieber et al., 2009), the Swiss World Atlas interactive (SWAi, 2010; Cron et al., 2009; Marty et al., 2009), GEOWARN Geospatial warning system (GEOWARN, 2003; Gogu et al., 2006), and Real-Time Cartography in Operational Hydrology (Lienert et al., 2009). After the development of a first version of the prototype it was presented to the above mentioned specialists who subsequently rated and prioritized specific elements and provided suggestions for improvement. The goal of these interviews was to determine the main priorities for the design of an optimal GUI, promising visualization methods, as well as the main functionality which should allow users to customize the visualizations in order to meet their requirements. Finally, the findings of the interviews were integrated in the first version of the prototype and will be explained in detail in the following sections.

User Definition and Content Requirements

Cartographic representations can only be optimized if end users and data types are known. As mentioned in the introduction of this paper, end users of our cartographic information system are specialists involved in different tasks of natural hazards management such as hazard assessments, spatial planning, planning of defense structures, emergency planning, etc. These experts encompass scientists, engineers, and spatial planners working for private companies, national or federal offices, or humanitarian organizations. Consequently, they come from different backgrounds and have different map reading skills. This very heterogeneous user group of experts will therefore exhibit different needs and requirements for hazard and uncertainty visualizations.

The goal of this research is to account for these different needs by offering a platform for the integration of various assessment results (including uncertainty measures and additional background information) as well as the possibility for an interactive customization of natural hazard visualizations (see Figure 1).

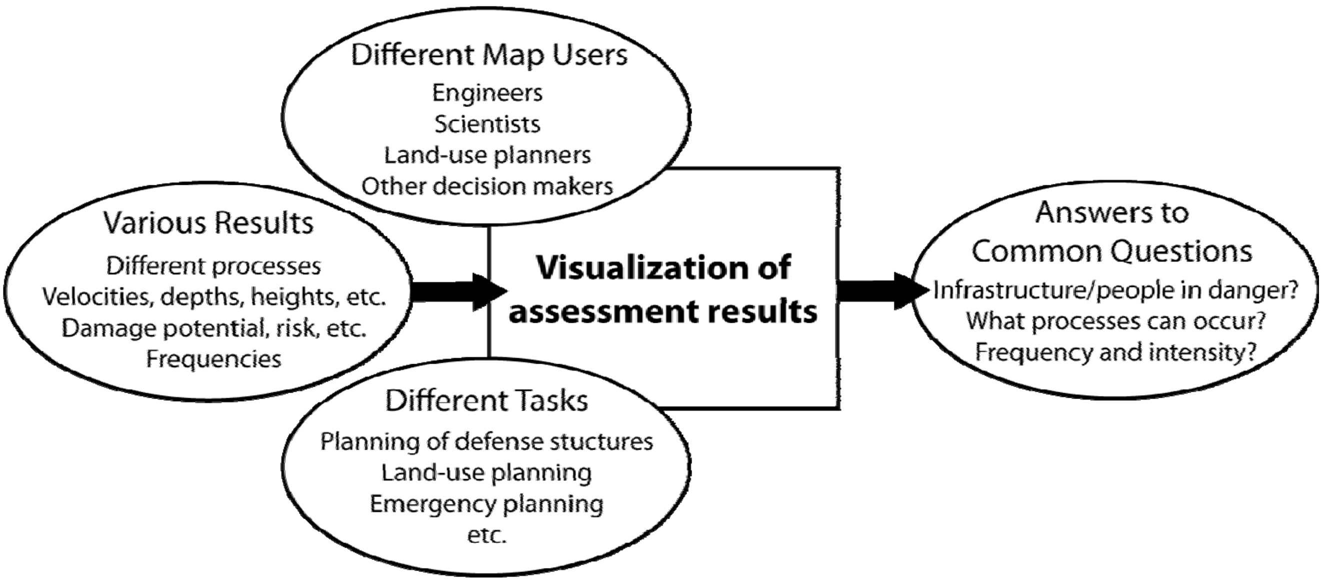

Figure 1: Requirements towards natural hazard visualizations

Although a variety of visualization methods have to be provided to meet the different visual preferences, the underlying data set will remain the same as all users are interested in the answer to the following questions: (1) Is a specific area (and consequently infrastructure and people) endangered by natural hazards? (2) What processes can occur? (3) How frequent and how intense will the hazardous events be? The level of detail the answers to these questions have to offer varies from user to user and from task to task. We therefore provide the option to interactively choose the data layers of interest as well as scale and dimension of presentation. Apart from thematic data map backgrounds for orientation in form of aerial images, topographic maps, and survey plans are available.

Thematic data includes assessment results of different natural processes such as snow avalanches, debris flows and flooding. These results encompass various data sets, for example snow heights, velocities, and pressure for snow avalanches, flow height and velocities for debris flows, or water depths and velocities for flooding. However, apart from standard assessment results, the system allows for the integration of additional information. Data sets are loaded into the cartographic information system in form of raster-based data (ascii-files) and are then converted into interactively queryable 2D and 2.5D symbolization (areal symbolization, bars and interpolated surfaces).

As mentioned in the introduction, uncertainty inherent to natural hazards assessment results presents an issue for many natural hazards specialists. The question of how to visualize this information forms a major part of this research and will be discussed in detail in section "Visualization of Uncertainties". Uncertainty information is also imported in form of raster files and converted into 2D and 2.5D symbolization that can be interactively queried.

Visualization Requirements

General Requirements

Chesneau's research (2004) showed that most web-based hazard maps are raster based and lack cartographic quality. Cartographic principles are often ignored because the mapmakers are domain specialists and not cartographers (Kunz and Hurni, 2011). In order to generate visually appealing and effortlessly readable maps, cartographic principles such as an appropriate choice of color, balance between thematic layers and base map, or maximum numbers of classes have to be followed.

Additionally, screen maps have to be designed coarser and simpler than paper maps in order to convey the desired information under less than ideal conditions of low screen resolution, increased viewing distance, and shorter reading time (Jenny et al., 2008). All these guidelines and suggestions are implemented in our cartographic information system: the offered colors, base maps, and layer combinations are in accordance with these rules and ensure cartographically high quality maps.

Symbolization Requirements

The Swiss standard coloring for hazard maps (yellow for low hazard, blue for moderate hazard, and red for high hazard, as explained in Loat and Petrascheck, 1997) are not always considered to be sensible or logical (Zimmermann et al., 2005).

We therefore offer different color schemes for the depiction of thematic data from which the user can choose the most appealing. Snow avalanche parameters for example can be visualized in grey, blue, or purple (see Figure 2), the cold colors reflecting the characteristics of snow. For all color schemes at least one of the options convenes the needs of color vision impaired users.

Further shortcomings of hazard maps include illegibility due to the included wealth of information and unsuitable symbolization (Zimmermann et al., 2005). The issue of information overflow can be solved by interactive navigation functions, such as a layer structure of the data or adaptive zooming. If the overlaying of several layers is of interest nonetheless, suitable area symbolization such as gridded patterns can avoid the overlapping of thematic information.

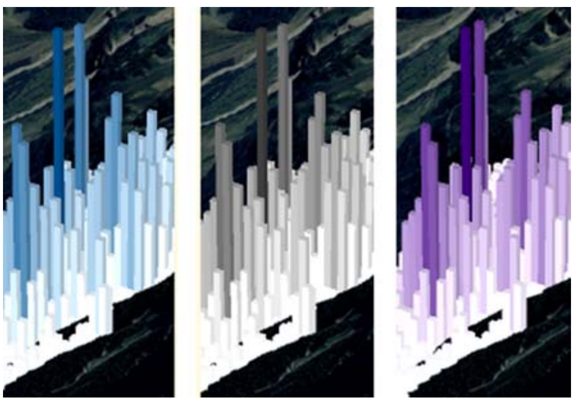

Figure 2: Different color schemes for the depiction of snow avalanche assessment results

In order to convene the needs of the heterogeneous user group, different visualization methods are offered: apart from traditional 2D maps also a block diagram mode (3D view of a rectangular extract of the surface) can be chosen as background for the thematic data (see Figure 3).

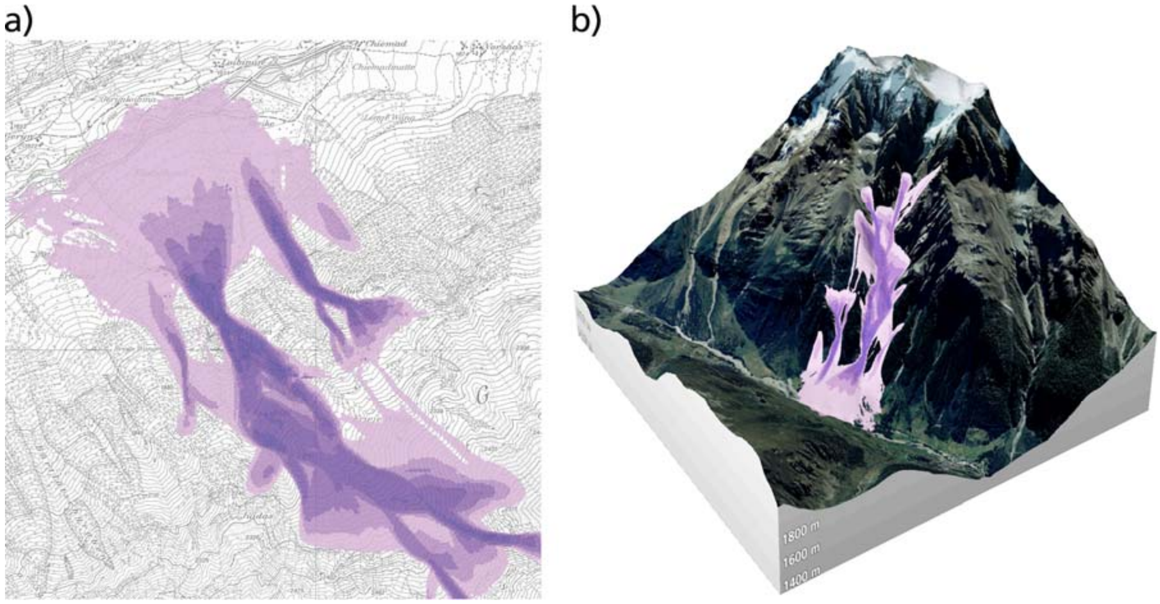

Figure 3: 2D map mode (a) and block diagram mode (b) with application of 2D symbolization

Hazard assessment results as well as uncertainty information can then be added in form of texture, bars, or interpolated surfaces. This 2.5D symbolization complements the standard 2D maps and gives an overview on the terrain and the dynamics of hazardous processes. According to the cartography experts real 3D symbolization such as little abstracted, photorealistic representations of hazardous processes does not bring any advantages for the analysis of natural hazards assessment results and was therefore not implemented in our system.

Functionality Requirements

A very significant element of the usability of MAIS is the degree of interactivity which is based on the richness of interactive functionality (Hurni, 2008). Cron et al. (2007) analyzed these functions and provide suggestions for structured GUIs. Their classification of functionality is based on Ormeling's (1997) outline and encompasses general functions, functions for navigation, didactic functions, cartographic and visualization functions, and GIS functions. General functions are permanently available for the users, irrespective of the displayed data. Navigation functions comprise functions for spatial, thematic, and temporal navigation. Didactic functions offer explanations about maps, predefined tours, movies, or images as well as self control functions to test the acquired knowledge. Cartographic and visualization functionality allows for the graphic modification of visualizations and are used for the enhancement of the map message. They encompass map manipulation, redlining (addition of drawings, labeling, and comments), and exploratory data analysis. GIS functionality serves for the handling of space and object oriented as well as thematic information. They include spatial and thematic information retrieval functions as well as analysis functionality.

To determine the importance of single interactive functions, we presented a list of potential functions (see Table 1) to the IKA experts. The experts were asked to prioritize the functions from 1 (must be implemented) to 4 (very low priority). The prioritization was evaluated and the findings served as guideline for the first prototype of our cartographic information system for the visualization of natural hazard results and inherent uncertainties. A summary of the findings concerning the prioritization of interactive functionality is provided in the following sections.

General Functions	Information about zoom factor (figure, e.g. 1 : 10 000) Graphic scale bar Switching between 2D and 3D mode Highlighting of legend Help menu Print option Jump to previous map display
Navigation Functions	Zooming Panning 3D navigation (rotation and tilting) Overview map Layer structure Search function for place names
Explanatory Functions	Integration of additional information about data and uncertainty Photo archive
Cartographic and Visualization Functions	Free addition and removal of layers to the display Layer transparency Free classification of thematic data Choice of colors
GIS Functions	Display of coordinates (x, y, z) Measurement tool Generation of cross sections Display of tooltips for attribute query Real GIS functions such as spatial intersection, creation of buffers, etc.

Table 1: List of potential interactive functionality that was rated by the cartography experts (Grouping according to Cron et al., 2007)

General Functions: The cartography experts considered a graphical scale bar, buttons to switch between 2D and block diagram mode, as well as highlighting the according legend entry when the mouse is moved over symbolization as the most important general functions for a cartographic information system.
Functions that are rated useful but not first priority will be implemented in a later phase of the project and include a help menu with explanation about the proper use of the functions, the option to go back to the last viewed map, and a print option.

Navigation Functions: Concerning the spatial navigation experts suggested prioritizing the functions of zooming, panning, tilting and rotation (for block diagram mode only), and the display of an overview map.
However, zooming is only judged as useful if adaptive zooming is implemented. Adaptive zooming means that each zoom level is generalized according to its scale so that the map is not only magnified, but also more information is displayed when zooming in (Brühlmeier, 2000).
Top priority for thematic navigation was given to the implementation of a layer structure so that data may be individually chosen for display by the users. The need for a search engine for names and places was assigned second priority.
Temporal navigation of natural hazard assessment data is not part of this research and according functionality will therefore not be implemented.

Explanatory Functions: Didactic functions are not needed for an expert system. However, the integration of explanatory functions, such as detailed information about the assessment results (methodology, date of assessment, etc.) as well as details about the uncertainty information (method of quantification, etc.) was rated to be of second priority. The implementation of a photo archive was listed as an interesting but not necessary feature.

Cartographic and Visualization Functions: First priority for map manipulation functionality was assigned to the free addition and removal of layers to the map display as well as the control over layer transparency to avoid concealment of important information. The altering of colors was rated second priority.
Redlining was only mentioned as innovative idea that could be considered as comments or drawings of experienced specialists might be of interest to other users.

Functions for exploratory data analysis should primarily include the free modification of data classification (choosing number of classes, thresholds, as well as coloring). The option of a split display for the comparison of different thematic layers is an idea that will be considered in a later stage.

GIS Functions: None of the proposed GIS functions was prioritized by our experts. The display of current cursor position coordinates and measurement tools were only assigned second priority.
Thematic and object related information (attribute information) can be retrieved and displayed in form of tooltip windows. Tooltip windows appear next to the cursor when moved over thematic symbolization (e.g. bars) and contain exact values of the assessment results as well as available uncertainty information. This functionality was considered to be important. However, apart from the display of tooltip information also the option to remove this additional window from the display was given high priority. Further development could foresee to offer different levels of tooltip information.
Analysis functions are used to generate new information and connections between spatial phenomena (Bollmann and Koch, 2001). None of these functions were assigned first priority as the goal of our system is visual data analysis and not the creation of new data sets. Analysis functionalities to be implemented in a later phase include merging, intersection, and aggregation of thematic layers. The generation of cross sections was rated to be of very low importance.

Visualization of Uncertainties

The dilemma of needing accurate assessment results for the planning of mitigation tasks to minimize the impacts of natural hazard events and the inability to provide these results without uncertainties has been a well discussed issue in the natural hazard management community for the last years. Some experts advocate the inclusion of uncertainty information in hazard visualizations while others argue that additional information only confuses the map reader. Evans (1997) investigated this issue and found that the graphic depiction of reliability information was accessible and comprehensible by all participants of her study. Also Leitner and Buttenfield (1997; 2000) as well as Aerts et al. (2003) found that the embedding of uncertainty information leads to a clarification rather than rendering a graphical display more complex.
Presently only a few hazard representations include information about uncertainty and existing visualization tools and techniques are quite rudimentary (Pang, 2008). In order to remedy this obvious shortcoming, we integrated information about uncertainty in our cartographic information system and offer different methods for its visualization.
Uncertainty encompasses different concepts such as imprecision, imperfect knowledge, inaccuracy, inconsistency, missing information, noise, ambiguity, lack of reliability, etc. (Pang, 2008). These aspects can be expressed in different ways, e.g. as statistical variations or spread, min-max range values, data quality or reliability, likelihood and probabilistic estimates, etc.
In our system, information about uncertainty includes at this point model uncertainties in form of standard deviation, range, and variation coefficient that have been calculated by a sensitivity analysis of the used numerical model. This information is interactively retrievable: on the one hand uncertainty can be displayed in a tooltip window when the cursor is moved over symbolization of a thematic layer, expressed as single scalar value. On the other hand we provide the option to visualize uncertainty either as additional layer (two separate maps; also called univariate display, see Figure 4a) or combined with the visualization of the assessment results (one map only; also called bivariate display, see Figure 4b and 4c).
If uncertainty is visualized in an additional layer, isolated from the assessment results in a separate layer, color is used for its representation in both, 2D and the block diagram mode. In the block diagram mode also the variable size (height of bars and interpolated surfaces) is used for the depiction of uncertainty values. In bivariate displays uncertainty visualizations can either be applied on top of the assessment results visualizations in form of proportional circles, density of speckles (after Djurcilov et al., 2002) of texture overlay (see Figure 4b), and contour lines (extrinsic visualizations) or directly be mapped to the assessment results visualization in form of changes in saturation (see Figure 4c) or transparency (intrinsic visualizations).

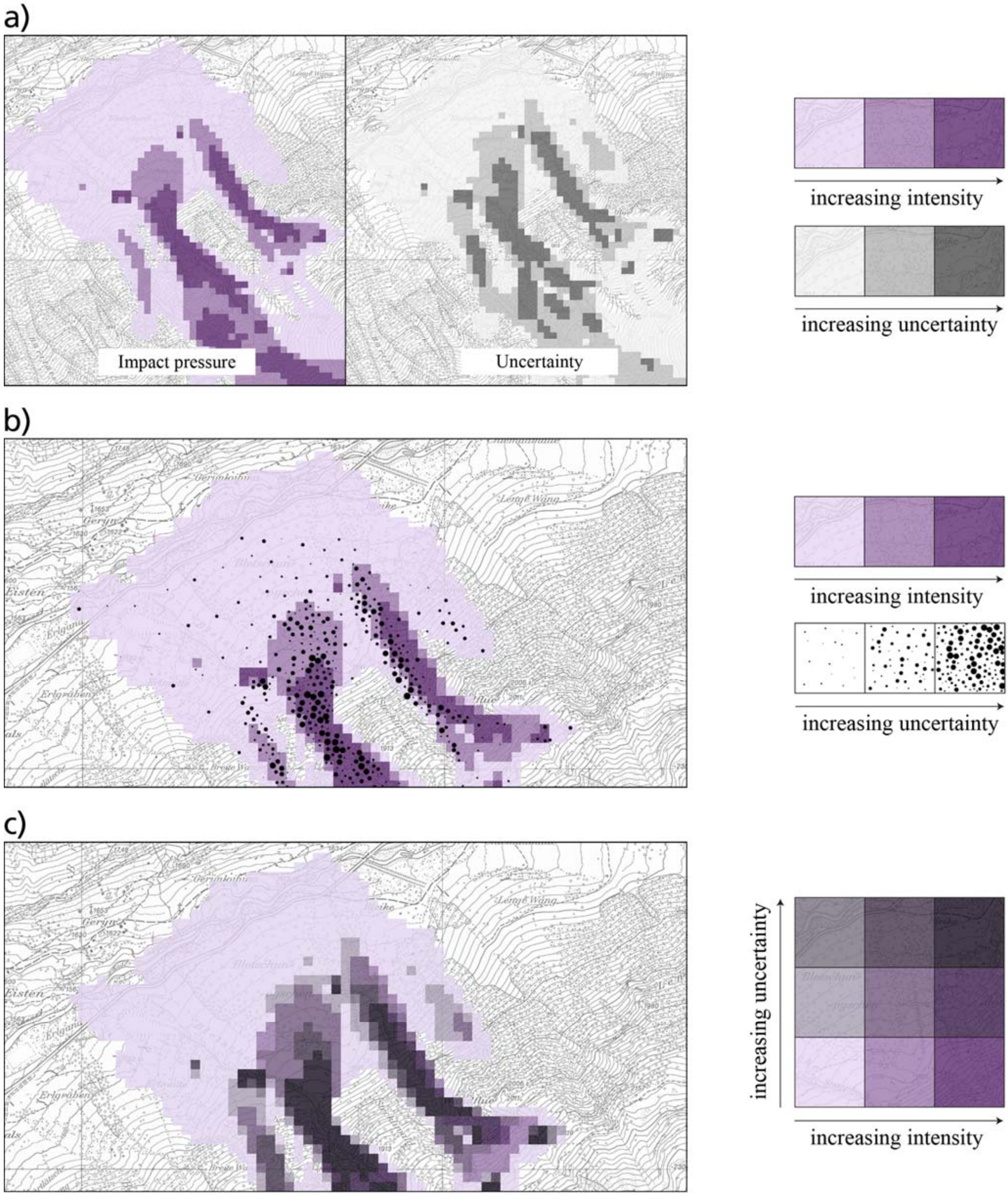

Figure 4: Uncertainty visualizations: (a) univariate method where impact pressure and uncertainty are displayed in two separate maps, (b) bivariate method where the visualization of impact pressure is overlaid with uncertainty information (extrinsic symbolization), and (c) bivariate method where intensity and uncertainty are mapped in the same layer by altering color brightness with intensity and color saturation with uncertainty (intrinsic symbolization)

Prototype

The implementation of the cartography experts' opinions concerning design and useful functionality resulted in a first version of the cartographic information system for the visualization of natural hazards assessment results and inherent uncertainties. It was designed as a Java Web Start application, which allows for the implementation of the needed interactivity and the 3D block diagram mode. The GUI of the system makes use of existing modules of the interactive version of the Swiss World Atlas (SWAi, 2010). This elaborate user interface has been designed for high school students and natural hazards experts should be able to use it without any time-consuming training. Until now, our cartographic information system provides standard assessment results of gravitational natural hazards for the study area of the "Stampbach" area in the community of Blatten, Switzerland. Figure 5 shows the GUI of our system; the map window is set to 2D map mode and the display shows the thematic layer "maximum pressure" and its standard deviation. Impact pressure is classified into five classes and symbolized in a blue color scheme. Standard deviations of the maximum impact pressures are added to the display as an extra layer and are symbolized by proportional point symbols in form of red circles. If the mouse is moved over the symbolization, a tooltip window appears, containing exact values of the assessment results as well as available uncertainty information. This feature facilitates the analysis of displayed data as the generalized visualization (only limited numbers of data classes can be distinguished) is complemented with information in the highest available spatial resolution.

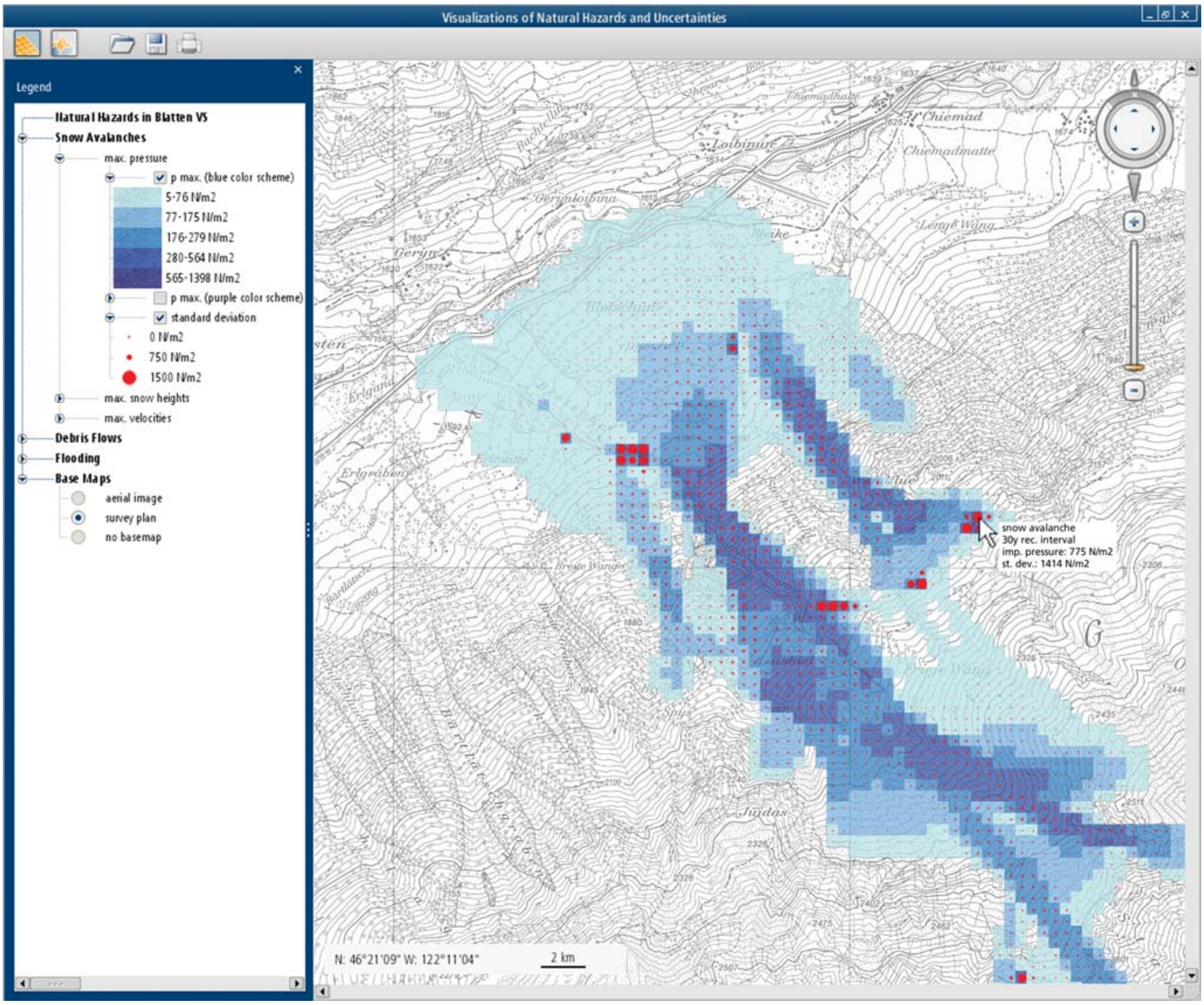

Figure 5: Graphical user interface of the cartographic information system for the visualization of hazard assessment results and associated uncertainties.

A schematic overview on the implemented functionality and the decision structure is presented in Figure 6. Basis of the system is a large amount of data, encompassing hazard assessment results, uncertainty information as well as different base

maps (aerial image, topographic map, and survey plan). Users can choose the data of interest by clicking on radio buttons and check boxes of the available layers in the provided layer tree (on the left in Figure 5). The selected assessment results as well as associated uncertainties can then be visualized according to the users' preferences; map symbolization includes 2D texture, bar symbols, and interpolated surfaces. This symbolization can additionally be altered by choosing from different color schemes. Switching between 2D maps and the block diagram mode is possible by two buttons placed in the menu bar. If the users are satisfied with the displayed cartographic visualization they can navigate spatially with the navigation tool (upper right corner of the map window), by mouse actions or the help of the keyboard. To assist navigation, the position of the cursor is displayed in form of geographic coordinates (including altitude) in the bottom left corner of the map window, together with a scale bar. This group of interactive functionality that is needed to generate the customized cartographic visualization of the selected data is summarized in Figure 6 as interactive functionality I. The order in which the offered functionality is used can vary from user to user (also iterative uses are possible).
Once the visualization on the screen meets the requirements of the user, this cartographic representation can be analyzed visually or in addition explored with the help of further functionality (e.g. tooltip window displaying detailed information (including uncertainty) whenever the mouse is moved over thematic data). If required, the map can be printed or saved. These additional interactive functionalities are summarized as interactive functionality II in Figure 6.

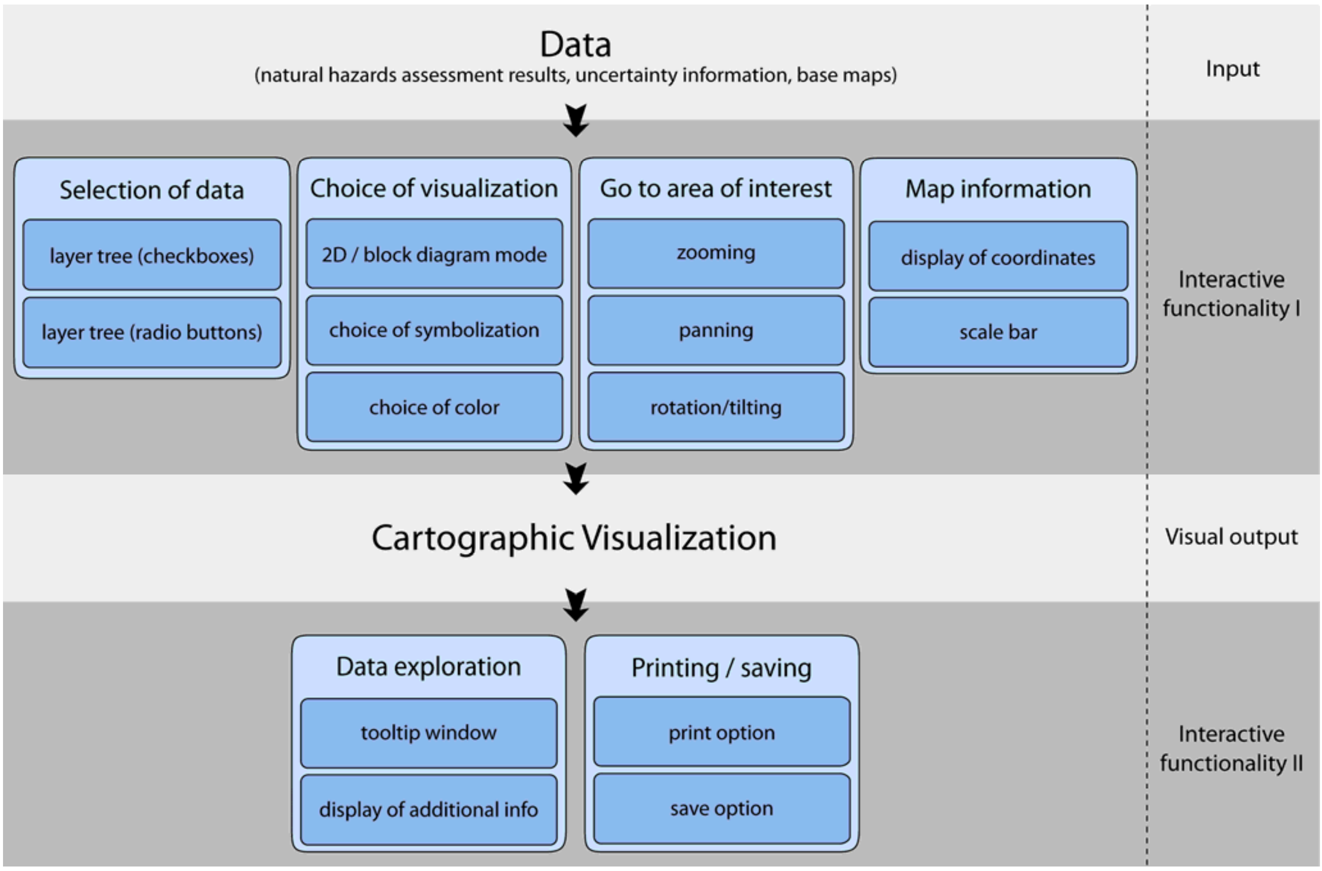

Figure 6: Schematic overview of the decision structure of the system: with the help of interactive functionality (group I) data can be selected and visualized according to the users' needs resulting in a cartographic visualization which can then either be analyzed visually or processed further with the help of additional interactive functionality (group II)

Expert Interview

Since the choice of suitable visualization methods as well as the development of the cartographic information system are based on cartographic considerations it is important to confirm their usability and effectiveness with the actual end users. We therefore conducted eight expert interviews in which natural hazards specialists explored the prototype and answered questions during approximately two hours. To reflect the heterogeneity of the user group of natural hazards specialists we interviewed experts with different education (geographers, engineers, geologists, and insurance consultants), different tasks in natural hazards management (conducting of hazard and risk assessments, risk communication, spatial planning, and

defense structure management), and different employers (private companies, research institutions, insurance companies, and state administration).
All experts showed interest in interactive systems for their potential to improve the communication of natural hazards information. The overall appearance of our prototype has been considered appealing; most experts appreciated the clearly structured layout without many buttons and menus.
In general, the suggested interactive functionalities and the offered visualizations were found to facilitate the interpretation of natural hazards assessment results. Feedback about specific elements of the cartographic information system was provided as follows:

Base map and thematic content: The included thematic information as well as the three available base maps (orthoimage, topographic map and survey plan) met the requirements of most experts. Suggested extensions included land-use plans and official survey data.

Thematic navigation: The individual selection of data was found to be important as visualizations should only contain data of interest. The layer tree was considered to be a straightforward method.

Spatial navigation: The offered spatial navigation functionality met the requirements of the experts and the usability of the navigation tool was rated as high.

Visualizations: The option to choose from different visualization methods was appreciated, as the maps can be customized according to the task at hand.
The offered color options (cold colors such as blue, gray, purple for snow deposit heights of avalanche events, dirty colors such as brown or olive for debris flow heights, and blue for inundated areas) were considered to be suitable. The customization of colors was found useful when color-vision impaired users can benefit. Experts with normal color view, however, should be able to interpret visualizations irrespective of the offered color scheme.
The block diagram mode was found helpful as additional visualization method to get an overview on the situation. However, all experts would switch to the 2D map mode for detailed data analyses.
Bar charts in the block diagram mode could be interpreted by all experts and were found to be a suitable representation method by most experts. Some experts criticized the lack of height comparison in steep terrain as well as occlusion caused by the great number of bars. Although occlusion is less of a problem with interpolated surfaces, they were rated less appealing by most experts, as they imply a continuity that was not calculated but interpolated. The application of 2D symbolization on the block diagram, however, was considered useful as the topography of the area remains fully visible.

Uncertainty Visualizations: For the discussion of uncertainty visualizations the six different methods presented in section "Visualization of Uncertainties" were rated by the experts. All suggested uncertainty visualizations were considered to be interpretable by expert users. Even intrinsic visualizations where two visual variables are combined in one raster cell were understood and found useful. Preferences for transparency or saturation as second visual variable were explained as follows: if the issue of uncertainty is emphasized, increasing saturation is preferred as it guides the visual attention towards the uncertain areas where raster cells are darker. Increasing transparency on the contrary, channels attention to the certain values and leads to an ignorance of uncertain raster cells.
While some uncertainty visualization methods allow for a quantitative analysis of uncertainty measures (e.g. univariate display, intrinsic methods, and proportional circle symbolization), others are more suited for an overview on the existing uncertainty situation (e.g. density of speckles in texture overlay). It was found important that several visualizations are offered in order to be able to choose the method needed for the task at hand. Although some experts required more time to interpret certain methods, this extra time was accepted in order to gain knowledge on the uncertainty situation. None of the experts found the offered uncertainty visualizations overwhelming, confusing, or useless.
In summary, the integration of uncertainty visualizations into an expert system was considered valuable as the knowledge of the spatial variability of existing uncertainties is important to reach certain decisions and furthermore to enhance the transparency of the decision making process.

GIS Functions: It was agreed that a print option and the possibility to export data are more important than sophisticated GIS functionality. If such operations need to be conducted, data can always be transferred to a fully functional GIS that is already known by the expert.

Additional Information: All experts found it important to include detailed information about assessment methods and uncertainty calculations. A pop-up window was suggested to provide this information.

Discussion

With the development of our cartographic system we respond to the issues of poor hazard visualizations, the need for customized representations, and the lack of uncertainty information. The system offers interactive functionality that enables users to select data of interest, choose the preferred visualization method, and analyze the displayed data (illustrated in Figure 6). The applied Java Web Start technology allows for immediate response to the interactive functionality as well as easy data availability, access, and update. The used rendering algorithms result in high quality visualizations in 2D and 2.5D. All available visualizations were produced according to cartographic design principles and are presented in high resolution.

Although the interviewed natural hazard experts preferred 2D maps as tool for detailed spatial analyses the addition of a block diagram mode is considered a useful supplement. This visualization of hazard data on an elevation model opens new options for the visual analysis of natural hazard assessment results.

The offered uncertainty visualization methods were well received by the experts who appreciated the provision of uncertainty information. They are confident that such visualizations will facilitate their natural hazards management tasks.

As the issue of uncertainty location and quantification in the field of natural hazards still presents a research challenge, the uncertainty visualization methods implemented in our cartographic system are a non-exhaustive selection. They are, however, examples of how uncertainties inherent to natural hazards assessments can be communicated and can serve as basis for uncertainty discussions among experts. An interesting point that has been observed is that the majority of the interviewed experts responded well to intrinsic visualizations (making use of color saturation and value to map uncertainties) although intrinsic methods seem to be more complicated. This was also observed by Drecki (2002) who evaluated different uncertainty visualization methods. However, Drecki (2002) as well as (Buttenfield and Beard, 1994) revealed that although the use of saturation is a preferred method, users seem to have difficulties in interpreting the visualizations and the color saturation method performs weakly in the evaluations. As we only use few different classes and support the data analysis with interactive query functionality, we believe that users will be able to interpret the offered uncertainty visualizations, even if the color saturation method is used. In order to validate this assumption and to assess our suggestions in general, future research endeavors will aim at gaining more feedback about the usability of the systems and at evaluating the effectiveness of the suggested visualizations. Usability tests will also clarify whether or not the lean GUI of our system that was so well received by the experts can allow for all interactivity necessary for the accomplishment of natural hazards management tasks.

Conclusions

Natural hazards experts welcomed the idea of interactive cartographic information systems for the distribution and communication of natural hazards data. For efficiency and usability reasons a lean GUI without many buttons and menus is appreciated.

The method of basing the GUI design as well as functionality considerations and visualization options on assessments conducted by cartographers proved to be successful in this case; only minor changes were suggested by the interviewed natural hazards experts.

The availability of different visualization methods allows experts to first gain an overview on the hazard situation and subsequently switch to 2D representations where a more detailed analysis is possible. Experts especially valued the integration of uncertainty visualizations. Although some of the offered methods are complex, experts were willing to invest some time for their interpretation. The gained knowledge on the uncertainty situation is believed to support their natural hazards management tasks, including decision making processes.

Overall, the presented interactive cartographic information system provides an innovative tool for the user specific visualization of natural hazard assessment results. In addition, the included uncertainty visualizations can render the system into a tool to assist in the current issue of uncertainty communication.

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