POSSIBILITIES OF INCORPORATING AND VISUALISING UNCERTAINTY IN NATURAL HAZARD PREDICTION MAPS

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Abstract

This contribution discusses the possibilities of incorporating and visualising uncertainties in natural hazard maps. Including uncertainties associated with prediction maps of future natural hazards such as mass movements, floods, and avalanches might increase the usefulness of natural hazard prediction map to decision makers in land-use planning.

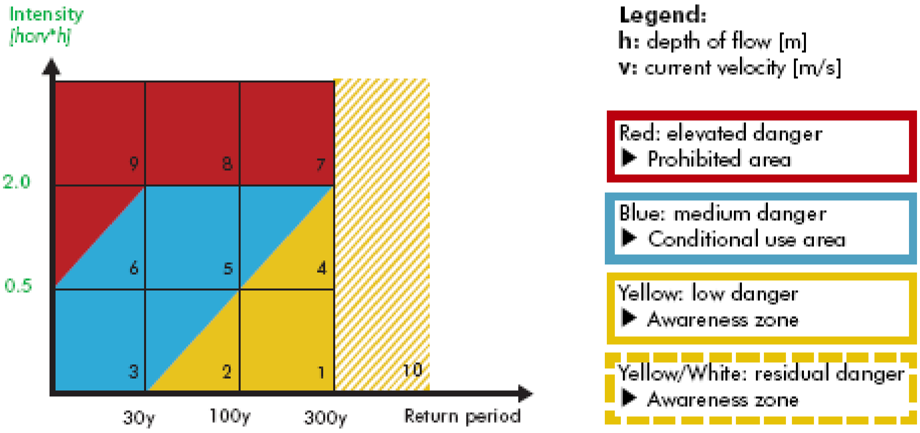
Today hazard prediction maps are usually created by applying a bivariate hazard matrix (magnitude-frequency diagram) to transfer hazard analyses results into a number of classes (e.g. 10 in Switzerland). Each class represents a certain magnitude and likelihood of occurrence of a hazardous process. The hazard classes are then applied to the study area which will then be divided into discrete zones. To a certain degree this approach already accounts for the uncertainties inherent in the analysis of natural hazards as it presents its outputs in ranges and not in absolute values. However, a user of this map product might want to know how valid and reliable boundaries between the displayed hazard classes are. In the conventional way of representation these suggest a sharp and sudden change in magnitude-frequency although the transition might be rather continuous and furthermore they are subject to uncertainties. Also, areas inside a hazard class are not homogeneous as one might assume from a cursory consultation of such a hazard prediction map. Therefore the uncertainties of prediction maps should be assessed and there are different types of them intrinsic to hazard analysis. These uncertainties can be introduced into the analysis during all its stages - data acquisition, data transformation, and visualization (Pang, Wittenbrink et al., 1997). This paper aims at indicating various techniques of uncertainty visualization applicable to natural hazard prediction maps.

1. Natural Hazard Prediction Maps

There is a great variety of concepts for the preparation and implementation of natural hazard prediction maps. In Switzerland Federal guidelines provide a casing for the preparation (Bundesamt für Forstwesen and Eidgenössisches Institut für Schnee- und Lawinenforschung, 1984; Loat and Petrascheck, 1997; Lateltin, Tripet et al., 1997; Zimmermann, Pozzi et al., 2005). Stötter, Belitz et al. (1999) list some concepts, practice, and give references of other abutting countries of the Alps.

Natural hazard prediction maps are usually generated by applying a bivariate hazard matrix (magnitude-frequency diagram) to transfer hazard analyses results into a number of "prediction" classes. Each class represents a level of likelihood of occurrence (return period) and an intensity of a future hazardous process.

Each of these classes is assigned a specific level of danger (see Figure 1). To obtain these classes a wide range of qualitative and quantitative models have been developed and applied in the reconstruction, simulation, and prediction of hazardous events and their spatial and temporal occurrence. The results of these analyses including scenarios and



uncertainties have to be documented in a report. However, the summary and representation of natural hazards will always have to be elaborated in form of a map (Figure 2).

Figure 1: Matrix for determining a hazard class in Switzerland (example for flood hazard) (Source: Zimmermann, Pozzi et al., 2005).

These maps have been the principal visual medium and are the basis for decision makers in hazard zoning and land-use planning. Applying the magnitude-frequency matrix to the natural hazard analysis output data acts as a classification. To a certain degree this approach already accounts for the uncertainties/statistical variation inherent in these data as it presents its outputs in ranges and not in absolute values. However, a user of this map product might want to know how valid and reliable boundaries between the displayed hazard classes are. In the conventional way of representation these suggest a sharp and sudden change in magnitude-frequency although the transition might be rather continuous

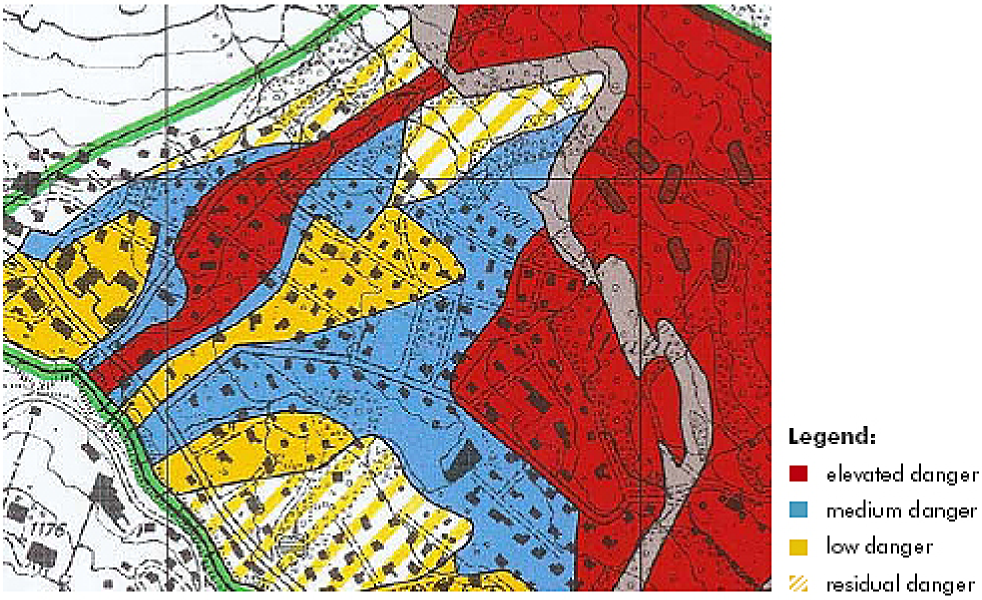


Figure 2: Hazard map of Sörenberg, Switzerland, original scale 1:5000. (Source: Zimmermann, Pozzi et al., 2005).

and furthermore they are subject to uncertainties/statistical variation. Also, areas inside a hazard class are not homogeneous as one might assume from a cursory consultation of such a hazard prediction map. Therefore the uncertainties of prediction maps should be assessed. There are different types of them intrinsic to hazard analyses.

2. *Visualising Uncertainty*

2.1. What is Uncertainty?

In this paper we will use the term in the broad sense used by Pang, Wittenbrink et al. (1997). This definition comprises statistical variation, errors and differences, min-max range values and noisy and missing data (Pang, Wittenbrink et al., 1997). MacEachren (1992) suggested expanding the scope of uncertainty from rather being a synonym for data quality by adding the issue of data variability (spatial, temporal, and thematic).

MacEachren, Robinson et al. (2005) give a very detailed overview and summarizes the development of conceptual frameworks for geospatial uncertainty. Other shorter definitions are given in the textbooks of Longley, Goodchild et al. (2005) or Slocum, McMaster et al. (2005).

According to Taylor and Kuyatt (1994) and the american National Institute of Standards and Technology (NIST), summarized in Pang, Wittenbrink et al. (1997), there are four ways of expressing uncertainty:

1. Statistical – given by the mean and standard deviation, used to calculate a confidence interval or distribution of the data.
2. Error – difference, or absolute valued error among estimates of the data or between known correct value and an estimate.
3. Range – the data should be in a given interval but cannot be quantified into the other two preceding definitions.
4. Scientific judgement (expert knowledge) – using all relevant information available, e.g. experience or general knowledge of processes, materials, and instruments.

2.2. Sources of Uncertainty

There are a wide variety of sources for uncertainty in geospatial analyses and representation. These were grouped by Pang, Wittenbrink et al. (1997) according to the three stages in (geospatial) information processing. These are: acquisition, transformation, and visualisation. At each step in this procedure (workflow) there is the possibility to introduce more uncertainty. Longley, Goodchild et al. (2005) extended this framework by adding conception and analysis (interpretation). The first source of uncertainty already lies in how we conceive about real world phenomena. The environment has to be conceived, simplified, abstracted, discretised, and categorized if one wants to handle the sheer amount of geographic data. The choice of analysing methods and approximations in the definitions of the objects under investigation both limit data acquisition and thus introduce uncertainty (Foody and Atkinson, 2002). Data from measurement, numerical models and data entry are all subject to statistical variability (Pang, Wittenbrink et al., 1997). The confidence level rises with increasing number of measurement, model runs, and entries. Numerical models and its parameters are a simplification of the system being modelled. They can produce uncertainty and error due to parameter sensitivity (or lack thereof), the choice of the algorithms, or computing imprecision (Pang, Wittenbrink et al., 1997). Human observation and data entry are variable and prone to error. Uncertainty in data transformation/processing occurs in e.g. unit or data format conversions, union of different data types, rescaling, resampling, and quantising. All transformations alter the original data and potentially introduce uncertainty (Pang, Wittenbrink et al., 1997). Uncertainty in the visualisation stage might be introduced through radiosity, volume rendering, interpolation, contouring, isosurfacing, and animation etc. (Pang, Wittenbrink et al., 1997).

2.3. Sources of Uncertainty in Natural Hazard Predictions

Natural hazard processes are often very complex. Single hazards, e.g. debris flows, often comprise of several singular processes that interact. Furthermore most hazards influence each other or occur in a chain of events (see below). As all natural processes they and their parameters are prone to spatial and temporal variability and they are hard to measure and predict. These particularities hamper the comprehension of the system "natural hazards", its interaction, its boundaries, its assessments, and in consequence the production of natural hazard maps.

In the course of the elaboration of a prediction map, several (empirical) models are applied at various steps of the hazard evaluation. Each of these produces data that exhibit certain variability. Each model's results then serve as input for other ones. Variability/uncertainty in thus passed over from one modelling step to another. An example of such a "chain of modelling"/process chain for the assessment of flood and associated hazards which need to be considered could look as follows: precipitation, run-off, bed load transport, debris flow, outburst probability, erosion, and accretion modelling. In order to avoid error propagation different models need to be applied in parallel, its results compared, and interpreted by the modeller.

An example of the great variability and uncertainties in the results of empirical formulae for estimating event magnitude used in debris flow hazard assessment gives Zimmermann (2006) and table 1 for the Glyssibach torrent, central Switzerland.

Author	**Formula**	**Estimated Event Magnitude**
Zeller (1985)	$M = 17{,}000 \sim 27{,}000 * E^{0.78}$	36,000 m^3
Kronfellner-Kraus (1985)	$M = K * J_c * E$	142,000 m^3
Lehmann (1993)	M = from flow chart	20,000 m^3
Rickenmann (1995)	$M = (110 – 2.5 * J_k)* L$	110,000 m^3
D`Agostino et al. (1996)	$M = 45 * E^{0.9} * J_c 1.5* IG$	57,000 m^3

Table 1: Results of empirical estimation formulae of debris flow event magnitudes in the Glyssibach torrent, Switzerland (after Zimmermann, 2006).

2.4. What is Uncertainty Visualization?

The paragraph given in Pang, Wittenbrink et al. (1997) is very well suited for our purposes. "Uncertainty visualization strives to present data together with auxiliary uncertainty information. These visualizations present a more complete and accurate rendition of data for users to analyze. (…) The ultimate goal of uncertainty visualisation is to provide users with visualisations that incorporate and reflect uncertainty information to aid in data analysis and decision making" (Pang, Wittenbrink et al., 1997). These visualisation techniques present data to users to raise the awareness of the location and degree of uncertainties.

2.5. Why Uncertainty Visualization in Hazard Mapping?

It has been postulated that hazard appraisal has to be conducted in consideration of the reliability of input data, evaluation methods (event cadastre, models etc.), and the degree of uncertainty that is inherent in the analysis results (IRAP, 2003). To better communicate these data/information that are to be reported in some way or another in an accompanying report, uncertainty visualisation techniques are promising. By transferring the reported uncertainties into a visual format accompanying or supplementing the conventional natural hazard prediction maps, uncertainty communication and thus awareness among decision maker and the public might be ameliorated. Land use planning decisions based on the hazard appraisal might thus become more transparent and better accepted. However, contrary reactions might as well result and the depiction of uncertainties in the hazard prediction maps might lead to the conclusion that the analyses are "wrong" or "weak" and decisions cannot be based on these fallible data. A feeling of insecurity rather than awareness in the public might arise. MacEachren, Robinson et al. (2005) discuss on decision making under uncertainty and state: "(…) the limited research available on map readers' use of cartographic representations of data uncertainty suggests that inclusion of this information is helpful to decision makers (…)." Further research on that topic needs be done.

3. *Visualisation Techniques*

3.1. Conception of Uncertainty and its Visualisation

There are different kinds of uncertainty to which decision makers are confronted. To address this fact, visual (and other) representations of uncertainty have to account for this variety (MacEachren, Robinson et al.; 2005). As a consequence, several researchers have tried to identify the components of uncertainty and specifically relate them to visual representation techniques. Many conceptions are based on the five initial categories for assessing data quality listed by the National Institute of Standards and Technology 1994 in the U.S. Federal Information Processing Standard 173 (Slocum, McMaster et al., 2005). These are: lineage, positional accuracy, attribute accuracy, logical consistency, and completeness. Semantic accuracy and temporal information were added as categories by the ICA Commission on Spatial Data Quality (Guptill and Morrison, 1995). Of these, positional and attribute accuracy have received the most interest in uncertainty visualisation research (Slocum, McMaster et al., 2005) and will also be focussed on in this study of the representation of uncertainties in natural hazard prediction maps. Buttenfield and Weibel (1988) (in MacEachren, Robinson et al., 2005) matched the initial five data quality components with data types (discrete, categorical, partitioning/enumeration, and continuous) and suggested methods of representation for each match. Graphical syntax is used for the accuracy categories which describe metric data. Either graphical or lexical syntax is applied to the other three (logical consistency, completeness, lineage) components that are more complex and abstract data. Other recent concepts in the geovisualisation domain were developed by Buttenfield and Beard (1994) or Gahegan and Ehlers (2000) and more are cited and briefly discussed in MacEachren, Robinson et al. (2005). Furthermore MacEachren, Robinson et al. (2005) give examples of uncertainty frameworks (e.g. Pang, Wittenbrink et al., 1997 or Gershon, 1998) in the scientific visualisation/information visualisation domain which has somewhat developed in parallel to that of the geovisualisation/GIScience domain.

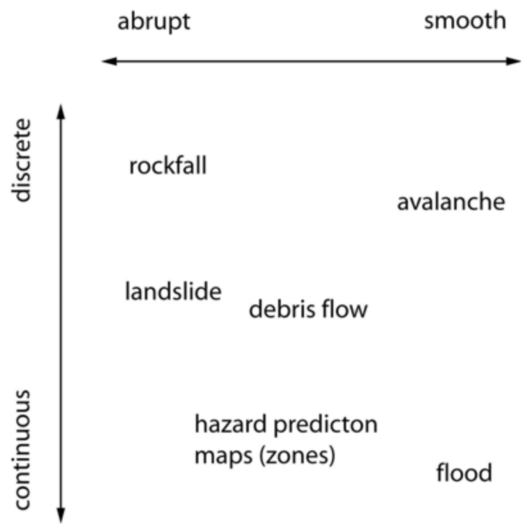


Figure 3: Continuity-abruptness phenomena space and some examples of natural hazard depictions. Adapted from MacEachren (1992).

The framework of Buttenfield and Weibel (1988) is a practical starting point to considerations on uncertainty visualisation in natural hazard prediction maps and related products such as intensity maps of flood, avalanche, rockfall or debris flow simulation results that need to be transferred into categorical natural hazard maps. Numerical hazard simulations due to the spatial characteristic of the hazard under investigation produce diverse data types that need to be treated differently in uncertainty visualization. Rockfall or avalanche simulation results are rather discrete lines that, in a subsequent analysis and interpretation process, need to be transferred into an area. Simulated flooded areas are rather continuous. The final product however, the categorized hazard maps, exhibit discrete objects - the different hazard zones or areas. Another spatial characteristic of natural hazards like other geospatial phenomena is the quite divers character of variation across space (MacEachren, 1992). Possible symbolisation methods that represent these graphic data models are given in MacEachren and DiBiase (1991) and MacEachren (1992) by "continuity-abruptness phenomena" diagrams. This framework might also be expanded to account for natural hazard and its uncertainty representations (Figure 3).

3.2. General Methods

MacEachren (1992) proposes three general methods for the representation of uncertainties, which can either be separated or combined with the data. The first two exhibit a separate relation and the later a combined relation (Drecki, 2002). The general methods are:

1. map pairs – individual maps for both attributes and its uncertainty, "maps compared" approach (Slocum, McMaster et al., 2005), "side-by side technique" (MacEachren, Thacher et al., 1994), "static comparison" (see also Drecki, 2002; van der Wel, Hootsmans et al., 1994).
2. sequential presentation – "user warned about uncertainty with initial map which is followed by a map of the data" or interactive tools to toggle between data and its uncertainty representation (MacEachren, 1992).
3. bivariate maps – attribute and uncertainty on same map, „maps combined approach" (Slocum, McMaster et al., 2005).

3.3. Graphic Variables, Tools, and Techniques

To implement the general methods several instruments have been developed and tested to visualise data and uncertainty. A central question to be answered is: which part of a sign-vehicle or symbol be utilized to depict the data and which to represent the uncertainty

(MacEachren, Robinson et al., 2005). The instruments are Bertin's graphic variables (Bertin, 1967), its static or dynamic extensions and many digital tools and techniques (MacEachren, 1992; McGranaghan, 1993; van der Wel, Hootsmans et al., 1994; or Slocum, McMaster et al., 2005). The graphic variables can be divided into intrinsic (those that are inherent to the display) or extrinsic variables (those that exist outside the display). Table 2 lists a compilation of these and indicates whether or not they are suitable for either univariate or bivariate displays in general and hazard prediction maps in particular. It is not surprising that if suitable for bivariate maps techniques are also usable for hazard maps. But it is to be tested if all of these will also be suitable for all kinds of natural hazards maps (different hazard type) and for the preceding intensity maps derived from (numerical) simulations.

Another branch in research in uncertainty visualisation has been the development of interfaces that allow users to interact with the displays (MacEachren, Robinson et al., 2005). Users can suppress or explore uncertainty information, control its display by setting thresholds (quality slider), adjust the visual dominance of either the data or the uncertainty, zoom in or out, and more. Basically most of the mentioned instruments in table 2 are suitable to incorporate in an interactive interface. Interaction however, has to be dealt with particular caution in natural hazard prediction maps because the results are often very sensitive and accidental or thoughtless manipulations might have grave implications. However, this most likely holds true for many geospatial applications in which uncertainty visualisation should be incorporated. Thus not all possible interactions or displays are meaningful and should be implemented. To find out what instruments are significant and helpful for users/decision makers more research is needed.

	univariate displays (maps separated)	bivariate display (maps combined)	hazard prediction maps
Graphic variables			
Intrinsic to display			
Location	-	-	-
Size	-	-/+	-/+
Colour value	+	+	+
Grain (texture)	+	+	+
Colour hue	+	-/+	+ (intensity maps), - (hazard maps)
Orientation	-	-/+	-
Shape	-	-/+	-
Pattern	+	+	+
Colour saturation	+	+	+
Crispness (contour crispness, fill clarity), focus	-	+	+ (hazard maps), - (intensity maps)
Transparency / Fog / Opacity	-	+	+
Resolution	-	+	+
Extrinsic to display			
Glyphs (compound point symbols), dials, arrows, bars, etc.	+	+	+
Visualisation tools / techniques			
Separated relation			
Static			
Static maps pair / double or multiple displays	+	n.a.	+
Dynamic			
Map sequence, toggling, flicking, fading, animation	+	n.a.	+
Combined relation (some might also be applied to univariate displays)			
Static			
3-dimensionality	+	+	+
Shading	+	+	+
Dazzling	+	+	+
Blending	-	+	+
Colour transformation	+?	+	+
Dynamic			
Blinking	-	+	+
Moving (fog) / Multiple positions	-	+	+
Zooming	+	+	+
Slicing / Quality slider	+	+	+

Table 2: Suitability of graphic variable, tools, and techniques for uncertainty depictions either in univariate, bi(multi)variate displays, or hazard prediction maps. (- = not suitable, + = suitable, -/+ = suitable but impractical) (Complied from MacEachren, 1992; McGranaghan, 1993; van der Wel, Hootsmans et al., 1994; Aerts, Clarke et al., 2003; Oehler, 2005; MacEachren, Robinson et al., 2005; Slocum, McMaster et al., 2005; and own considerations).

4. Concluding Remarks

To date hazard prediction maps are mostly static representation of danger categories. The visual depiction and inclusion of uncertainties has not been undertaken yet. Due to the characteristics of natural hazards there is a great variety of possible uncertainties being introduced in the course of a hazard assessment. Numerical simulations provide ratio data depicted in intensity maps. Other empirical modelling or mapping approaches however, provide either quantitative or even qualitative (nominal, ordinal) data. The differences in the spatial characteristics of natural hazards, type of modelling, and its resulting data determine the ways in which uncertainties, provided they can be properly assessed, can be displayed and integrated in the hazard intensity and the categorized hazard prediction maps. Estimations of the variability in spatial, thematic, and temporal attributes of hazard assessments are difficult. The use of parallel methods, Monte Carlo simulation, geostatistics, error propagation, Bayesian network, and adjustment calculation are possible and can only be mentioned here. Despite all the differences in hazard characteristics there is a great variety of suitable graphical variables, tools, and techniques that can be applied to this issue. In a next step, several prototypes implementing various visualisation techniques and maybe some interaction will have to be realized and tested. In expert interviews their potential to raise awareness and facilitate decision making will have to be evaluated. This is to filter meaningful implementations of uncertainty visualisation in natural hazard analysis and prediction maps.

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