https://doi.org/10.5194/egusphere-2026-3789
Preprint. Discussion started: 15 September 2026

How map design shapes natural hazard risk understanding and perception: a case study from the Canton of Lucerne

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Abstract

Maps are an important tool for communicating natural hazard risks and motivating protective action. Their effectiveness, however, depends on how users perceive and interpret the information presented, making careful design and empirical evaluation essential. This study describes an iterative, co-designed and evaluation process of prototype natural hazard risk maps developed for the Canton of Lucerne, Switzerland. It involved focus group discussions and an online survey of 193 residents. The results indicate that the colour scheme had no significant effect on map comprehension, suggesting that a rigorous, user-centred design process can produce robust and effective maps. Instead, individual characteristics, particularly homeownership, which is associated with higher age, and perceived map quality emerged as stronger predictors of comprehension. Exposure to the maps also led to a measurable increase in spatial risk perception, demonstrating that risk maps can serve as effective communication tools in their own right. Based on these findings, we recommend embedding risk maps within broader, participatory communication strategies, and structuring information in a layered manner to accommodate different levels of expertise and user needs.

1 Introduction

Natural hazards expose a substantial threat to Switzerland. Floods currently endanger approximately one-fifth of the Swiss population, while around seven percent live in regions potentially susceptible to avalanches, landslides, or rockfalls (Federal Office for Environment, 2024b). Over the past century, Switzerland's population has more than doubled to currently 8.96 million inhabitants (Federal Statistical Office, 2024). As a result, the number of people exposed to hazards has increased, partly because the availability of safer areas for settlement has declined.

These hazards threaten not only lives and property but also have significant economic implications: almost two million jobs, accounting for around a third of the national workforce, are located in these hazard-prone zones. The annual average damage costs (1972-2023) caused by natural hazards in Switzerland are approximately CHF 306 million (Federal Office for Environment, 2024a). Floods and debris flows account for over 90 % of recorded losses while avalanches, landslides, and rockfall remain the leading causes of fatalities (Liechti and Badoux, 2024). Although the number of deaths has decreased over the last decades, financial losses have increased due to growing exposure of asset values in hazard-prone areas (Badoux et al., 2016; Federal Office for Environment and Federal Statistical Office, 2009; Federal Statistical Office, 2024). These trends

https://doi.org/10.5194/egusphere-2026-3789
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underline the importance of developing effective protection measures as well as public information strategies to ensure a safe and resilient society.

In Switzerland, the management of natural hazard risks is a shared responsibility distributed between political authorities, professionals, and private individuals. The Confederation sets legal frameworks and coordinates national strategies through agencies such as the Federal Office for the Environment (FOEN). Cantonal authorities are responsible for mapping natural hazards, implementing protective measures, and integrating risk considerations into land-use planning. Municipalities execute specific interventions and inform the population. Private individuals are expected to take personal precautions, such as securing property or respecting hazard zone regulations (Federal Office for Environment, 2016, 2024b; Federal Office for Environment and Federal Statistical Office, 2009).

A key element in this system is risk communication. It involves the exchange of information between stakeholders, ranging from authorities and scientists to communities and individuals, about the nature of risks and how to respond to them (Cirella et al., 2014; Scandizzo, 2005). Risk and hazard maps have emerged as a crucial product to inform diverse audiences about natural hazards. By visualizing hazard processes in their spatial and temporal dimensions, maps enhance public awareness and provide a scientific basis for planning and mitigation strategies (Cirella et al., 2014; Kjellgren, 2013; Wenk et al., 2018). They support informing and warning the public, as well as (institutional) decision-making (Lindell, 2020; Wenk et al., 2018).

Hazard and risk maps can serve as a powerful communication tool since they convey warning messages that influence how individuals perceive and respond to threats (Lindell, 2020). However, their effectiveness depends on whether users are able to interpret and understand the information correctly. Research has shown that people often struggle with the interpretation of hazard maps (Marti et al., 2019; San Martín et al., 2024). Even when technically accurate, many remain unintuitive, in particular for non-experts (Dransch et al., 2010; Kjellgren, 2013). Marti et al. (2019) demonstrated that a non-specialized audience can understand the main points of hazard maps, but interpreting these maps for specific purposes and answering advanced questions remains difficult.

To make maps more accessible to non-technical audiences, design choices play a crucial role. Recognisable landmarks, for instance, help users orient themselves more quickly, particularly when they are familiar with the area. Moreover, precise spatial references like streets, buildings, or other local features, allow users to link the abstract visualization to real-world places. This makes the information feel more relevant and, at the same time, easier to comprehend. Associative colours and intuitive symbols also play an important role: they not only aid understanding but also help reduce the risk of misinterpretation (Fearnley et al., 2018; Jégou, 2023). Additionally, Dallo et al., (2020) have shown for seismic risk that combining maps with textual information improves user understanding. Other studies stress the value of engaging users during the design process and testing visual formats empirically (Fearnley et al., 2018; Kjellgren, 2013).

Map comprehension is, however, not uniform across users. Individual characteristics, such as age, educational background or gender, can significantly influence cartographic interpretation abilities. Moffat and Marne (2025) show that age plays a key role, as map-reading and navigation skills tend to decline with age due to cognitive changes. Educational background represents another critical factor, as formal cartographic instruction enhances spatial thinking abilities and map interpretation skills throughout school years (Szigeti-Pap et al., 2023). Furthermore, familiarity with the mapped area, local knowledge, and previous exposure to similar cartographic representations can substantially improve user performance and reduce cognitive load during map interpretation (Rittschof et al., 1996). In addition, factors such as previous knowledge and personal experience

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play a critical role in shaping user understanding (Dallo et al., 2024; Maidl et al., 2021; Peters, 2008; Siegrist and Gutscher, 2008). Considering these user characteristics is therefore essential for the design of hazard and risk maps (Thompson et al., 2015). Although preferences and map reading abilities can vary considerably across user groups, practical and resource constraints often limit the feasibility of tailored solutions. For instance, decisions must be made about which map to present to a mixed audience and how to ensure consistent messaging. As a result, communication typically relies on a single main design.

Despite the recognised importance of effective visual risk communication, empirical evidence remains limited. Only a few studies (e.g., Dallo et al., 2020, 2024; Marti et al., 2019) have investigated this issue; however, no detailed study has yet been conducted for a synoptic risk map. Therefore, there is a clear need to assess how effectively prototype maps communicate natural hazard risks from a user perspective, particularly when designed to inform public awareness and promote preparedness.

This paper addresses this gap by investigating how different user groups perceive and interpret a prototype risk map for natural hazards in the canton of Lucerne. Using a combination of focus groups and an online survey, we examine users' risk awareness and spatial understanding. Furthermore, we examine the comprehensibility of the map and user preferences regarding visual elements such as colours and spatial detail. Additionally, the study explores how individual factors, including age, education, gender, home ownership or prior experience, influence interpretation. Based on these insights, we develop recommendations for improving visual risk communication.

2 Research questions

Risk maps are increasingly used as tools to communicate spatial hazard information to non-expert audiences. However, their effectiveness depends not only on cartographic design but also on how users perceive, interpret, and respond to the information presented. Despite growing interest and needs to communicate natural hazard risks, empirical evaluations involving laypeople remain rare (Dallo et al., 2024). This study addresses this gap by evaluating a prototype natural hazard risk map developed for the canton of Lucerne.

Building on the research gaps identified above this study addresses the following three research questions on the case of the canton Lucerne:

1. How do different colour schemes influence the perception and understanding of natural hazard risk maps?

While colour is recognised as a key cartographic variable, it remains unclear whether specific schemes systematically affect objective comprehension, perceived clarity, or behavioural intentions among lay users.

2. How do individual factors influence map perception and understanding?

Given that sociodemographic characteristics shape both risk perception and interpretive ability, this question examines which user characteristics act as barriers or facilitators to effective map use.

3. How does engaging with different risk maps impact risk perception of natural hazards?

Beyond spatial orientation, risk maps may function as risk communication instruments that actively shape hazard awareness and preparedness intentions, an effect this study seeks to quantify.

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To address these questions, we adopted a mixed-methods approach, beginning with an iterative stakeholder focus group to refine the prototype map, followed by a quantitative online survey with a representative sample of residents from the canton of Lucerne. This study received ethical approval from ETH Zürich (Project 25 ETHICS-051), and all participants provided informed consent prior to taking part.

3. Map development

The risk maps were developed by the canton of Lucerne in collaboration with the Swiss Seismological Service at ETH Zurich. The underlying risk data, originally provided in raster format, was transformed into continuous surface data through buffering techniques in ArcGIS to improve visual clarity. To give users meaningful spatial context, the base map incorporates the elements Wenk et al. (2018) identify as most essential: water bodies, major roads and highways, railway lines, and building outlines at detailed zoom levels.

To display risk levels, we adopted a three-tier legend (low, moderate, and high), keeping the style consistent with the hazard maps already provided by the canton of Lucerne (Geoportal Kanton Luzern, 2026). A risk definition, based on FOEN (2024b), was embedded directly in the map to ensure users understand what the visualisation represents. The text explains that the risk depicted reflects the probability and expected damage of natural hazard events, accounting for hazard frequency and severity, the number of exposed assets, their vulnerability, and consequential damage. A more detailed supplementary description was made available for users seeking additional depth. The exact definition including the maps can be found in the Supplementary Materials.

In the map design, particular care was taken to avoid white areas, thereby reinforcing the understanding that no locations are entirely free of risk. In addition, lighter colours indicate lower risk levels, while darker colours are reserved for higher risks, following the recommendation of Gaspar-Escribano and Iturrioz (2011). Due to the highly asymmetrical distribution of the risk data (many values in the lower ranges and few values with high risk), they were divided into distinct value ranges and implemented as separate GIS layers, using a multi-colour scheme instead of a single colour scheme (Kunz and Hurni, 2011). Various binning approaches were tested to represent the calculated risk for individual grid cells as accurately as possible. As risk varies continuously across space, discrete class boundaries were deliberately avoided. Instead, a continuous colour gradient was used to reflect both gradual spatial variation and the absence of natural thresholds in the underlying data. This approach aligns with the recognition that risk values are fundamentally continuous, even though they are frequently discretised for communication purposes (Schneider et al., 2023; Severtson and Myers, 2013).

Additionally, we examined the different versions at various zoom levels. As such maps are often embedded in interactive viewers, it is essential that they remain legible at every zoom level. Furthermore, individual hazards must be understandable both in combination and separately. Accordingly, we presented participants with the maps at different zoom levels, as both a synoptic overview and as process specific versions.

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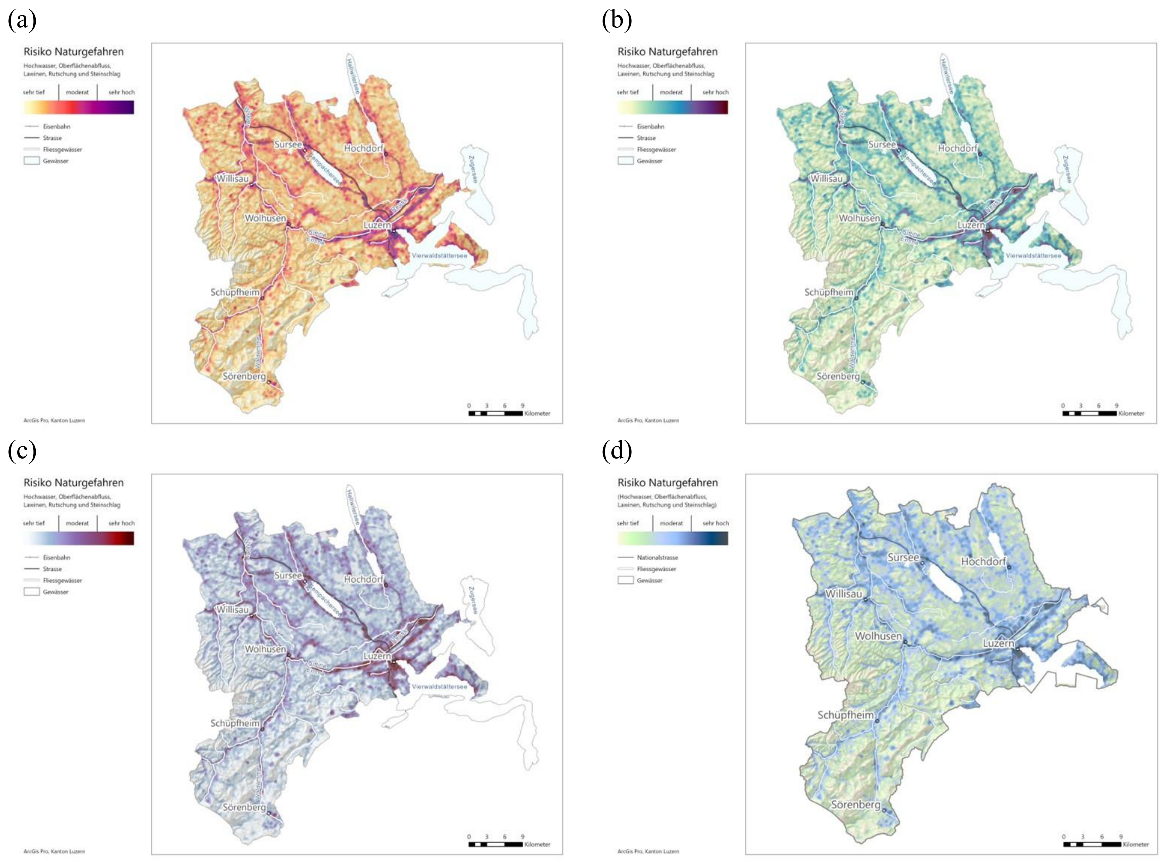

Figure 1: Preselected colour schemes used in the focus group discussions. Risk values are identical across versions, with only colour hues varying. Panel (a) shows version 1 (yellow to pink to purple), panel (b) version 2 (yellow to blue to purple), panel (c) version 3 (blue to red), and panel (d) version 4 (yellow to blue). Panels (a) to (c) depict the final versions used in the online survey, while panel (d) shows the focus group version, in which water bodies are truncated at the cantonal border. The tested maps selected for the online survey are provided in Appendix C.

We developed multiple versions of the colour schemes inspired by Crameri et al. (2020) and assessed them first via an internal expert assessment for visual clarity and colour-blind accessibility. Four prototypes were carried forward into the focus group phase (see Figure 1): version 1 (yellow-pink-purple), version 2 (yellow-blue-purple), version 3 (blue-red), and version 4 (yellow-blue).

Based on the focus group discussion feedback, versions 1 through 3 were refined and tested further in the online survey. All cartographic refinements informed by the focus groups were applied consistently across all three versions; only the colour scheme varied between designs. Throughout this iterative process, the map design, including cartographic elements and the risk description, was progressively adjusted to better meet the needs of the target audience.

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4. Focus groups

4.1 Approach

Following the creation of initial map prototypes, two focus group discussions were conducted to evaluate both their understanding and perception. For this exploratory purpose, focus groups are particularly well-suited. As Brynman (2012) notes, they allow a detailed examination of a specific theme and enable researchers to understand why people feel the way they do. At the same time, a variety of perspectives on a particular issue can be obtained and how participants debate about it. According to Wilkinson (1998), this makes them more reflective of how meaning is formed in everyday life compared to individual interviews.

Two distinct participant groups were recruited to represent different levels of prior knowledge: an expert group and a layperson group. The expert group comprised seven participants from cantonal departments closely related to natural hazards and hazard management (2 females, 5 males; 30 to 44 years old (M = 36)). The layperson group consisted of six participants with little to no prior knowledge of natural hazards, recruited from various departments within the canton of Lucerne (4 females, 2 males; 26 to 59 years old (M = 44)).

Both groups worked with A3 printouts of the natural hazard risk map of the canton of Lucerne, at different zoom levels and for different hazard combinations: a canton-wide overview map, with and without explanatory text, as well as process-specific maps covering water-related hazards (flooding and surface runoff), avalanches, landslides, and rockfall. The groups' map versions differed in one respect: the layperson group mainly worked with colour scheme version 1 (yellow-red), while the expert group worked with version 2 (yellow-blue-purple). This allowed for a qualitative comparison of how the two schemes supported spatial reasoning and risk communication. A full description of the map versions is provided in the Supplementary Material.

Both focus group discussions lasted around 60 minutes and followed a structured format with five phases. In the introduction phase (10 min), we welcomed participants, explained the session goals and discussion guidelines. In the exploration phase (25 min), participants were exploring the printouts. To simulate a realistic scenario, participants had to imagine purchasing property in a specific city (Kriens) and identify high risk areas using the maps. They were also asked to describe which elements they attended to and what caused confusion. The reflection phase (10 min) invited participants to point out uncertainties and evaluate the legend style and risk description. In the comparison phase (5 min), different colour scheme variants were presented and ranked. A final summary phase (10 min) gathered key takeaways and collected sociodemographic data. The full discussion guide is provided in the Supplementary Material.

Both sessions were audio-recorded and subsequently transcribed. Analysis followed a structured qualitative approach: transcripts were reviewed and systematically coded by thematic categories derived from the discussion guide (map comprehension, design elements, colour preferences, risk perception, and practical relevance). Recurring issues and suggestions raised independently across both groups were prioritised for integration into the revised map versions used in the online survey (see Section 0).

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4.2 Results

Both groups demonstrated a reasonable understanding of the risk concept as presented on the maps. Participants correctly associated high-risk areas with densely populated zones, major valley rivers, and critical infrastructure such as the city of Lucerne and its main train station. They also recognised that risk is shaped not only by hazard exposure but by the concentration of assets and population. Laypeople were additionally able to associate general risk to the hazard types: they identified correctly that water-related hazards as the dominant source of risk.

Even though they correctly identified the areas at risk, both groups indicated that this would not be the decisive factor in personal location decisions. It was noted that considerations such as transport access, proximity to services, and property value typically take priority. Several laypeople echoed this, stating they would accept living in higher-risk zones if the location was sufficiently central or well-connected. Experts further regarded the maps as more suited to institutional applications (e.g., spatial planning, insurance, and infrastructure projects) than to private decisions. For those they considered hazard maps to be more relevant than risk maps.

A shared point of criticism across both groups concerned the descriptive risk text. Participants in both discussions initially read it as a generic definition of risk rather than a specific, data-derived metric. This prompted calls for greater transparency about the numerical basis of risk levels, such as potential losses in Swiss francs per return period, and for clearer communication of which hazard types are included in the depicted risk. Experts additionally raised concerns about the limited coverage of non-water hazards in rural areas, noting that the absence of data for other processes could make those zones appear safer than they are.

The cartographic design was another area of considerable feedback. Both groups called for more prominent and clearly labelled roads, particularly at detailed zoom levels, and for better visual differentiation between roads and railways. Lake Lucerne was not immediately recognisable in either session, partly because being cut off in the middle due to the cantonal border. Additionally, both groups recommended explicit labelling and blue colouring for major water bodies. Laypeople found mountain regions difficult to identify and requested stronger relief contrast or clearer symbols such as triangles. They also proposed to include a familiar background layer such as Google Maps. They further noted that the term 'culverted waterbodies' (in German: ‘eingedolte Gewässer’) was unfamiliar and should be replaced with a more accessible alternative. Experts additionally suggested the inclusion of municipal boundaries at medium zoom levels and object-level risk indicators at detailed zoom to clarify what drives local risk concentrations.

Regarding colour schemes, a yellow-red colour scheme was clearly favoured. Among experts, it received 71 % of votes; among laypeople, support was unanimous (100 %). In both cases, the high contrast and intuitive association of red with danger were cited as the main advantages. Blue and green tones, used in the alternative schemes, were widely perceived as conveying safety or evoking nature and water, leading participants to feel they could downplay real risk.

4.3 Insights from focus group discussions informing map design

The two focus group discussions directly informed subsequent design refinements to enhance the risk maps’ effectiveness and readability. The following amendments were considered and incorporated into the versions later tested in the online survey:

- Waterbodies (e. g., Lake Lucerne) should be fully depicted, and large rivers made more prominent in zoomed-in views. Key water bodies should be labelled for better orientation. Additionally, the term 'culverted waterbodies' was not well understood and needs to be replaced with a more commonly known alternative (e. g., 'overbuilt watercourses').
- Railway lines were often confused with roads. To address this, we differentiated them visually by using thicker crossbars, and a distinct colour and line style.
- Participants suggested including more roads, particularly in zoomed-in views, with major roads more prominently labelled and rendered with thicker lines Some also proposed changing the road colour to white or even bright yellow. We consequently labelled the most important transport routes but refrained from further adaptations, as these would have made the map appear too busy.
- The definition of risk on the map needs to be simplified and stripped of technical jargon. A two-layered explanation – first a concise, plain-language summary, followed by more in-depth technical details – was recommended to accommodate different user needs.
- Map design and background should be depicted with a stronger relief contrast and include settlement boundaries at medium zoom levels. Users also expressed interest in visualizing affected assets (e. g., critical infrastructure or natural protection areas).

5. Online survey

5.1 Approach

The online survey targeted the population of the canton of Lucerne. It was built using Unipark.

The survey was structured into seven questions blocks. The first one included the age check and the gender quota. The second block focused on participants' familiarity with mapping tools in general and natural hazard information. In the third block, participants' risk perception of natural hazards was assessed. For blocks three and four, participants were randomly assigned to one design version and first answered questions concerning a synoptic map showing an overview of all natural hazard risks in the canton of Lucerne. Second, they were confronted with two zoomed in process maps for flooding and avalanches, respectively, and answered a set of questions of understanding. Block five included the second measurement of their risk perception, controlling for a potential effect of looking at the different maps. In the sixth block, their preferences for background layer scheme and their comparative preference for one of the three designs was assessed. The survey concluded with a final block on sociodemographic information. The detailed questionnaire can be found in the Supplementary Material.

5.2 Sample

In total, 197 participants filled in the survey. The canton of Lucerne has approximately 400'000 inhabitants (LUSTAT Statistik, 2025). The sample recruited by the specialised company Bilendi was based on best effort. Participants needed to be living in the canton of Lucerne, be at least 18 years old and we added a quota for gender. Three participants were excluded for completing the survey in less than five minutes and therewith investing significantly less time than the average of around 18 minutes. One participant was further excluded for always choosing the same item. The sample shows a slight

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underrepresentation of participants with compulsory education and a certain underrepresentation in the age groups 20 to 39 and 40 to 64, see Table 1.

		Survey	LU
Gender	Female	52.3	50.0
	Male	47.2	50.0
Education	Compulsory education	6.1	13.1
	Secondary education	43.5	33.5
	Tertiary education	50.3	49.4
Age	20–39	35.5	25.2
	40–64	44.7	35.5
	65–84	17.3	16.9
	85+	0.5	2.6

Table 1: Sociodemographic variables in percentages of the sample (N=197) compared with the population statistics of the canton of Lucerne for 2024 (LUSTAT Statistik, 2025).

5.3 Analyses

The collected data was analysed using R (2026.01.0). Descriptive statistical analyses were conducted in the first instance, including measures such as mean, median, standard deviation, variance, and skewness. Following this, we applied inferential statistical methods to examine relationships between variables. One-way analysis of variance (ANOVA), linear regression models, and t-tests were used to test for statistically significant differences between groups; Cronbach's alpha was calculated to assess the internal consistency and reliability of the scales used (Bland and Altman, 1997; Kim, 2014; Rutherford, 2011; Ståhle and Wold, 1989; Tavakol and Dennick, 2011). To analyse the interaction between different factors, a covariate analysis was conducted using linear regression (Alexopoulos, 2010; Rutherford, 2011).

Various indices were built, which are shortly described in the following. Risk perception was measured with six items (see Supplementary Materials) and resulted in an index with a Cronbach's Alpha of 0.86 (N=193), demonstrating good internal consistency. We further built a four-item index on spatial risk perception measured before and after participants were exposed to the risk maps, both resulting in a Cronbach's Alpha of 0.7 (N=193) showing acceptable consistency.

An important element of the study are the various items measuring participants understanding of the differently designed maps. We constructed four comprehension scores, each representing the mean proportion of correctly answered items within a given question set. The first assessed participants' overall understanding of the synoptic map. The second captured their ability to assign correct risk levels to defined cities depicted on the synoptic map. In addition, participants estimated the likelihood that the old town of Lucerne would be affected by a severe natural hazard within the next 100 years. The third and fourth scores focused on comprehension of two process maps covering water-related and avalanche risk, respectively. These four scores and the likelihood estimate were assessed for each of the three map designs, resulting in 15 measures in total.

To enable comparisons across map designs, we calculated three types of aggregate scores. First, an overall comprehension score was computed for each map design by aggregating all five measures. Second, a synoptic map score was derived by

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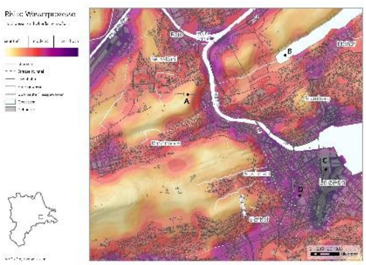
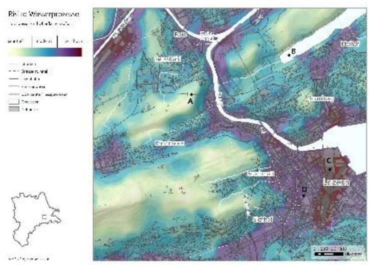
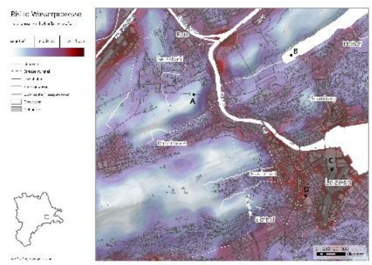
aggregating the two comprehension scores and the likelihood estimate related to the synoptic map. Third, a process map score was derived by aggregating the two comprehension scores related to the process maps.

5.4 Results

5.4.1 Map understanding and assessment

On average, participants answered 15.17 out of 25 comprehension questions correctly. For the synoptic map, participants answered on average more than half of the nine comprehension questions correctly (M = 5.57, see Table A1). The biggest challenge was recognising that no area within the canton is entirely risk-free, with only 29 % of participants answering the question correctly. Participants also struggled to assign correct risk levels to specific cities (M = 1.56 out of 5) and to recognise that the probability of a future event cannot be derived from the map (66 % incorrect answers). Detailed values are given in Table A2. Participants assessed the maps overall as trustworthy, informative, useful, clearly structured, comprehensible, and visually appealing with means between 3.54 to 3.85 out of 5.

Figure 2: Mean values of how favourably participants perceived the tested map designs (N = 193).

Version 1	Version 2	Version 3
		
M = 1.65	M = 2.05	M = 2.31
SD = 0.83	SD = 0.76	SD = 0.73

Preferences regarding visual presentation revealed clear patterns. Map design version 1 was most favoured, receiving the highest ranking, followed by version 2, and version 3, indicating a consistent preference for version 1 over the other designs (see Figure 2). Bonferroni Post-hoc comparisons confirmed significant differences between all three designs: version 1 was preferred over both version 2 ($\Delta = 0.40$, $p < .001$) and version 3 ($\Delta = 0.66$, $p < .001$), and version 2 was preferred over version 3 ($\Delta = 0.26$, $p = .002$). In addition, the colour scheme of version 1 was rated significantly more favourably than that of version 3 ($F(2, 190) = 37.123$, $p < .001$).

5.4.2 Influence of colour schemes on understanding

Each participant viewed three maps of consistent design: a synoptic overview and two zoomed-in process maps.

We first examined whether colour scheme affected participants' map comprehension, using map design as the independent variable and the four comprehension scores and one likelihood estimate as dependent variables. ANOVAs revealed no significant effects of colour scheme on any of the measures (see Table 2 and Table A3).

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	ANOVA results
Understanding synoptic map by map designs	F(2, 190) = 1.439, p = .240
Understanding risk level for cities on the synoptic map by map designs	F(2, 190) = 2.356, p = .098
Understanding water related risks by map designs	F(2, 190) = 0.42, p = .658
Understanding avalanche risk by map designs	F(2, 190) = 0.651, p = 0.523

Table 2: ANOVA results for understanding scores by map designs (N=193).

In a next step, we repeated these analyses using the three aggregate scores: the overall comprehension score, the synoptic map score including the likelihood estimate, and the process map score. Again, the map design had no significant impact on the overall comprehension of the maps (F(2, 190) = 1.071, p = 0.345) (see Table A4).

We further tested whether synoptic and process comprehension scores differed depending on the type of map participants evaluated. Across all map designs, process comprehension scores were consistently higher than synoptic comprehension scores, indicating a tendency for better understanding of process-related information, and this effect was statistically significant (F(1, 186) = 9.31, p = .003) (see Table A1). There was no significant main effect of map design (F(2, 175) = 0.42, p = .657), and no significant interaction between map design and knowledge type (i.e., whether questions concerned the synoptic overview or the process maps) (F(2, 186) = 1.84, p = .161). Including covariates into the analyses revealed significant effects of age, living situation, general risk perception, and perceived map quality, though it did not lead to a significant effect of map design (see Table B1).

We further examined the potential influence of several covariates on the effect of map design on comprehension: age, gender, employment status, education, living situation, risk perception, spatial risk perception (measured before exposure to the maps) as well as perception of the map design. Although significant effects of individual covariates were observed, as discussed in the following chapter, none led to a significant interaction with map design (see Table B2).

Despite the general understanding, some differences emerged in how participants perceived risk intensity of moderate and low levels depending on the colour scheme. In the case of Sörenberg, which is classified as risk level 3, the average perceived risk varied notably between versions. In version 1, participants rated the risk lower compared to version 2 and version 3 (F(2,190) = 6.136, p = .002), see Table B3. A similar trend was seen for locations in the low-risk category (marked with an arrow, see figures in Appendix C): version 1 was rated lowest whereas version 2 and version 3 received similar and significantly higher values (F(2,190) = 3.948, p = .021). In this instance, the issue is that the risk was most frequently rated as "non-existent" for version 1.

5.4.3 Influence of personal factors on understanding

Several personal factors were found to influence participants' map comprehension. A multiple linear regression analysis showed that map comprehension is primarily influenced by individual characteristics. Higher perceived map quality was associated with significantly better comprehension (b = 1.12, SE = 0.33, p = .001). In addition, older participants showed lower comprehension scores (b = −0.06, SE = 0.02, p = .006). Participants' living situation was also related to comprehension, with homeowners scoring lower than renters (b = −0.73, SE = 0.29, p = .014). These two variables are also linked since older

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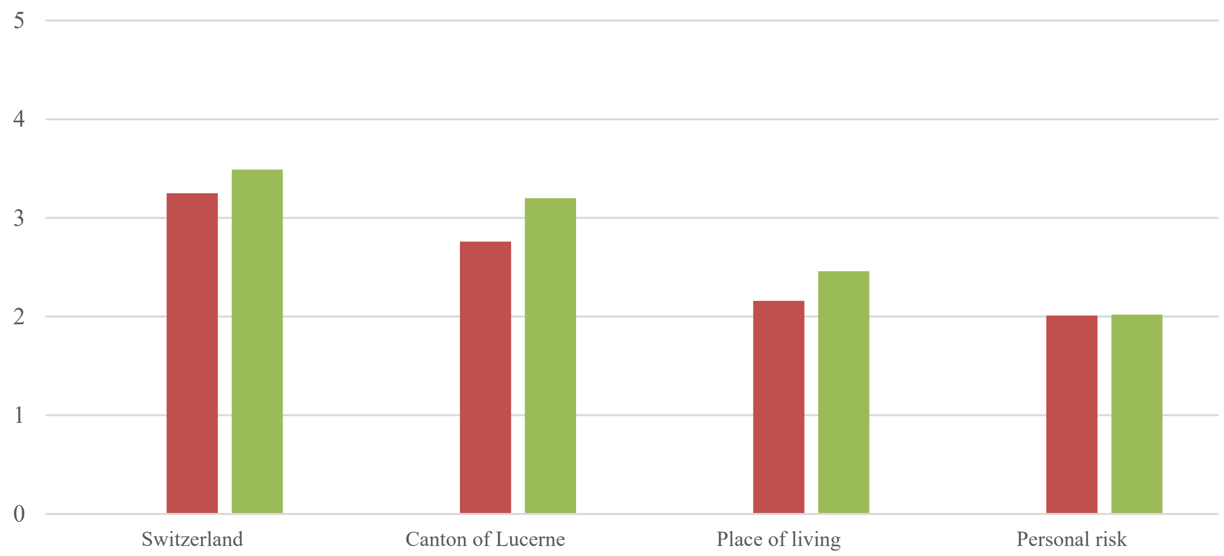
participants are significantly more likely to own their home compared to younger participants (F(1, 191) = 7.688, p = 0.006). Furthermore, higher general risk perception was associated with lower comprehension (b = −0.87, SE = 0.36, p = .015).

In contrast, gender, employment status, education level, and spatial risk perception (measured before map exposure) were not significantly related to comprehension (see Table B4).

5.4.4 Impact on risk perception

We measured spatial risk perception before and after participants were exposed to the risk maps. A paired t-Test revealed a significant change: participants' spatial risk perception was higher after having seen and assessed the maps (t(192) = -6.792, p = 0, Cohen's d = 0.489). This effect was accentuated for renters (M = 2.85, SD = 0.63), who compared to homeowners (M = 2.6, SD = 0.56), had a significantly higher spatial risk perception after having seen the maps (F(1, 191) = 4.43, p = 0.037). In addition, we observed that women's spatial risk perception increased more strongly after viewing the maps than men's (M = 2.90, SD = 0.61 vs. M = 2.67, SD = 0.60). No significant difference in risk perception was observed between genders or renters and homeowners before being exposed to the maps. As shown in Figure 3 there is, however, a tendency for perceived spatial risk to decrease with increasing personal exposure.

Figure 3: Spatial risk perception before (red) and after (green) risk map exposure (N = 193). Mean risk perception scores are shown regarding Switzerland, canton of Lucerne, place of living, and personal risk. Scores are measured on a scale from 1 to 5. Risk perception increased across all geographic scales after exposure, with the largest absolute change observed at the cantonal level, while personal risk perception remained largely unchanged.



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6 Discussion

This study was conducted to support the canton of Lucerne in designing and evaluating a comprehensive map to depict the risk for natural hazards. The revised Federal Act on Hydraulic Engineering published in August 2025 requires all cantons to prepare risk overviews helping to identify risks, justify the need for action, set priorities for future measures as well as facilitate the dialogue and raise awareness among those responsible (Risikoübersichten (CH und Kantone), 2026; Bundesversammlung der Schweizerischen Eidgenossenschaft, 1993). Maps are a well-established and accepted means to communicate the results of such assessments to a wide variety of end-users including the public. However, only when carefully designed, they are understood and perceived to be useful.

We therefore initiated in close collaboration with the Natural Hazard Office in Lucerne an iterative process to improve the original design of the risk overview maps and developed a range of prototypes to be tested with focus groups and after another round of improvement in an online survey with inhabitants of the canton.

6.1 Key findings

The results show that map design, operationalised through different colour schemes, had no significant effect on participants' understanding. In the online survey, the map design did not impact participants' comprehension of the synoptic map, which provides an overview of all natural hazard risks in the canton of Lucerne, nor of the two process maps depicting a zoomed-in view of water-related risks and avalanche risks respectively. When controlled for different covariates, the impact of map design remained non-significant.

Nevertheless, participants in both the focus group discussions and the online survey expressed a clear preference for the colour scheme ranging from yellow to dark purple (version 1). The only shortcoming of this version was that participants tended to underestimate risk in areas marked as moderate to low. The yellow–red gradient appears to draw attention primarily to high-risk zones, unintentionally diminishing the visual prominence of moderate and low-risk areas, likely due to the strong visual contrast between the colour extremes.

We attribute the comparable performance of the different map designs in terms of comprehension to the extensive iterative design process. Since all cartographic refinements were applied consistently across all three versions and only the colour scheme varied, differences in comprehension cannot be attributed to unequal design quality. Collaboration between experts from different disciplines, combined with the stepwise refinement of the prototypes, resulted in final products that participants consistently rated as highly appealing, trustworthy, and informative. These findings highlight the importance of a rigorous and thoughtful design process in the development of natural hazard risk maps (Dallo et al., 2024; Meyer et al., 2012; Schneider et al., 2025).

On average, participants answered 65 % of the comprehension questions correctly, comparable to the range identified by Dallo et al. (2024) identified for earthquake risk maps. Participants experienced the greatest difficulty in recognising that there are no areas entirely free of risk within the canton of Lucerne. While most participants correctly identified that the highest risks occur in urban areas and along river valleys, they found more detailed questions challenging, such as estimating specific risk levels for particular locations on the synoptic view. We observed that participants answered significantly more questions correctly on the process maps compared to the synoptic map. This suggests that, while participants are able to identify the big picture on the synoptic map, they benefit from a higher zoom level when addressing more detailed questions. The canton of

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Lucerne has implemented the evaluated design (version 1) by making the risk overview map available on its GIS website (Risikoübersicht Naturgefahren synoptisch • Risikoübersicht Naturgefahren • Geoportal Kanton Luzern, 2026), thereby enabling users to explore specific questions at an appropriate zoom level.

In contrast to colour schemes, the online survey indicates that individual characteristics play a key role in map comprehension. In particular, older participants demonstrated significantly lower levels of understanding. This finding contrasts with previous research on earthquake risk communication in Switzerland, where older participants performed better in interpreting map-based information (Dallo et al., 2024). In addition, participants who evaluated the maps more positively reported fewer difficulties with the knowledge questions, suggesting that familiarity with map-based products and favourable perceptions may facilitate comprehension. This is supported by Fuchs et al. (2009), who emphasise that the more accessible certain information, the easier the depicted information can be processed.

Exposure to the maps had a measurable effect on spatial risk perception. After viewing and assessing the maps, participants reported significantly higher levels of perceived spatial risk, in line with previous studies showing that hazard maps can increase awareness and concern (Sun et al., 2024). However, participants tended to perceive the overall risk for the wider Lucerne region higher than the risk at their specific place of residence, while rating their personal likelihood of being directly affected as comparatively low. This pattern reflects a well-documented gap between general awareness and personal relevance in risk communication, whereby individuals recognise risks at a broader scale without translating this awareness into perceived personal vulnerability or behavioural change (Becker et al., 2017; Wachinger et al., 2013).

A more detailed examination of this exposure effect suggests that differences in comprehension may translate into differences in risk perception for specific participants groups. Spatial risk perception among homeowners, who are likely to be older, was significantly less influenced by exposure to the maps compared to renters. One explanation may be that limited understanding led to lower risk estimates. In addition, psychological mechanisms may contribute to this pattern. The preparedness paradox suggests that if past events, such as avalanches or floods, did not result in substantial personal damage, individuals may infer that future threats are similarly harmless (Kruger et al., 2019). Similarly, the desire to avoid cognitive dissonance may lead homeowners to downplay risks, as acknowledging them could imply the need for costly protective measures or evoke emotional discomfort (Vermeulen, 2014). At the same time, women showed a significantly greater increase in spatial risk perception than men after engaging with the maps. This is relevant for the implementation of precautionary measures, as decisions related to housing and property are often influenced by gendered roles and responsibilities. Taken together, these findings are particularly important, as older individuals are more likely to own property and are therefore in a position to implement precautionary measures.

6.2 Practical implications

Our approach demonstrates how risk overview maps for natural hazards can be designed and refined through a co-design process that actively involves end users. While different colour schemes can be applied, their effectiveness depends on careful development and testing of map elements with target audiences.

The design principles developed for the canton of Lucerne provide transferable insights for the communication of risk overviews in other regions and for other contexts. In particular, maps should be recognised as a relevant communication tool in their own right, as they already provide a direct benefit by increasing perceived spatial risk. However, risk maps can only achieve their full impact when accompanied by appropriate communication. Simply making them available (online) is not sufficient (Kjellgren, 2013). Engaging and participatory communication formats have the potential to enhance preparedness (Becker et al., 2013; Maidl et al., 2021).

Moreover, our analysis shows that not all user groups are equally well reached by these products. Targeted efforts are therefore needed to better include and address those groups for whom comprehension and impact remain limited. This includes developing tailored communication approaches and supporting interpretation, for example through clearer explanations or guided elements. In particular, it is important to better understand the motivations of homeowners and to identify ways to encourage the implementation of precautionary measures.

Risk maps should be conceived as multi scale systems that allow users to move between overview and more detailed representations, as users benefit from higher zoom levels when addressing specific questions. In addition, enabling users to explore maps interactively can further enhance understanding and engagement. Information should be structured in a layered manner, combining simple, accessible explanations with more detailed content to accommodate different levels of expertise. This is supported by Kunz and Hurni (2008), demonstrating that a layered structure as used in GIS is a valid approach to explore.

When using map design version 1 (yellow-pink-purple), we recommend increasing the saturation of the low-risk levels to a strong yellow and transitioning between colours more smoothly, so that the map appears more balanced and conveys a more continuous risk gradient. This modification would nonetheless need to be retested. Cartographic literature supports such considerations: Kovesi (2015) emphasises that the incremental change in perceptual lightness across the map should be uniform.

Finally, communication strategies should explicitly address the gap between general awareness and perceived personal risk, for example by linking map-based information to local impacts and personal consequences.

6.3 Limitations and future studies

The study area is limited to the canton of Lucerne, which facilitated the evaluation, as participants were familiar with the region. However, the findings do not provide insights into potential regional differences in the perception of natural hazard risk maps. Given that risk perception and familiarity with hazards vary across contexts, future research should explore cross cultural comparisons to assess whether similar design elements are effective in different regions or settings.

In addition, the evaluation was based on a static version of the risk map. While this represents a relevant and valid use case, as such maps are often reproduced in leaflets or media outlets, they are in practice increasingly embedded in interactive environments, such as the GIS portal of the canton of Lucerne. The absence of interactive features may have limited participants' engagement and their ability to explore spatial information in depth. Future research should therefore examine how interaction with such features influences the comprehension and perception of risk maps. It would also be valuable to investigate how risk maps presented on such platforms are perceived and contextualised in relation to other risks and hazards, particularly given evidence that prior consideration of one hazard can influence the perception of another (Vinnell et al., 2026).

Beyond these specific limitations, the study highlights the value of the chosen methodological approach. The structured evaluation of a prototype risk map with end-users proved highly informative. Although such an approach may appear

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straightforward in theory, empirical evaluations of this kind remain uncommon in practice. Risk maps are often designed and disseminated without systematically involving the public or assessing their comprehensibility.

The findings demonstrate that incorporating user perspectives can yield meaningful and differentiated insights into how risk information is understood and interpreted. Future research should build on this approach by further integrating participatory and user-centred methods into the development and evaluation of risk communication tools. Such approaches may also help to better understand how to effectively reach and support those user groups identified in this study as having greater difficulty interpreting the maps, in particular older participants and homeowners.

7 Conclusion

This study challenges the assumption that visual design choices, such as colour schemes, are the primary drivers of comprehension in natural hazard risk maps. Our results show that, when maps are developed through a rigorous and iterative co-design process, different colour schemes can perform equally well in terms of understanding. Instead, comprehension is shaped more strongly by user characteristics and perception of the map design. This shifts the focus from optimising isolated design elements to prioritising a holistic, user-centred design processes.

At the same time, the findings confirm that risk maps are effective communication tools: exposure to the maps led to a measurable increase in perceived spatial risk. However, participants consistently rated risks at the regional level higher than at their own place of residence, revealing a persistent gap between general awareness and perceived personal vulnerability. This gap is critical, as it limits the potential of risk maps to trigger behavioural change and preparedness.

Importantly, the results demonstrate that risk communication is not equally effective across all user groups. Homeowners, who are more likely to be older and in a position to implement precautionary measures, were less responsive to the maps, while women showed a stronger increase in perceived risk. These differences underline that risk maps do not operate in a neutral way but interact with existing perceptions, experiences, and decision contexts. Designing "one size fits all" solutions is therefore insufficient, instead, tailored approaches are required.

Risk maps should not be considered as standalone visual products; they should be understood as components of a broader communication strategy. Their effectiveness depends on how they are embedded in interactive, participatory, and user-oriented formats that support interpretation, consider differences between user groups, and explicitly bridge the gap between general awareness and personal relevance.

Finally, this study demonstrates that integrating user perspectives through systematic, empirical evaluation is not merely beneficial but essential. Without such approaches, risk maps risk remaining technically sophisticated but communicatively ineffective. Future research should therefore move beyond evaluating isolated design features and instead focus on how risk communication tools function in real world contexts, how they influence behaviour over time, and how they can be tailored to those audiences most in need of support.

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485 **Appendix A: Map comprehension values**

	N	M	SD	M per score	Max per score
Synoptic					
Map design 1	64	5.89	1.71		
Map design 2	66	5.45	2.13	5.57	9
Map design 3	63	5.37	1.74		
Cities					
Map design 1	64	1.72	1.02		
Map design 2	66	1.32	1.13	1.56	5
Map design 3	63	1.65	1.23		
Probability					
Map design 1	64	0.34	0.48		
Map design 2	66	0.30	0.46	0.34	1
Map design 3	63	0.38	0.49		
Water					
Map design 1	64	4.27	1.12		
Map design 2	66	4.08	1.53	4.19	5
Map design 3	63	4.22	0.99		
Avalanche					
Map design 1	64	3.50	1.02		
Map design 2	66	3.62	1.09	3.51	5
Map design 3	63	3.41	1.01		

Table A1: Mean scores of comprehension by map design (N=193)

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Items of synoptic map comprehension	**% of correct answers**
The greatest risk of natural hazards exists along watercourses.	89.1
The areas around the cities of Lucerne and Sursee a higher risk of natural hazards than the rest of the canton of Lucerne.	83.4
The yellow-green areas show where there are forest areas.	77.7
Natural hazards cannot cause major damage outside densely populated areas.	67.9
I can recognise mountains by their yellow-green colour.	57.5
In the purple-coloured areas, avalanches that cause major damage must be expected.	53.4
The risk of natural hazards is lower in Sörenberg than in Wollhusen.	50.8
The risk of natural hazards is greatest in densely populated areas.	48.7
There are areas in the canton of Lucerne where there is no risk of natural hazards.	28.5

Table A2: Percentage of correct answers per item for the synoptic map comprehension (N = 193).

	N	M	SD	Min	Max
Overall map comprehension					
Map design 1	64	15.72	3.47	2	22
Map design 2	66	14.77	4.49	0	22
Map design 3	63	15.03	3.29	4	22

Table A3: Mean scores for overall map comprehension.

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	Comprehension	N	Mean	SD
Map design 1	Processes	64	3.88	0.95
	Synoptic	64	3.81	1.13
Map design 2	Processes	66	3.85	1.19
	Synoptic	66	3.39	1.32
Map design 3	Processes	63	3.82	0.86
	Synoptic	63	3.51	1.17

Table A4: Descriptives comparison between synoptic map comprehension and process map comprehension.

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Appendix B: Influence of covariates on map comprehension by map design

Map design	F(2, 175) = 0.42, p = .657
Comprehension (synoptic vs. process)	F(1, 186) = 9.31, p = .003
Covariates	
Age	F(1, 175) = 7.87, p = .006
Gender	F(2, 175) = 0.45, p = .636
Employment	F(2, 175) = 0.78, p = .462
Education	F(2, 175) = 1.14, p = .323
Living situation	F(1, 175) = 5.64, p = .019
Risk perception	F(1, 175) = 5.56, p = .020
Spatial risk perception	F(1, 175) = 1.03, p = .312
Map design perception	F(1, 175) = 10.89, p = .001
Map design x comprehension type	F(2, 186) = 1.84, p = .161

Table B1: Differences between synoptic map comprehension and process map comprehension by map design with covariates (N = 193).

	Df	F	p	Partial η²
Map design	2	0.417	0.659	0.005
Covariates				
Age	1	7.409	0.007	0.041
Gender	2	0.595	0.553	0.007
Employment	2	0.619	0.540	0.007
Education	2	1.047	0.353	0.012
Living situation	1	6.007	0.015	0.033
Risk perception	1	6.097	0.015	0.034
Spatial risk perception	1	1.356	0.246	0.008
Map design perception	1	10.791	0.001	0.058
Residuals	175	NA	NA	NA

Table B2: Overall map comprehension with covariates by map design (N = 193).

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	Version	N	M	SD	p
Sörenberg	Version 1	64	2.23	1.16	0.002615
	Version 2	66	2.67	1.06	
	Version 3	63	2.90	1.06	
	All	193	2.60	1.12	
Arrow location	Version 1	64	1.05	1.12	0.020899
	Version 2	66	1.62	1.42	
	Version 3	63	1.60	1.39	
	All	193	1.42	1.34	

Table B3: Descriptive differences between Sörenberg and Arrow location across Versions 1, 2, and 3. Answer options were: No risk, 1 = very low risk to 5 = very high risk.

Predictor	Estimate	Std. Error	t	p
(Intercept)	14.615	2.330	6.272	0.000
Age	-0.062	0.022	-2.771	0.006
Gender male	0.757	1.231	0.615	0.540
Gender divers	0.202	1.261	0.160	0.873
Other	-0.322	0.398	-0.809	0.420
Retired	-0.368	0.526	-0.700	0.485
Secondary	-0.255	0.727	-0.350	0.727
Tertiary	-0.250	0.454	-0.550	0.583
Homeowner	-0.732	0.294	-2.492	0.014
Risk perception	-0.872	0.356	-2.454	0.015
Spatial risk perception	0.506	0.491	1.033	0.303
Map design perception	1.116	0.327	3.413	0.001

Table B4: Linear regression on the influence of personal factors and overall map comprehension (N = 193).

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Appendix C: Prototype maps used for the online survey

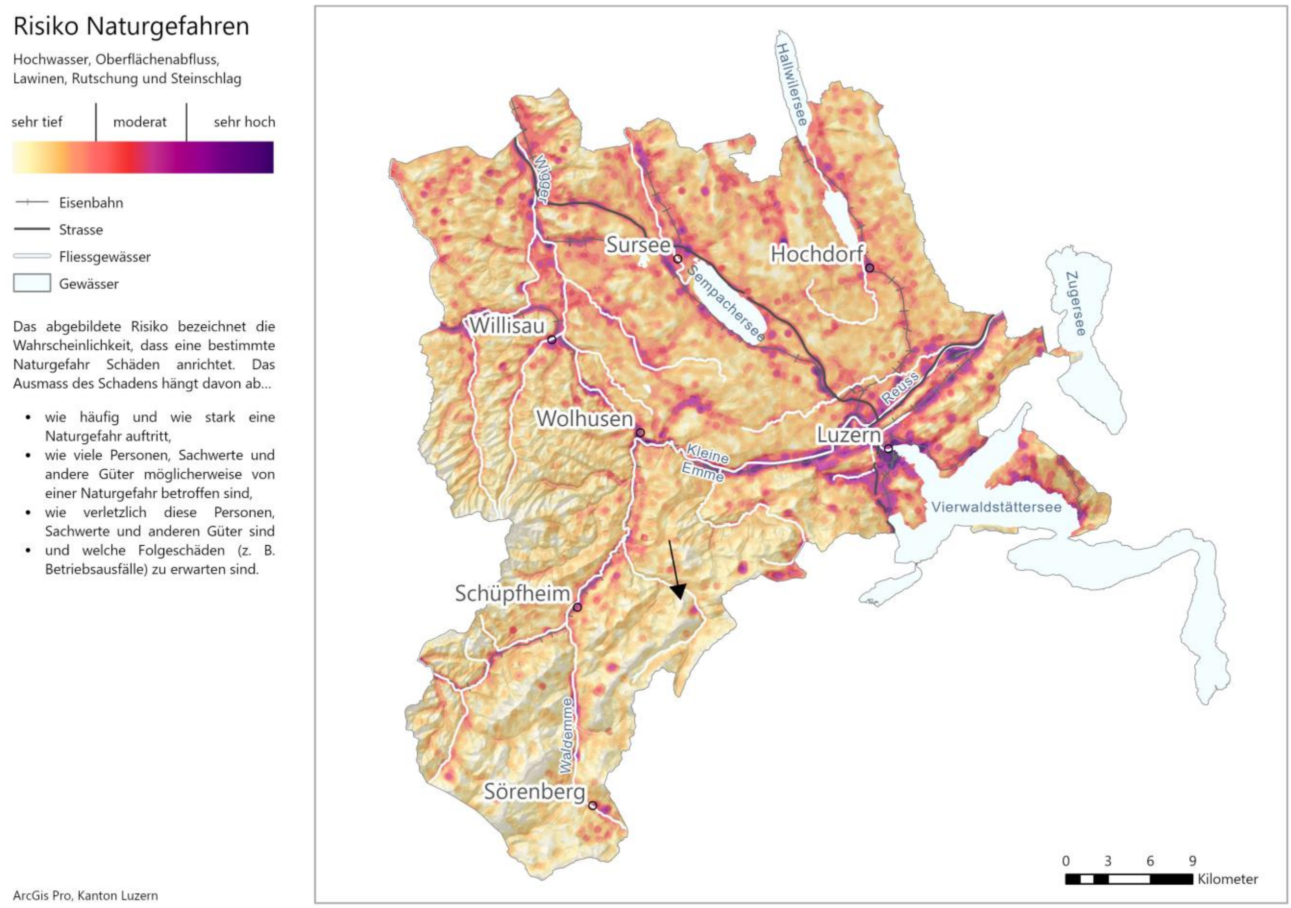

Figure C1 Synoptic risk map (Version 1; yellow–pink–purple colour scale) used in the online study to communicate the spatial distribution of natural hazard risk in the Canton of Lucerne, integrating floods, surface runoff, avalanches, landslides, and rockfall into a single risk representation (original format: A3). The arrow is connected to Table A7.

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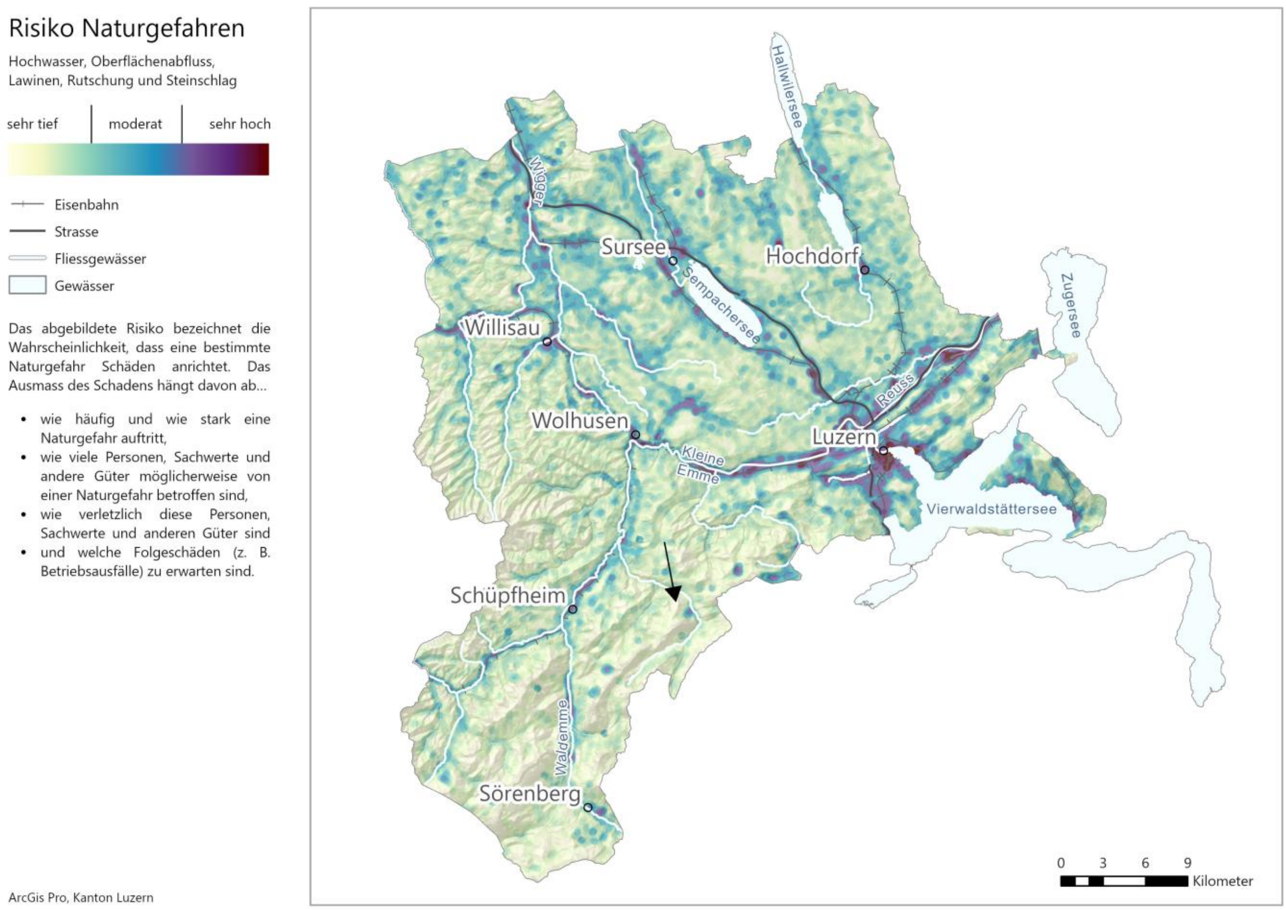

Figure C2: Synoptic risk map (version 2; yellow to blue to purple colour scale) used in the online study to communicate the spatial distribution of natural hazard risk in the Canton of Lucerne, integrating floods, surface runoff, avalanches, landslides, and rockfall into a single risk representation (original format: A3).

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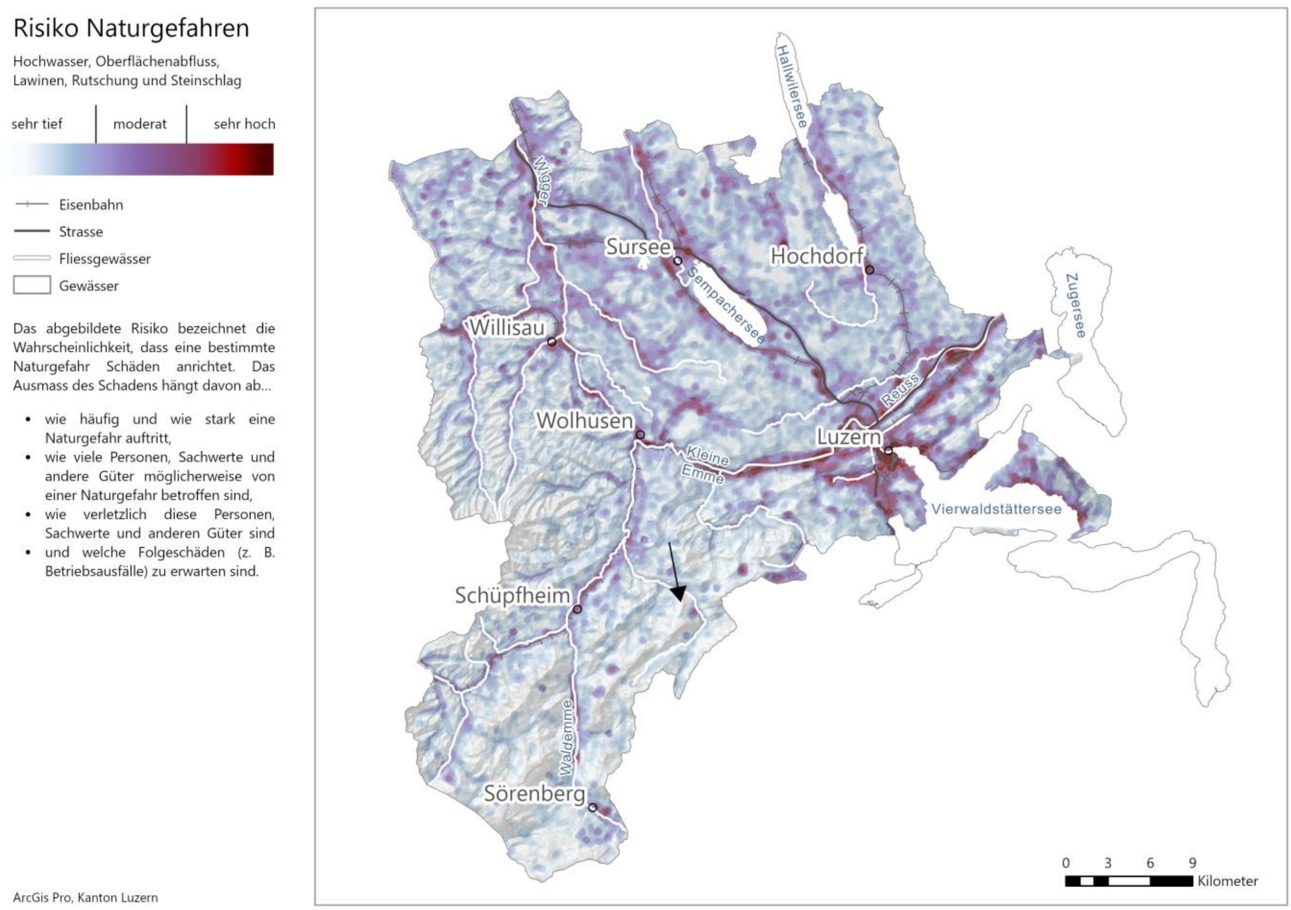

Figure C3: Synoptic risk map (version 3; blue to red colour scale) used in the online study to communicate the spatial distribution of natural hazard risk in the Canton of Lucerne, integrating floods, surface runoff, avalanches, landslides, and rockfall into a single risk representation (original format: A3).

https://doi.org/10.5194/egusphere-2026-3789
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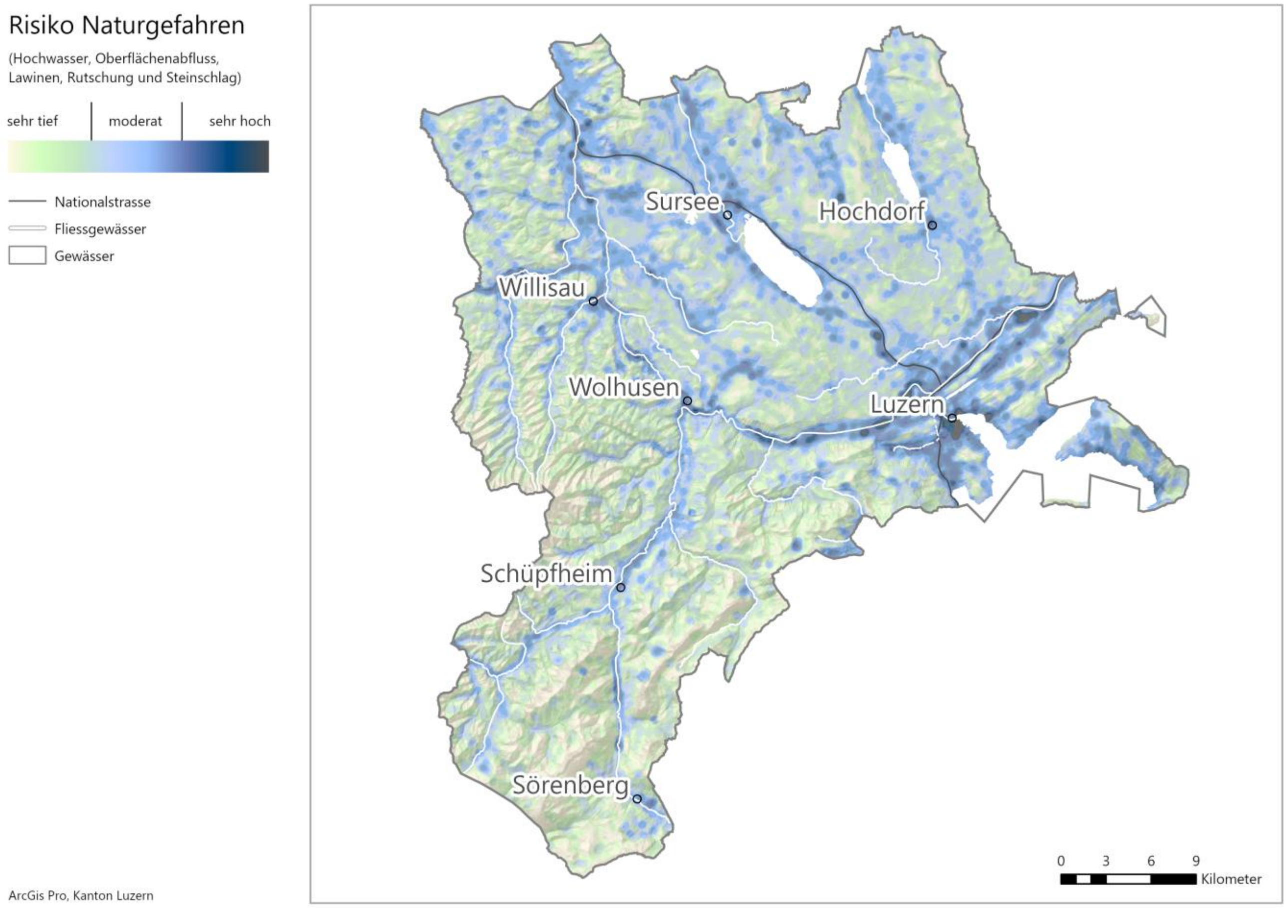

Figure C4: Synoptic risk map (version 4; yellow to blue colour scale) used during the focus group to communicate the spatial distribution of natural hazard risk in the Canton of Lucerne, integrating floods, surface runoff, avalanches, landslides, and rockfall into a single risk representation (original format: A3).

Code and data availability

As this study was conducted on behalf of the canton of Lucerne, the underlying data are only available upon request and subject to review and agreement with the commissioning party.

Author contributions

Mika Chadzelek developed the study design, discussion guide, and online survey as part of her Master's thesis, in close collaboration with Lorena Kuratle, Michèle Marti, and representatives of the Canton of Lucerne. The tested prototypes were developed in a co-design process by Kathrin Habegger from the Canton of Lucerne, with significant expertise input from Donat Fulda. Michèle Marti reassessed the collected data and expanded the analysis, building on Mika Chadzelek's Master's thesis, and synthesised the findings for this publication.

Acknowledgements

This study was carried out as part of the Master's thesis of Mika Chadzelek, under the supervision of Michèle Marti, with support from Lorena Kuratle.

Co-design of the map prototypes: Kathrin Habegger, Donat Fulda, Serena Liener, Claudio Wiesmann, Mika Chadzelek, Lorena Kuratle, Michèle Marti

Design and documentation of the focus group discussions: Mika Chadzelek, Lorena Kuratle, Michèle Marti

AI use

The authors used AI-based tools (Claude, ChatGPT) to support language editing and to assist with coding for the statistical analysis in R. All scientific content, analysis, interpretation, and conclusions are the authors' own, and the authors reviewed and verified all AI-assisted output.

Financial support

The study was financially supported by the Canton of Lucerne.

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