Review of multi-hazard indices

Focus on methods applicable for a Swedish context

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Abstract

A literature review of methods where different hazards are combined into a multi-hazard index or method are presented in this report. The purpose of the review is to get an insight into approaches to combine different hazards into a multi-hazard index or method.

To directly combine hazards, it is necessary to present them with the same unit of measure. This can be done with different measures for normalizing or using weights. Maps are often used to get an understanding of the spatial distribution of the hazard as well as the hazard level. No specific method or tool that can be applied directly for relevant hazards in Sweden have been found in this review. However, several general principles and methods that are considered valuable for the Extreme-Index project are identified.

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Summary

The world continuously faces challenges in terms of extreme weather events like wildfires and flooding. Therefore, a need exists to quantify and visualize risk as a basis for decision-making by nations, regional and local governments, and first responders. This report is part of the project “EXTREME-INDEX: A new multi-hazard vulnerability index”, financed by MSB and FORMAS.

The project will develop and implement a multi-hazard tool which can include different types of extreme natural events, for example wildfires, heatwaves, droughts and flooding, and the potential interaction between these different events. The tool will consist of several single-hazard indices and a methodology for their combination.

The focus of this report is to present a literature review of methods where different hazards are combined into a multi-hazard index or method. The purpose of the review is to get an insight into approaches to combine different hazards into a multi-hazard index or method. A systematic method was used in the review and a total of 29 papers were reviewed carefully.

Different principles for standardising hazards and methods to combine single hazards have been identified in this review. To directly combine hazards, it is necessary to present them with the same unit of measure. This can be done with different kinds of techniques; however, it is difficult especially if existing risk index methods are used to describe the hazard. A less sophisticated procedure, but still sufficient, is to overlay the hazards on a map to see where high index values coincide. By using maps, it is easy to understand spatial distribution of the hazard as well as the hazard level. The latter can be illustrated with color codes.

This review gives an overview of the area and different areas that are considered important when studying multiple hazards. No specific method or tool that can be applied directly for relevant hazards in Sweden have been found in this work. However, several general principles and methods that are considered valuable for the project are identified.

Preface

This is an interim report in Work Package 2 (WP2) in the project “EXTREME-INDEX: A new multi-hazard vulnerability index” financed by MSB and FORMAS.

The project will develop and implement a multi-hazard tool which can include different types of extreme natural events, e.g., wildfires, heatwaves, droughts, and storms as well as pluvial, fluvial and coastal flooding, and the potential interaction between these different events. The tool will consist of several single-hazard indices and a methodology for their combination. The combined index will be associated with an assessment of the rescue service capabilities and possible human response.

In WP2 an inventory of the indices, tools, and methods available for risk assessments for natural hazards (with focus on wildfires and flooding) is conducted. The inventory will provide direct input to WP3 and WP4. The focus in this report is to review different approaches to combine different hazards into a multi-hazard index or method.

Contents

1 Background

The world is facing challenges in terms of extreme weather events like wildfires and flooding. Therefore, a need exists to quantify and visualize risk as a basis for decision-making by nations, regional and local governments, and first responders. Efficient management to mitigate consequences or minimize the vulnerability of society to hazards requires the quantification of those hazards and risks. That quantification involves information on the type of event, probability of the specific event occurring, magnitude of the event as well as exposure to the hazard and associated damages. In the case of wildfire, variables like temperature, moisture content and wind velocity are used to create indices and hazard maps to represent the wildfire danger. Similar indices and hazard maps can be developed based on other variables for flooding.

A society's exposure to hazards and the magnitude of potential consequences can be expressed using a so-called risk index. Risk indices can be constructed for different types of hazards and they can be applicable to different areas and levels of the society, from individual buildings or facilities to countries or even entire continents. An example of the former is the fire risk index methods for buildings; such an index can be applied to a certain building as a cost-effective screening tool for prioritizations between different fire safety measures [1]. On the other hand, there are risk index methods on a larger level (national and international), like the WorldRiskIndex [2]. This index provides an approach to assess risk and vulnerability towards hazards on a country scale and allows the comparison of countries at a global scale.

In a project financed by the Swedish Civil Contingencies Agency (MSB) and FORMAS, a multi-hazard risk index, EXTREME-INDEX, will be developed to assist prediction of emerging risks on a local, regional, and national level to support various stakeholders for strategic training and resource planning. The tool will consist of several single hazard indices and methodology for their combination. The focus in this project will be on implementation of wildfires (forest and WUI) and flooding/storms (urban and coastal) into the developed framework.

Regarding studies of single hazards there are a multitude of established approaches to express the risk associated with the specific hazard. This is, for example, clear based on the previous studies of wildfires [3] and flooding [4] in the Extreme-Index project. However, when it comes to analyses of multiple hazards (events occurring simultaneously or in close or in succession) there are much fewer studies [5].

There is a range of difficulties when studying multiple hazards. Kappes et al. [5] give four arguments to why multi-hazard risk analyses are not just the sum of the single hazards, namely: (1) the hazard characteristics and the methods to analyze them differ; (2) the hazards influence each other and it might be needed to described a chain of hazards; (3) methods to describe vulnerability vary between hazards; and (4) a variety of risk descriptions and quantification measures exists, which has to be adjusted to allow the comparison of different risks. These arguments all make it challenging to analyze multi-hazard risks.

Nonetheless, there are a range of different possibilities and approaches that can be used when combining hazards into a multi-hazard risk index. As an example, in the previously mentioned WorldRiskIndex, the exposure to the five included natural hazards (earthquakes, cyclones, floods, droughts and sea level rise) are summed into one exposure value that is divided by the exposed population [2]. Furthermore, not all studies on multiple hazards attempt to involve all relevant hazards in a defined area, instead they can be distinguished as more-than-one-hazard approaches. In this case, the hazards are primarily defined thematically, e.g. weather related hazards that are specifically related to high (or low) precipitation, or hazards that are specifically related to an earthquake. Further, in some cases the joint analysis of two or more hazards might be necessary, when one hazard triggers a second, e.g., when an earthquake leads to a landslide [5]. This is sometimes referred to as cascading hazards.

One of the major novelties of the EXTREME-INDEX is that the tool developed will utilize existing and established index methods. This means that approaches to combine methods that probably express the individual hazards differently, needs to be identified or developed. It should also be stressed that the focus in this report is on multi-hazard rather than on the vulnerability of the society. To obtain a perception of the consequences to society, and therefore also the risk of the multiple hazards, vulnerability aspects need to be considered.

1.1 Objective

The objective of the work presented in this report is to review different multi-hazard approaches and how different hazards can be combined into a single tool. This means that the work has specific interest in identifying how different hazards can be combined into a single tool and how cascading effects or synergistic effects between hazards have been treated in other studies.

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2 Methodology

The methodology applied in this work has also been applied in two previous review studies conducted within the project [3][4]. Hence, this chapter is based on the methodological description in these previous reports. Figure 1 illustrates the methodology for the literature review.

The applied methodology is systematic and transparent and resembles the structure for literature review presented in previous literature [6]. The fundamental idea is that by reviewing relevant references, different approaches for multi-hazard analysis is deemed to be covered.

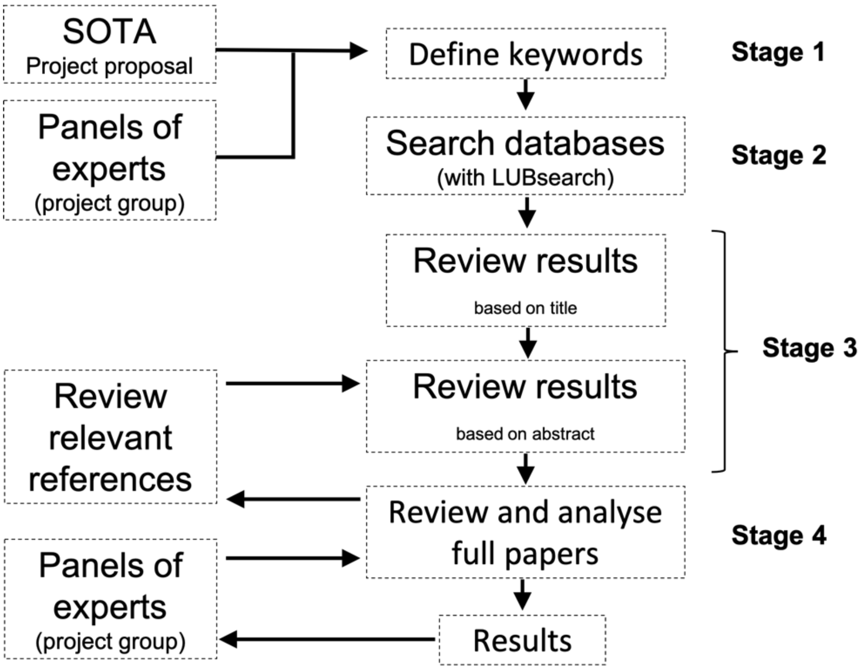

Figure 1: Methodology used in literature review.

2.1 Define keywords

The review started with the definition of keywords (Stage 1, see Figure 1). The list of keywords was developed based on experience from the previous reports in the project. The focus was on methods that are applicable for hazards relevant in Sweden, consequently, wildfires and flooding were given extra attention in this study. The following set of keywords and search combinations were defined:

- “multi* hazard ind*” wildfire*
- “multi* hazard ind*” flood*
- “multi* risk ind*” wildfire*
- “multi* risk ind*” flood*
- “numerous hazard ind*” wildfire*
- “numerous hazard ind*” flood*
- “numerous risk ind*” wildfire*
- “numerous risk ind*” flood*

Refinements, truncation (*) and quotation marks (“ “) were used to narrow down the results.

2.2 Search databases

In Stage 2 (see Figure 1) the search to identify relevant papers was conducted using LUBsearch [7]. LUBsearch is Lund University Libraries’ search service for articles, e-books, books, etc, providing access to large parts of the libraries' electronic and physical collections. The search engine is a specialized search engine with a large index of entries from research publishers and from subject databases. The contents of the library catalogue, LUBcat, is also included, along with large parts of Lund University Research Portal through SwePub.

Both Web of Science and Scopus are included in LUBsearch. Web of Science includes a range of different types of publications, such as journal papers, websites and conference proceedings. Scopus claims to be the largest abstract and citation database of peer-reviewed literature, scientific journals, books, and conference proceedings. Scopus has a larger coverage (> 20,000 journals) compared to Web of Science (> 12,000 journals). However, Web of Science is said to have a greater time period of coverage than Scopus. By using LUBsearch the scientific literature is considered to be covered satisfactorily.

2.3 Review results

The search resulted in a total of 92 titles. All the results were exported to spreadsheet and reviewed in two steps according to Stage 3 in Figure 1. Due to rather low number of articles all the abstracts were read to obtain an idea of whether the paper included relevant information about multi-hazard approaches relevant for a Swedish context.

2.4 Review and analysis of full paper

A total of 29 papers were selected for a full review, Stage 4 (see Figure 1). The main reason for omitting papers were that they did not cover natural hazards or that they did not cover an actual multi-risk tool or method. The reviewed papers were summarised in a spreadsheet. The list of references in these papers were also reviewed (so-called "snowballing") to identify and review additional relevant papers. This was done to minimize the risk of overlooking important papers about multiple hazards. Once all relevant references had been studied, relevant parts of the reviewed paper were then summarised in this report (see Chapter 3).

3 Results

The following topics are used to structure the analysis of the reviewed papers.

- Principles for standardising hazards
- Relationships between hazards
- Methods to combine single hazards into multi-hazards
- Examples of existing multi-hazard tools

Kappes et al. [5] give a good overview of these areas, and the work presented here is in many cases based on the work by Kappes et al.

3.1 Principles for standardising hazards

One of the major challenges with performing multi-hazard analyses is that the hazard characteristics are very different. Hazards differ in nature, intensity, frequency, and possible effects [5]. This makes it difficult to compare different hazards, but in order to facilitate some comparisons the reference unit needs to be standardized in some way. Kappes et al. [5] state two major techniques for such standardization, namely: qualitative classification of hazards; and the use of indices.

Regarding qualitative classification, intensity and frequencies can be defined to classify hazards into several classes. This approach was applied in the ARMONIA project [5][8] where three different intensity scales (low, medium, and high) of four different hazards were created (see Table 1). Since the different intensity scales in Table 1 are based on quantitative levels it can be regarded as a semi-quantitative classification as well.

Table 1 – ARMONIA hazard intensity classification from [5][8].

Hazard	Intensity scale			Parameter
	Low	Medium	High	
Flood	< 0.25	0.2-1.25	> 1.25	Flood depth (m)
Forest Fire	< 350	350-1,750	> 1,750-3,500	Fire line intensity (kW/m)
Forest Fire	< 1.2	1.2-2.5	2.5-3.5	Approximated flame length (m)
Volcanoes	< 5	5-10	> 10	Intensity = volcanic explosive index
Landslide	< 5	5-15	> 15	Percentage of landslide surface (m^2) vs. stable surface (%)
Seismic	< 10	10-30	> 30	Peak ground horizontal acceleration (% of 9.81 m/s^2)

There are also examples when an intensity class is combined with a frequency class, and the combination of these two classes determines the hazard level. As an example, Thierry et al. [9] used five different intensity classes which for each hazard (all related to volcanic activity) was determined according to damage level assessed by experts. The intensity level was combined with frequency classes which resulted in five hazard classes ranging from "negligible" to "very high" hazard. In total nine hazard maps (one for each hazard) were created. The maps were then superimposed to find areas were hazards overlapped. Similar approaches of combining intensity and frequency are applied in the Swiss guidelines on analysis and evaluation of natural hazards in mountain areas (referenced by Kappes et al [5]) and in a study on earthquakes and tropical storms [10]. Chiesa et al. [10] used a qualitative classification of the hazards from "low/none" to "extremely high". The combined hazard was then presented with the help of a matrix (see Table 2).

Table 2 – Matrix for multi-hazard determination from [10].

Earthquake hazard	Tropical storm hazard			
	Low/none	Moderate	High	Extremely high
Low/none	Low/none	Moderate	Moderate	High
Moderate	Moderate	Moderate	High	High
High	Moderate	High	High	Extremely high
Extremely high	High	High	Extremely high	Extremely high

Qualitative classification schemes will naturally differ between different methods and studies due to the different hazards included and different purposes of the method or study. As an example, the frequency classification of the Swiss approach regarding mountain hazards is very different [5] from the study by Thierry et al. [9] regarding hazards related to volcanic activity.

Qualitative classification (such as that in Table 2) offers a rather simple way to compare hazards; however, they are in general developed for a specific application and are often also limited to a certain geographical area. Therefore, it becomes difficult to use such a method in another context or translate information to studies performed under other circumstances. In general, it will be very difficult to compare results between studies where the same hazards but with different classifications schemes, are applied. To use information from a study based on qualitative classification, careful examination of how the classification scheme is developed and applied, is needed.

The second technique for standardization described by Kappes et al. [5] is the use of indices. The index approach allows for quantifying hazard levels instead of only ranking them (as in the case with the qualitative classification). There are a range of different index methods available for single hazards, and inventories of such methods regarding wildfires [3] and flooding [4] have been conducted previously within the Extreme index project. As an example, wildfire indices are often based on weather data (some more comprehensive indices include information e.g., on topography and vegetation). If the weather is warm and dry, creating favourable conditions for a wildfire to ignite and spread, this should be represented in the calculated index value. However, even though a quantitative measure is established using an index, it can be become very difficult to compare or combine different hazards presented with different index methods given significant differences in scale. This could potentially be avoided by normalising values calculated using different methods and combining the normalised values (Section 3.3).

3.2 Relationships between hazards

As presented in Section 3.1 single hazards can be compared and combined in different ways, to a multi-hazard assessment. The approaches and examples given in Section 3.1 assume that there is an independence between the different hazards, and they can be summed up to some overall hazard. However, there might be relationships between the hazards and new and different hazard patterns may emerge due to the combination of hazards that differ from the simple sum of all single hazards [5]. The disregard of such relationships between hazards can lead to miss-estimation of the multi-hazard. It is, therefore, important to investigate and account for any possible relationships between the single hazards in a study.

There is no uniform approach or terminology applied when it comes to relationships between hazards. Terms like cascading effects, coinciding hazards and domino effects are used to describe the situation when one hazard is triggered by another [13], e.g., Forte et al [14] assessed possible multiple cascading effects caused by volcanic eruptions, like ash fall out and landslides. There are other terms that are far less precise such as compound hazards, multiple hazards, interactions, and synergistic effects [5]. As an example, Hewitt and Burton [15] differentiate between compound and multiple hazards. They describe compound hazards as several processes acting together like wind, hail, and lightning damage in a severe storm. Multiple hazards, on the other hand, are described as when processes of quite different kinds accidentally coincide or follow one another, like when a hurricane is followed by landslides or floods.

Kappes et al. [5] state that the level of understanding of relationships between hazards is very limited, and this hampers multi-hazard risk research that explicitly tackles such interactions. There are, however, essentially two methods to assess related hazards according to Delmonaco et al. [16]. The first is to investigate the individual possible chains of hazardous events and try to assess probability values; while in the second method, the risk for coincidence of different hazards is merely assessed, without necessarily assuming any direct linkage between them. The first approach requires a lot of data and can be very complex, while the second is less data demanding and easier to grasp. Event trees can possibly be used to present the chain of events and probabilities in the first method; but, the method is rarely applied due to its rigor [5]. In the second method, which is more frequently applied, a matrix can be applied to identify relationships between hazards or describe the level of interaction using scores. An example of the latter has been applied by the Department of Homeland Security [17].

Besides the general methods for related hazards according to Delmonaco et al. [16], there have been approaches developed for specific hazard relationships, such as the GIS method developed by Carrasco et al. [18] for floods and landslides. Another area regarding specific hazard relations mentioned by Kappes et al. [5] is landslides triggered by earthquakes. In such methods, the focus is on the stability of slopes and the magnitude of earthquake that will trigger a landslide.

Regarding forest fires, it has been seen that the possibility for floods increase in a burnt area. Cannon and de Graff [21] investigated return intervals and rainfall threshold intensities for the initiation of floods after forest fires. They identified that the threshold of rainfall intensities for a burnt area was lower than in an unburned area.

Kappes et al. [5] state that relationships between hazards are complex. There are different methods to overcome this, e.g., classifications and schemes; but they have been developed for a specific purpose and cannot be generalized. Kappes et al. quote Menoni [22] concerning the fact that it is hard to find common units of measure regarding multi-hazards since they are in general connected to a specific context. However, Kappes et al. [5] state that a possible solution could be to use a multi-hazard risk approach (i.e. probability of a certain consequence in numbers), instead of multi-hazard. The probabilities of different consequence can be based on historical data. The major advantage of comparing risks rather than hazards is that risks from different hazards are directly comparable since the possible consequences in numbers or probabilities of a specific outcome has been described or quantified as part of the risk assessment. However, as Marzocchi et al. [23] mention the spatial (area under investigation and the required level of detail) and temporal scale (time window) also need to be defined before analyzing multi-hazard risk. The type of approach to represent the multi-hazards can; however, affect the results. Liu et al. [19] saw, in a case study in China, that there were clear inconsistencies in the results when and index approach and a risk-based approach were compared. Therefore, risk assessors must understand the relative merits of the used approach and be able to communicate the results [19].

There are of course alternative methods. As an example, Youngeun and Chang-Sug [20] used 73 existing risk indicators and a text analysis of 3098 newspaper articles published over 24 years to identify indicators that are likely to occur at the same time with other risk indicators.

3.3 Methods to combine single hazards into multi-hazard

To be able to combine different hazards it is important to have similar units of measure. In the case of the work by Thierry et al. [9], qualitative classification is used, and the highest hazard level of overlapping hazards is adopted. However, a different approach was adopted in the work by Chiesa et al. [10] since, for example the combination of low/none and high hazard results in moderate level, and low/no hazard combined with extremely high results in high overall hazard (see Table 2).

In the Global Risk Analysis initiate by the World Bank, indices for six different natural hazards (earthquakes, volcanoes, landslides, floods, drought, and cyclones) are combined to identify hotspots [11]. In this method single-hazard analyses are conducted by reviewing historic data and using modelling. Results for the single hazards are calculate for grid cells rather than for countries, which makes it possible to present levels at subnational scales. The single-hazard indices are translated into hazard classes (low, medium, and high), and in grid cells where hazards labelled as high overlapping, the hazards are added together. The result of the analysis is then the number of hazards, labelled as high, that affects each grid cell.

Another example that Kappes et al. [5] mention is a study conducted in the Eastern Mediterranean (21 countries) [12]. El Morjani et al. [12] model intensity levels of five natural hazards (floods, heat, wind, landslides, and seismic activities) separately, and classify them into five classes according to separately defined thresholds. As an example, a classification scheme according to the US National Weather Service (see Table 3) was used to classify heat hazard.

Table 3 - Correspondence between the intensity level of heat hazard and the US National Weather Service classification used by El Morjani et al. [12].

Intensity level	Heat index	Dangers	Category
Very High	54°C or higher	Heat stroke or sunstroke imminent	Extreme danger
High	41-54°C	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.	Danger
Medium	32-41°C	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity	Extreme caution
Low	27-32°C	Exercise more fatiguing than usual	Caution
Very low	Not in the original classification scheme by the US National Weather Service		

The different natural hazards are then summed up after being weighted according to normalized weights (see Table 4) that are based on historic data about the different hazards impact on people and economics. The multi-hazard is then expressed as in six different intensity levels (from “very low” to “very high”). Since all individual hazards are calculated/modelled with a resolution of 1 km^2 a final multi-hazard map with this resolution can be presented.

Table 4 - Normalized weights applied to the different hazards when calculating the multi-hazard, from [12].

Hazard	Normalized weight
Seismic	0.41
Flood	0.36
Wind	0.09
Heat	0.08
Landslide	0.06

Liu et al [24] also used weights but, in this case, they were only based on the average human life loss associated with each one of nine studied natural hazards. In this way, a multi-hazard map over China was created, where color codes were used to indicate the risk level (from low to high).

Pagliacci and Russo [25] also normalize the different hazard prior to combining them. But instead of using certain weights, the difference between the max and mean value are applied in the method to get the normalized hazard indicator, x_i', see equation below.

$$x_i' = \frac{x_i - \min{(x_i)}}{\max(x_i) - \min{(x_i)}}$$

i is any of the three hazards (flood, landslide and seismic) Pagliacci and Russo [25] studied. The normalized data is then combined into a single index value by taking the average of their squares.

In some cases, however, there may be no clear maximum value (100%), which might preclude the calculation of normalised values, as done by Pagliacci and Russo [25]. To base the weight on historic data (see Table 4) may provide a better solution; but could on the other hand create additional problems if e.g., climate change results in a positive or negative risk trend over time, causing drift in the normalised values.

By expressing hazards in terms of risk (probability of a certain consequence in numbers or for example probabilities of loss of life), as mentioned in Section 3.2, the possibility to combine single hazards into a multi-hazards measure becomes more reasonable. The multi-hazard risk is then derived based on the sum of the single hazard risk. There can also be weights connected to the single hazards if some hazards are considered more important.

3.4 Examples of existing multi-hazard tools

Several initiatives to create methods for analyzing multiple hazards have been mentioned in the previous sections, and there are specific reviews, e.g. by Liu [19], that list different methods. Nonetheless, Kappes et al. [5] state that there are three major platforms for the automated computation of multi-hazard risks on a national level. These are Hazus, RiskScape, and CAPRA. However, the platforms are all very different with regard to methodology.

Hazus [26] is a nationally standardized risk modeling methodology developed by U.S. Federal Emergency Management Agency (FEMA). It is a GIS-based software that allows for identification of areas with high risk of natural hazards. The software estimates physical, economic, and social impacts of earthquakes, hurricanes, floods, and tsunamis and holds a collection of inventory databases for every U.S. state and territory. Different stakeholders use Hazus for different reasons. Mitigation planners, and emergency managers use Hazus to determine potential losses from disasters and to identify effective mitigation. Response planners use the software to identify potential impacts from hazardous events and to develop effective response and preparedness tactics. Hazus can also be used during an on-going incident. A recent postdoc project, funded by MSB, investigated the potential for modifying parts of Hazus for Swedish conditions [27] concluded that while the potential for a Swedish implementation exists of the methodology there are significant challenges in terms of data needs and broad involvement of relevant stakeholders.

RiskScape [28] is a software developed in New Zeeland that can be used to help users with decisions about planning and mitigation regarding hazards. RiskScape is based on a generic technology for complex risk modelling for different natural hazards and elements of risk. The model is general and is able to accommodate any hazard, asset or fragility model. Different geospatial functions are applied and RiskScape can be used as an add on to standard GIS packages. RiskScape 2.0 is under development and it said to provide an enhanced system for scenario and probabilistic risk analysis.

CAPRA (Comprehensive Approach to Probabilistic Risk Assessment) [29] is an open-source software. The initial goal with the CAPRA project was to improve the understanding of disaster risk due to natural hazard events (like earthquakes, tsunami, hurricanes and floods) in order to generate incentives to develop planning and mitigating measures. CAPRA includes different software modules for different types of hazards, a standard format for exposure, a vulnerability module, and an GIS-system for mapping. Historic and stochastic approaches are employed to simulate hazard intensities and frequencies across a country or region. The hazard information can be combined with the data on exposure and vulnerability. The results are expressed in different risk metrics. CAPRA has been applied in Central and South America, Africa, Europe, and Asia.

In addition to these three comprehensive platforms there are a range of other methods and projects presented in the literature. One example is the the ARMONIA (Applied Multi Risk Mapping of Natural Hazards for Impact Assessment) [8][30] whose overall aim was to provide the EU with a collection of harmonized methodologies for producing integrated risk maps to achieve effective spatial planning procedures in areas prone to natural disasters in Europe. ARMONIA is a multi-risk assessment tool used to provide a composite visualization of different risks in an area. The project aimed at a general methodology to be implemented at the local scale; however, it is uncertain if any such application is in place.

4 Summary of findings and conclusion

This report gives an overview of different principles for standardising hazards and methods to combine single hazards. Different examples of existing multi-hazard tools are also studied. No specific method or tool that can be applied directly for relevant hazards in Sweden has been found. Nonetheless, several general principles and methods that are considered valuable for the Extreme Index project have been identified.

Based on this review, it is clear that it is necessary to transform different hazards into the same unit of measure to be able to compare them. This can be done using some qualitative nomenclature (as presented in e.g., Table 1) or by normalising the hazard values. However, there may be no clear maximum value (which could preclude the calculation of normalised values). Another option could be to calculate the risk of different hazards, which would result in them having the same unit of measure, making the different hazards directly comparable. However, it can be very difficult or even impossible to assign consequences and probabilities to these relatively rare events in a satisfactorily manner. A less sophisticated way of combining hazards could be to overlay the hazards on a map to illustrate areas where high index values coincide. This could be a method to initially combine existing hazard indices without transforming or normalizing them.

Even though hazard relationships have been studied in the reviewed literature, there is no standardized way to take synergetic effects into account. This needs to be done on a case-by-case basis, and connections between the hazards included in the project should be evaluated to be able to include any significant synergetic effects that might exist.

In most of the studies reviewed, maps are often used to illustrate the hazards or combination of hazards. This is a method that makes it easy to understand spatial distribution of the hazard as well as the hazard level. The latter is often illustrated with color codes.

It is not planned to account for the vulnerability of the society in the tool developed in this project. However, the multi-hazard index tool should be developed in a way that it can be applied with information on the vulnerability in a specific case (e.g., municipality or region) to evaluate the risk and resource needs in specific case studies. In this way the tool can be applied in different local settings without needing to be modified for each analysis.

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