Swedish Civil
Contingencies
Agency

RESEARCH/STUDY

Extreme-Index

A vulnerability index for multiple natural hazards

Natural hazards

In this report, natural hazards are defined as incidents which occur in the natural environment which have the potential to impart negative consequences for life, property and the environment.

Extreme-Index: A vulnerability index for multiple natural hazards

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Summary: Extreme-Index is a research project that has developed a practical index method to predict community vulnerability to multiple natural hazards, occurring in a restricted geographical area or at approximately the same time. The developed method has been applied to wildfires and flooding, with a proof-of-concept approach for their combination. This report provides a high-level overview of the work with references to the main reports and publications produced within the project.

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Preface

The Extreme-Index research project has been funded by the Swedish Civil Contingencies Agency (MSB) as part of a joint call together with a Swedish Research Council for Sustainable Development (FORMAS). The project has been run as a collaboration between Lund University, the Swedish Meteorological Institute (SMHI) and the National Research Council of Canada (NRC).

A Reference Group has been connected to the project, whose valuable input to the project is gratefully acknowledged:

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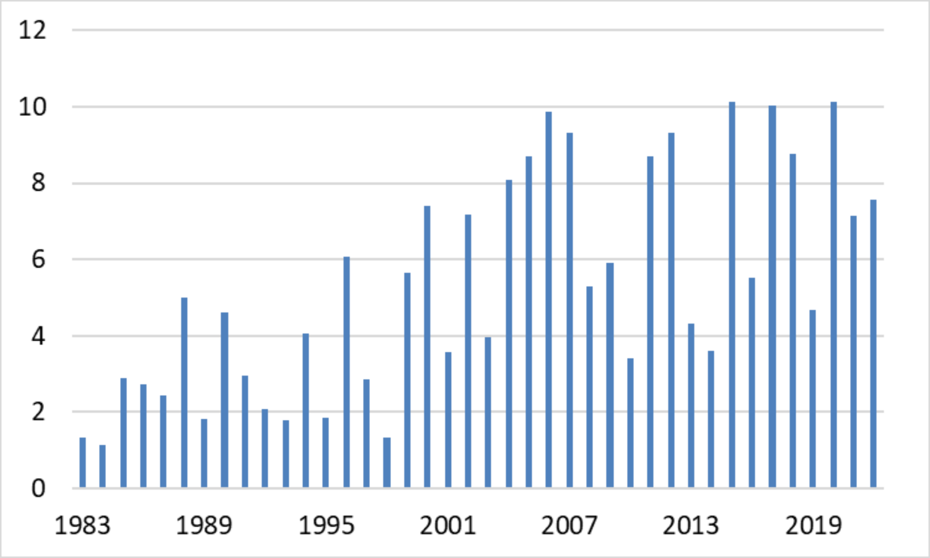
Introduction

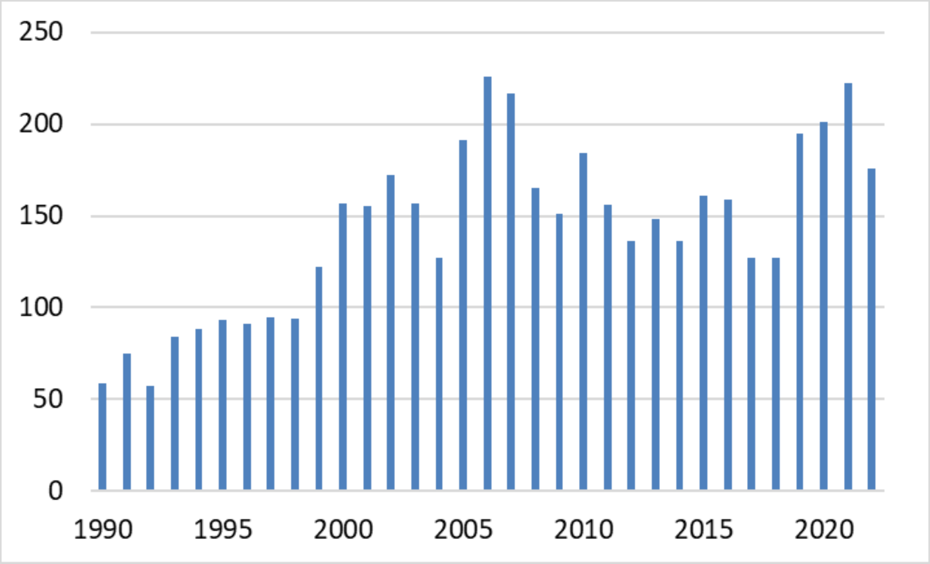
The world is facing significant challenges in terms of access to resources, increasing and diversifying population, and extreme weather events. In most developed countries, the cost of fire is estimated to at least 1% of the Gross Domestic Product (GDP) [1]. Indeed, the global impact from wildland fire is, while presently varied in number, steadily increasing in terms of area burned, see e.g. Figure 1 [2, 3]; and the number of injuries due to wildfires was at its all-time high in 2023 [4]. Similarly, the number of floods in recent years has escalated, see Figure 2 [5].

Figure 1: Area burned in wildfires in the US 1982–2022 in millions of acres



Source 1: Statistica [3].

Figure 2: Global number of floods between 1990–2022



Source 2: Statistica [5].

In their most recent Assessment Report [6], the IPCC has stated that "widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred" and that "[h]uman-caused climate change is already affecting many weather and climate extremes in every region across the globe." This is also true in Sweden and is expected to result in new patterns of wildfires and flooding in the future. There is a clear need for the FRS to have tools to support training and prediction of future resource needs in light of climate change. The Extreme-Index project was created in an effort to address this need.

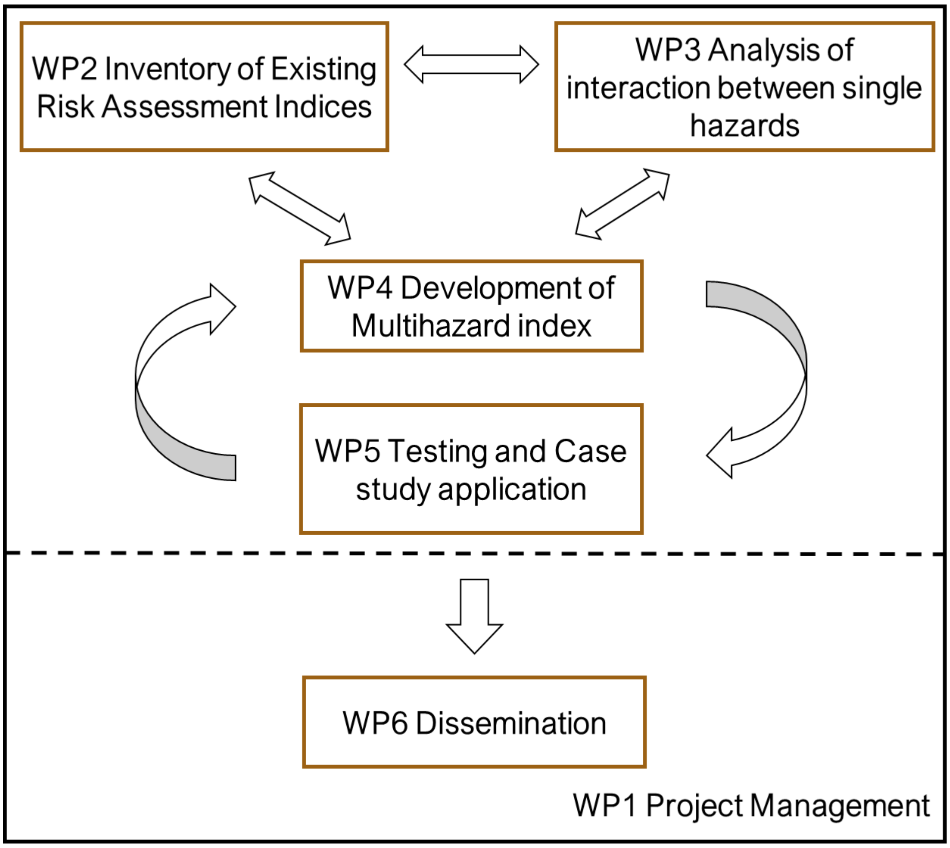
Project aims and objectives

The project aims to improve Fire and Rescue Service (FRS) preparedness for climate change with a focus on the effect of increased extreme weather on weather dependent natural hazards, by increasing our understanding of when and where multiple natural hazards manifest in Sweden, with a focus on wildfires and flooding.

Methodology

The Extreme-Index project was based on four main work packages (WP2-5) plus project management (WP1) and dissemination (WP6), see Figure 3.

Figure 3: Schematic of the Extreme-Index project



Source 3: Extreme-Index research application.

Work package 1: Project management, focused on reporting, management of the reference group and organization of project meetings.

Work package 2: Inventory of existing risk assessment indices, focused on the development of an inventory of the indices, tools and methods available today to collect information about risks in different domains, and relevant data resources to quantify that risk [7–9].

Work package 3: Analysis of interaction between single hazards, focused on improving the processes leading to compound hazards based on four cases: Case A – forest fire and spring flooding, Case B – multiple flooding events, Case C – drought/heat wave and forest fire, and Case D – storms and coastal flooding [10–12].

Work package 4: Development of multi-hazard index, focused on the development of a modular index method for investigating the risk of wildfires (forest and grass fires) and flooding, both individually and together [13].

Work package 5: Testing and case study application, focused on the investigation of experience from examples of wildfires and flooding and multiple hazards; and on collecting information from stakeholders on planning practices in relation to natural hazards.

Work package 6: Dissemination, focused on communication of project results including regular publication of newsletters, organization of seminars and development of reports and papers.

Canadian National Guide for WUI Fires

One of the partners within the Extreme-Index project has been the National Research Council of Canada (NRC). Their participation has provided invaluable exchange of ongoing research by NRC. An overview of the Canadian research input to this project is summarized below. Although the challenges faced by Canada are specific to its location, lessons can be drawn internationally – especially from attempts to develop national guidance to enhance resilience and mitigate consequences of wildland urban interface (WUI) fires.

Wildland-Urban Interface Fires and their Impact

When wildfires spread into the wildland-urban interface (WUI), an area where houses and other human developments meet or are mixed with wildland vegetation, the consequences can be extreme. In the last decade, WUI fires in Canada and around the world have devasted communities. In Canada, for example, WUI fires have resulted in loss of life, injuries, displacement of thousands of residents, and loss of thousands of structures and billions of dollars. Additionally, in 2023, wildfires have burned more than 18M of hectares of forests. It is expected that these threats will have consequences. The threat posed by WUI fires is growing and their risks are expected to increase in the coming years, as urban areas expand into wildlands, rural areas increase in population, and wildfires become more frequent and severe due to climate change [14].

Building wildfire resilience

In 2016, the National Research Council of Canada (NRC) and Infrastructure Canada launched a five-year Climate-Resilient Buildings and Core Public Infrastructure (CRBCPI) [15] initiative to integrate the consideration of climate resilience into building and infrastructure design, guides and codes. Given the increasing threat of WUI fires in Canada, improving the wildfire resilience of buildings and communities has been one of the initiative's primary goals. At the outset, an examination of current practices and existing Canadian and international reference documents was conducted which revealed a lack of national wildfire guidance for Canada's WUI areas.

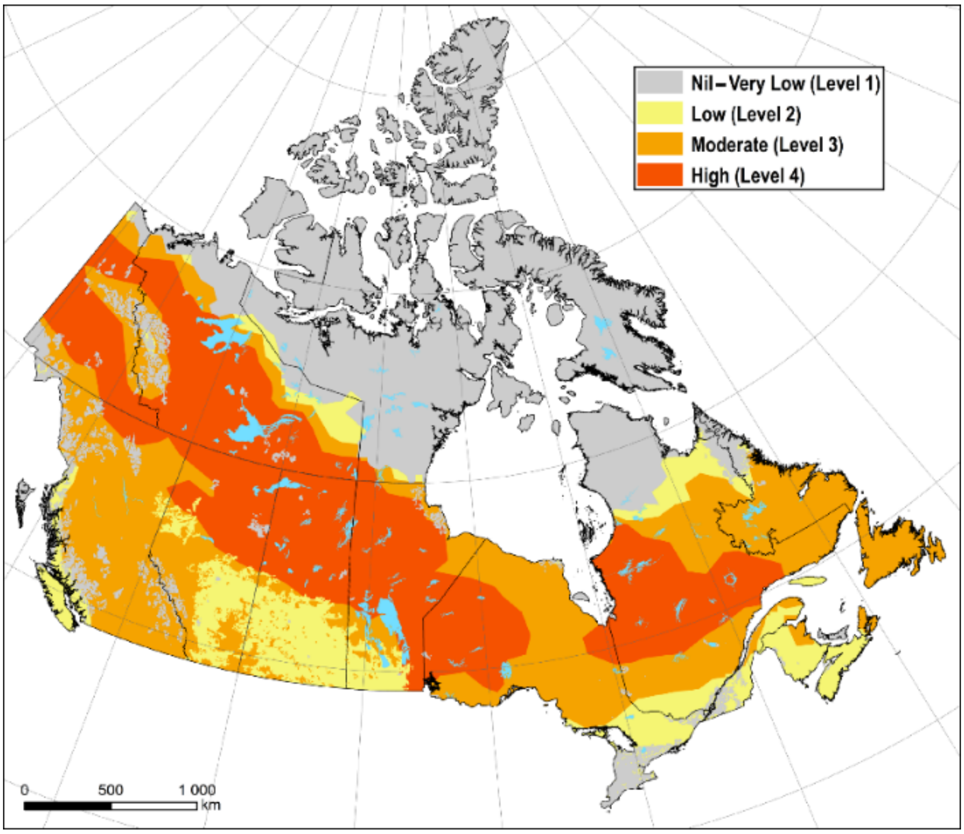
The National Guide for Wildland-Urban Interface Fires [16], the first of its kind for Canada, was published with guidance concerning hazard and exposure assessment in 2022. Drawing on recent wildfire research, existing codes, standards and guidelines, and new insights from international experts, the Guide provides comprehensive support for WUI areas across Canada, including recommendations on: hazard and exposure assessment; vegetation management and construction measures; community planning and resources; and, emergency planning and outreach.

Hazard and exposure assessment

The first step in applying the Guide is to carry out a hazard and exposure assessment, which allows users to identify the recommendations that will be most beneficial.

In the Guide's assessment method, the hazard level of a location is determined from a hazard map (see Figure 4), provided by the Canadian Forest Service of Natural Resources Canada. The hazard level, which ranges from Nil–Very Low (Level 1) to High (Level 4), takes into account regional topography, potential fuel and weather conditions, wildfire ignitions, and the possibility of extreme fire behaviour. The Guide's recommendations are intended for locations with a hazard level greater than Level 1.

Figure 4: Historical wildfire hazard mapped from spatial burn probability outputs based on wildfire growth simulations driven by historical weather and wildfire locations



Source 4: NRC National Guide for Wildland-Urban Interface Fires [16].

To identify recommended building-scale measures, the local exposure level also needs to be determined. The exposure level is used to determine which of the vegetation management and construction measures outlined in the Guide are recommended for the WUI fire protection of a particular building. The Guide provides both simplified and detailed assessment methods. The simplified method considers local fuel conditions and the potential for ember transport, radiant heat or direct flame contact. The detailed method further considers local topographic conditions, fuel percent cover, and hazard level. The exposure level, which ranges from Nil to High, indicates the potential for exposure to ignition sources if a high-intensity fire occurs nearby. The Guide's building-scale measures are intended for buildings with an exposure level greater than Nil.

Vegetation management and construction measures

The vegetation management measures include recommendations for landscaping, fuel removal or reduction, firebreaks and setbacks. The construction measures include recommendations for exterior walls and cladding, roofs, foundation walls, supporting elements for raised or elevated buildings, doors and windows, and decks, balconies and porches. To determine which construction measures are recommended, the building is assigned a construction class (CC), ranging from CC1(FR) to CC3, on the basis of its exposure level and the extent to which vegetation management is applied up to 100 m from the building.

If vegetation management extends further from the building, the construction class will be higher and the recommended construction measures will be less stringent, e.g., without vegetation management, a building with a high exposure level would be assigned to construction class CC1(FR), and non-combustible external wall cladding would be recommended. With vegetation management extending 100 m from the building, the same building would be assigned to construction class CC3, and exterior wall cladding with limited ignition resistance would be recommended. This means that, in many cases, the construction costs associated with WUI fire protection measures can be reduced by managing the vegetation surrounding the building.

Community-scale guidance

In addition to building-scale measures, the Guide provides community-scale recommendations on community planning and resources, as well as on emergency planning and outreach.

To support community and resource planning in the WUI, the Guide sets out considerations and recommendations for demographic analysis, land use and development, access and egress routes, utilities, public transportation, and firefighting resources. The Guide also sets out considerations and recommendations for evacuation planning, emergency communications, public education, and outreach communications to support emergency planning and outreach in the WUI. This extensive guidance will enhance community protection from and resilience to WUI fires.

Impact of the Guide

On the whole, the measures recommended in the Guide will help to minimize the impact of WUI fires by reducing their likelihood and severity, inhibiting their spread, and improving the effectiveness of community response.

The implementation of the Guide's recommendations is expected to save lives, protect homes, businesses and communities, and reduce the long-term cost associated with human developments in the WUI. An impact analysis report prepared for the NRC by the Institute for Catastrophic Loss Reduction (ICLR) indicates that, by adopting the Guide across Canada, approximately $4 would be saved for every $1 spent on mitigation [17]. The potential cost savings are predicted to increase with climate change.

The Guide is a valuable resource for anyone wanting to improve the wildfire resilience of buildings or communities in the WUI, including local governments and authorities, planners, emergency managers, developers, insurers, and property owners. With this resource, the WUI areas of Canada will be better able to adapt to the increasing frequency and severity of wildfires in the changing climate.

When and where do hazards occur?

Unlike the situation in Canada, Sweden has historically been less affected by natural hazards. However, it does experience several kinds of hazards that cause economical losses as well as increased mortality, e.g. as in the case of the project focus on flooding and wildfires. Moreover, recent studies show that single natural hazards may be combined in different ways, leading to cascading or co-crowding effects and turn them into so-called "multiple" or "compound" hazards.

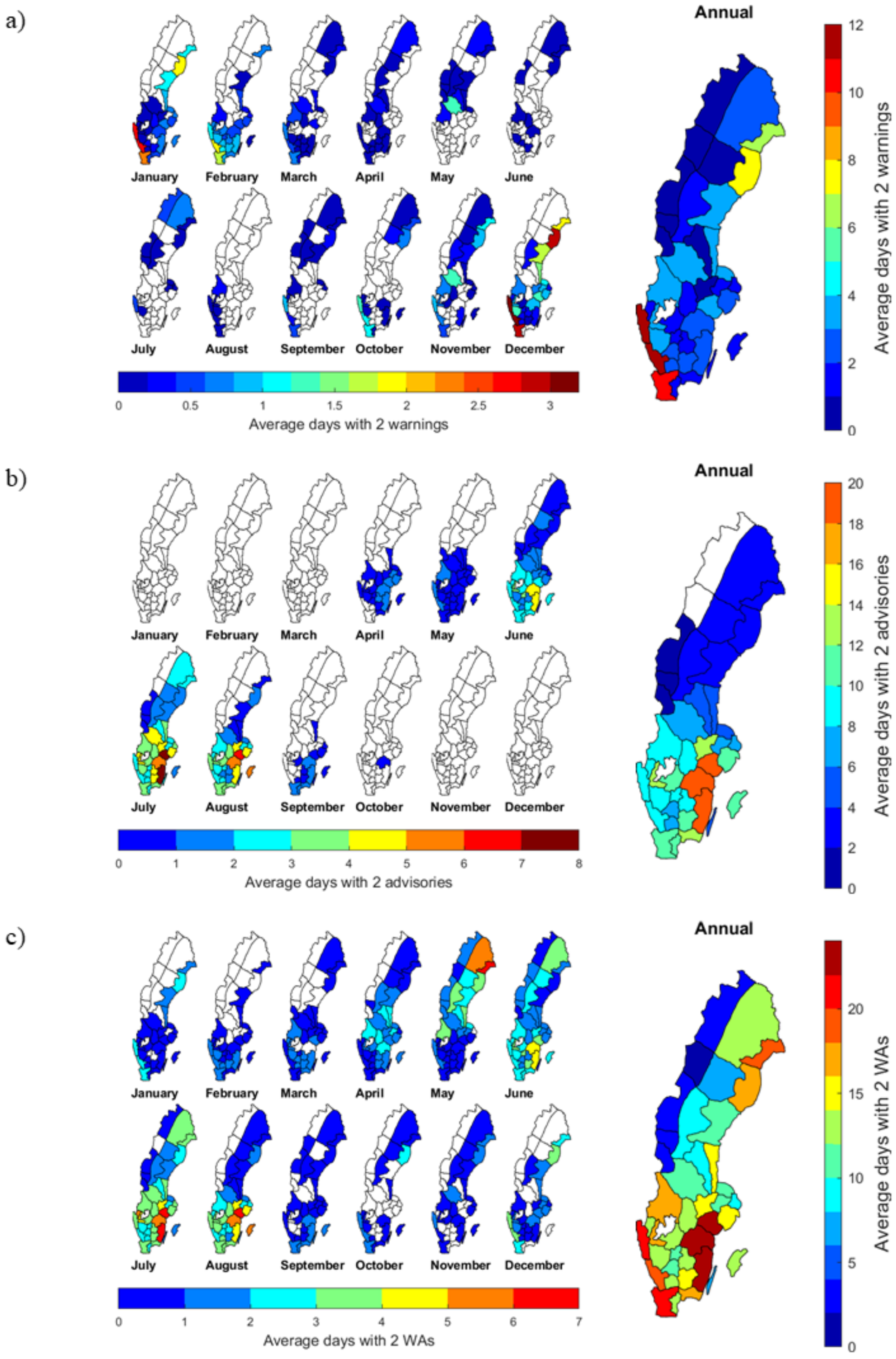
In this study we aim to view the natural hazards from multiple perspectives. We complied weather warnings and advisories (WA) issued by SMHI from 2011 to 2020 and conducted a comprehensive quality assurance. The studied WA have focused on the fields of meteorology, hydrology and oceanography. Four statistical metrics were designed and calculated as a basis to investigate the occurrences of single and multiple hazards in terms of their distribution in time (at daily level) and space (at warning district level). Combinations of up to four types of single hazards occurring on the same day and district have been explored, but we focused on two-type combinations (so-called double WA).

For single hazards, high river flow and heavy snowfall were found to be the most common warnings, in terms of the overall number of affected days and districts, followed by the warnings of strong wind gusts and high ocean level. Except for high temperatures, advisories were more frequently issued than warnings, with on average more than 1000 advisories issued per year (e.g. for risks of fire and water scarcity).

Analyses of hydrology-related multiple hazards (double WA) revealed that 1) districts along the west coast and the north-east coast were most affected, in particular during winter (December–February), 2) high river flow and strong wind gusts was the main warning combination including hydrology, ranked up high in all metrics, with most affected districts located along the west coast in southern Sweden, 3) high river flow warning combined with grassland fire advisory is the main hydrology-related combination of one warning and one advisory, and 4) water scarcity and forest fire stands out as the most frequent combination of two advisories.

In addition, the occurrence of simultaneous occurrences of increased risk for drought have been examined as a predictor of wildfire hazard [10].

Figure 5: The spatial distribution of the monthly (left) and the annual (right) average number of days with different types of double warnings and advisories in the period 2011–2020: (a) two warnings, (b) two advisories, and (c) one warning and one advisory. Note the different scales on the different bars



Source 5: Yang et al. [11].

Assessing Hazard

Single hazards

An overview of wildfires and flooding as individual single hazards has been made and is summarized in two project reports [8, 9].

In the case of the review of wildfire indices, the review resulted in a proposal of four indices which are recommended for further use in the project, i.e.: Fire Weather Index (FWI), Fosberg Fire Weather Index (FFWI), Keetch-Byram Drought Index (KBDI) and the Nesterov Index. Further analysis of these indices resulting in a peer reviewed publication [12], which came to the conclusion that the FWI is an acceptable method for the assessment of wildfire hazard in Sweden.

In the case of the review of flooding indices, ten different methods were determined to be interesting for the project were identified, i.e.: Coastal Index, Daily Flood Index, EPIC and ERIC, Flash Flood Potential Index (FFPI), Flood hazard index, Flood index, Index combining SPI and TWI, Geomorphic Flood Index and mapping of flood risk in Europe. Each method was described including its required input variables, whether testing or validation of the method has been done and the method’s advantages and disadvantages. Since the applicability of the methods uncovered in the literature review were limited, it was determined that the flood risk method used in the project should be based on the methods used today by SMHI in Sweden supplemented by novel methods developed by Lund University within the project. The developmental work has resulted in one peer-reviewed publication [18].

Multiple hazards

Multi-hazard assessment, while important, remains challenging. The project collated and assessed various existing methods to evaluation multiple hazards. This work has been presented both in a report [7] and in a peer-reviewed paper [13]. One of the major challenges associated with performing multi-hazard analyses is that the hazard characteristics may be very different, e.g., in nature, intensity, frequency, effects and consequences. To make a comparison possible, the reference unit needs to be standardized in some way. Kappes et al. [19] identify two major techniques for such standardization, i.e. qualitative classification of hazards, and the use of indices. In this project, the focus has been on the use of indices although some qualitative methods have been explored.

The combination of fires and flooding may seem incongruous, but such combinations can potentially occur in Sweden during the spring melt when river flows are high and when last year's grass is dry. Examples (outside of the wildfire setting) of fire and flooding combinations include cascading events where storm flooding resulting in damage to power lines can result in fires, see Figure 6.

Figure 6: Aerial view of flood and fire damage caused by Hurricane Sandy at Breezy Point Neighbourhood in Queens NY

Source 6: US FEMA, Andrea Bocher.

Even when hazard data is available, it can still be very difficult to compare or combine different hazards presented with different index methods given the prevalence of different scales in different disciplines. This can be avoided by normalizing values calculated using different methods and combining the normalized values, or by comparing calculated values against a historical benchmark to allow the prediction of a statistical difference; but even this has potential challenges when there is not an obvious maximum value to normalize against to bring all indices onto the same scale. Within the project, combining hazards has been explored through the case studies in WP3. Final recommendations for a single combinatorial method have not been possible to develop but work has begun as described in the ensuing chapters.

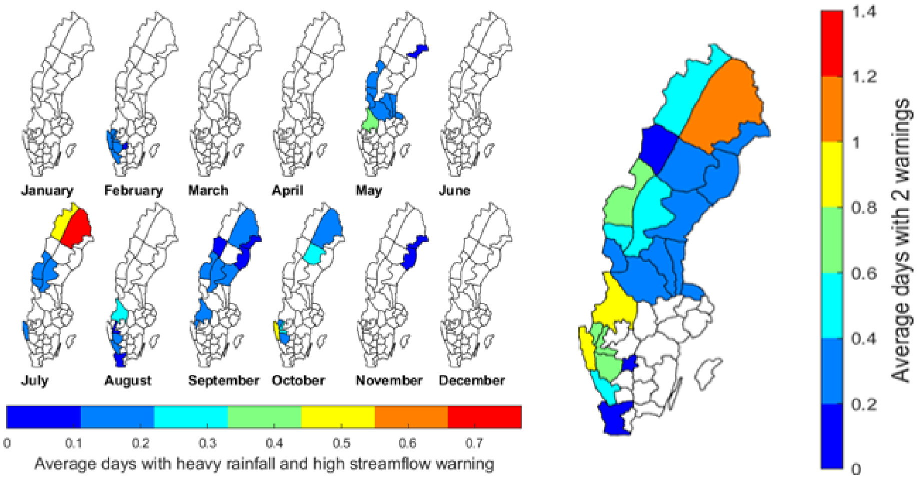
Methods to assess different types of flooding hazard

Pluvial and fluvial flooding

A combination of pluvial and fluvial flooding[1] is caused by different types of precipitation, where long-term accumulated river flow caused by an extended period of rainfall (or snow melt) leading to fluvial flooding, may coincide with pluvial flooding caused by short-term high-intensity rainfall, e.g., cloudburst. The precipitation events involved may occur simultaneously or successively.

Preliminary analysis (see Figure 7) shows the potential risk of this type of compound event has a limited frequency in a Swedish context (i.e., <2 days per year everywhere in Sweden, during the 10-year period). The most risk-prone period is from May to October but in different parts of the country. The districts with elevated risk are mainly located in Norrbotten county and in south-western Sweden. In Norrbotten July stands out as the end of the spring flood period and a period of high-intensity rainfalls. In the south-west, two areas stand out: (i) Västra Götalands län, Bohuslän and Göteborg, and (ii) Värmlands län.

Figure 7: Average number of days per year and per month during 2011–2020 with simultaneous warnings issued for heavy rainfall and high streamflow, respectively



Source 7: Yang et al. [11].

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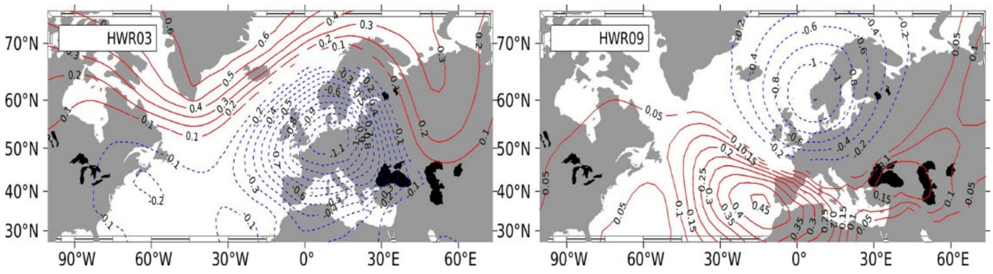
[1] Fluvial flooding occurs when the water level in a river/lake/stream overflows onto adjacent land. Ppluvial flooding occurs when extreme rainfall creates flooding independent of overflowing rivers/lakes/streams – involving either surface water floods (e.g. overwhelmed drainage) or flash floods (e.g. produced by torrential rain).

A real pluvial-fluvial event in Ljungby municipality, southern Sweden, took place in July 2004 and has been used as a case study in the project. Flooding as well as infrastructural damage was reported following extremely high stream flow. To improve our understanding of the physical mechanism and identify influencing factors, a hydrological model, S-HYPE, was employed to simulate streamflow at hourly/daily timesteps, and large-scale atmospheric circulation patterns were studied to explore the physical mechanisms and influencing area.

A set of 12 hydrological weather regimes (HWR) were classified and optimized using anomalies of daily mean pressure fields from ERA-Interim as predictors and daily precipitation at 40 precipitation stations distributed in Sweden as predictand. By Chi-squared testing, HWRs of Type 3 and Type 9 (see Figure 8) were proven significantly linked to heavy rainfall at risk levels of 20/10/5 events per year in Ljungby area. Their occurrences are considered a good indicator to detect extreme rainfall from a meteorological point of view.

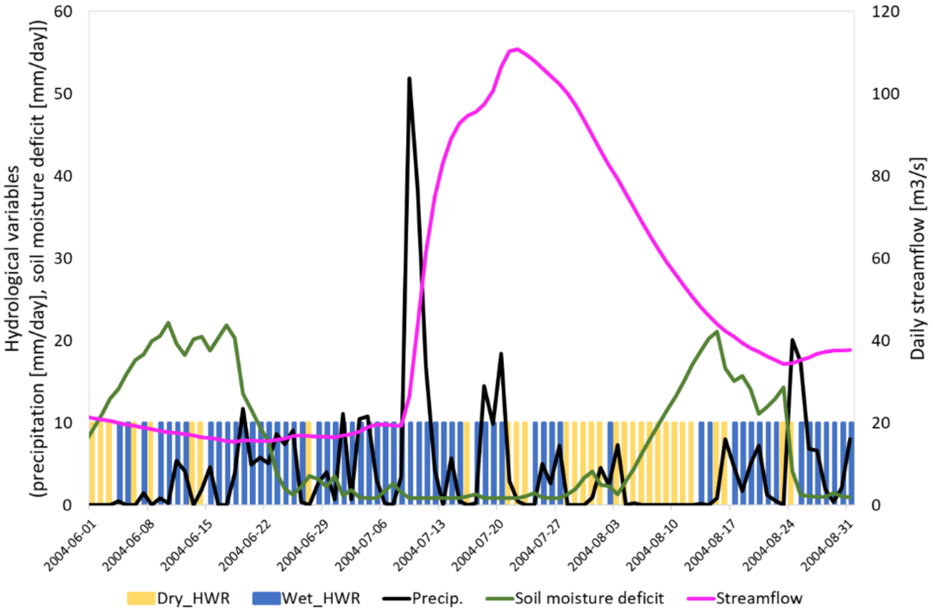
Figure 8: Composite maps of hydrological weather regimes (HWR) type 3 (left) and type 9 (right)



Source 8: NA.

In addition, the hydrological variable soil moisture deficit was shown to play an important role in the event. It describes how much of the field capacity is available to hold water. Continuous rainfall in June largely reduced the capacity to be close to zero by the end of month. Around the same time, a 3-day heavy rainfall, caused by HWR03, brought ~100 mm precipitation, which together with fully saturated soil caused an abrupt increase in streamflow, to almost 10-year return period. A medium sized rainfall occurring one week later caused an extra jump in streamflow up to a 50-year event (see Figure 9). The case study has shown how a combination of meteorological circulation pattern analysis and hydrological modelling can be used to characterize and investigate compound extreme events. The approach is general and can be used to analyze also other combinations, e.g. heat waves leading to drought and water scarcity.

Figure 9: Hydrological variables and hydrological weather regimes (HWR) during flooding period in Ljungby, 2004



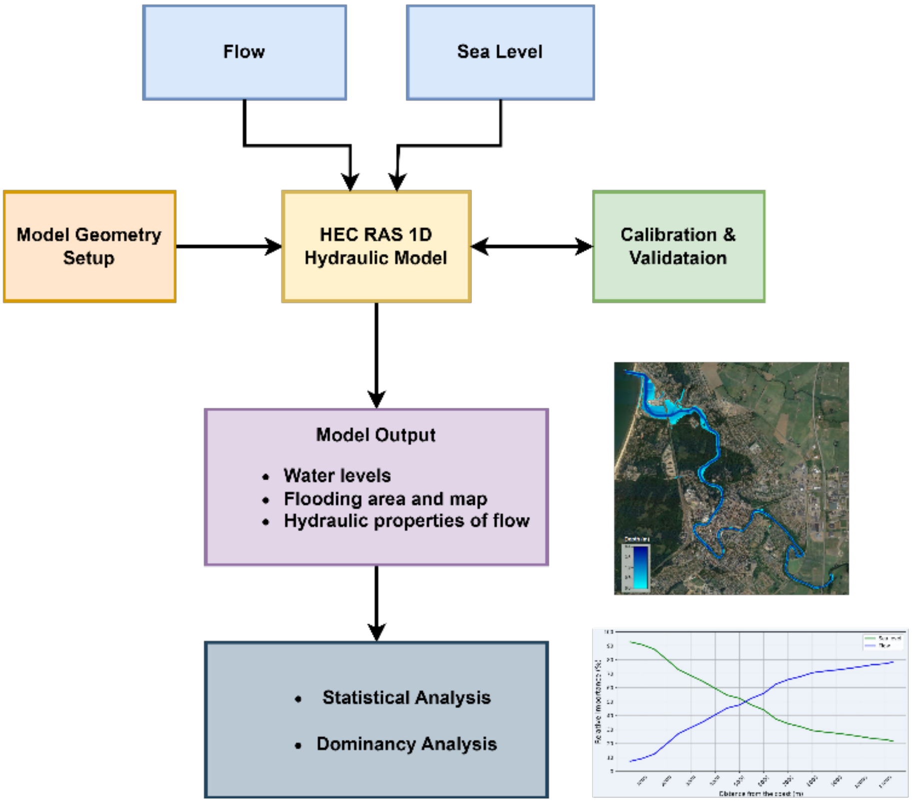
Source 9: NA.

Compound effects of sea level and flow on fluvial flooding in coastal areas

Floods are natural hazards that have been studied by scientists and engineers for centuries because of their impact on human development and activities. Most floods result from several drivers interacting that are random in nature but possibly correlated. One such example is river-induced flooding in coastal areas, which is determined both by sea level and river runoff. These two drivers could display coherent behavior since they may be generated by the same meteorological event. The variation in sea level is a function of tide, storm surge, local winds, and long-term sea level rise, which in turn exhibit the influence of a multitude of drivers. The importance of different drivers, their inter-relationships, and subsequent influence on flood characteristics are a challenge to determine and quantify, especially regarding the statistical properties of the floods.

The main objective of the present study was to quantify the compound influence of sea level (SL) and flow (Q) on river-induced flooding in coastal areas. These primary drivers often exhibit coherent behavior to be considered when performing analysis in flood risk management. To describe and quantify the compound effects of SL and Q on flooding, a methodology was developed involving simulations with a hydraulic model employing long-term series of input data from which statistical properties of output quantities such as river water level and flooded areas can be established. The modelling approach and some typical results are described in Figure 10 with focus on Rönne å. The modeling approach was implemented at three different coastal river reaches in southern Sweden (i.e., Rönne å, Lagan, and Säveån) for which detailed data on sea level, river flow, and river bathymetry and adjacent topography were available. Model results were also employed in dominance analysis to quantify the relative influence of SL and Q on the river water level along the studied reaches. In addition, simplified, empirically based equations were derived to predict the river water level at any location based on SL and Q that may be used by stakeholders for forecasting or in risk assessment where many alternatives need to be considered.

Figure 10: Workflow chart for the modelling approach and some results for Rönne å

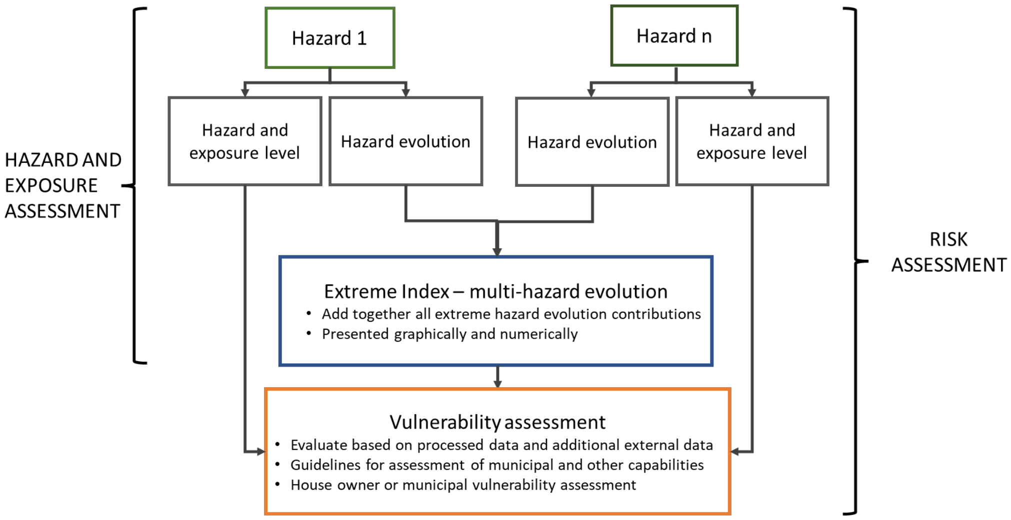


Source 10: NA.

Methodology for assessment of natural hazards

During the project, a modular framework has been developed generically to facilitate the inclusion of new hazards in the future, incorporating both wildfires and flooding as individual hazards, see Figure 11. The added value of this modular approach is that a specific FRS might have an interest in one but not both hazards included in the framework; or the hazards may be temporally or geographically distant implying that, even when interested in both hazards, their potential interaction is not of interest. The modular methodology allows the hazards to be investigated individually or together in a layered approach. The methodology includes a hazard and exposure assessment and a vulnerability assessment which together constitute the risk assessment framework. The risk assessment is conducted using a combination of probability for the manifestation of the hazard in question and the consequences of this manifestation. In this application, the hazard level (HL) contains information concerning the burn probability (>1 ha) while the consequences of the event are a function of the exposure level (EL) and the vulnerability assessment (VA).

Figure 11: Generic presentation of modular multi-hazard risk assessment framework



Source 11: McNamee et al. [13].

The hazard and exposure assessments are data driven and based on local geographic data defining hazard level (HL), exposure level (EL) and single/multiple hazard evolution (HE/MHE). Determination of the HL, EL and HE depends on the hazards of interest. The HE is then combined into an MHE, which is called the Extreme Index. When developing the Extreme Index, normalized hazard evolution values can be added together with a simple arithmetic sum or weighted sum depending on the relative importance of the hazards investigated in the specific geographic area of interest. Once the hazard and exposure has been assessed, the vulnerability assessment investigates the level of vulnerability (i.e. level of susceptibility to potential impacts and the capacity to cope with said impacts) of a community, specific building or infrastructure. How this is done will depend on the geographical region and the item of interest.

Hazard and exposure assessment

The hazard and exposure assessment for wildfires is based on a methodology developed by NRC in Canada [16]. This breaks the assessment into three steps: 1) Determination of need, 2) Hazard Level determination, 3) Exposure Level determination. Similarly, the methodology developed for flooding has used the same steps although the underlying analysis has been adjusted to suit flooding rather than wildfires.

Extreme-Index – a combination of hazards

Within the project, in order to calculate the *Extreme-Index*, a code was developed that could calculate and illustrate when in time the included hazards overlap. For wildfire, proof-of-concept was tested using three different individual hazard levels based on Sjöström and Granström [20], i.e.: 1) FWI=11, corresponding to the highest FWI-value with low risk of wildfire, 2) FWI=17, corresponding to the highest FWI-value with moderate risk of wildfire, and 3) FWI=22, corresponding to the highest FWI-value with high risk of wildfire. For flooding, the value of the three different individual hazard levels was based on three different percentiles calculated from the included statistics over the water flows in the considered water streams, i.e., the 80-, 90-, and 96-percentiles, which correspond to the 5-, 10-, and 25-years return flow.

The identified level of risk for each hazard is determined based on input of weather data for calculation of the FWI and flow for the calculation of the flooding risk. These can then be combined, arithmetically or geometrically, to determine the combined level of risk. More work is needed to test the methodology and determine the best approach.

Vulnerability assessment

The HL and EL assessments provide spatial information by identifying locations that are both exposed to a hazard and vulnerable to it, while the Extreme Index provides temporal (and to a certain extent geographic) information on the presence of multiple hazards. Together these components form input to facilitate a vulnerability assessment (VA) for structures in the geographical area of interest. The vulnerability assessment itself is outside the scope of the Extreme-Index project. Therefore, it has not been further developed, beyond identification of a place holder for this activity in the methodology.

Conclusions and future work

Extreme-Index is a research project that has aspired to develop a practical index method to predict community vulnerability to multiple natural hazards, occurring in a restricted geographical area or at approximately the same time. The reason to consider temporal and geographic proximity is that natural hazards tend to call on the same personnel, and to a degree physical, resources, i.e. the Fire and Rescue Service (FRS). The aim of the project was therefore, to create and index method that can assist the FRS predict changing resource needs (personnel, competencies and physical resources) in light of climate change.

The developed method consists of individual approaches to assess the vulnerability to single-hazards, in this application wildfires and flooding, and a proof-of-concept approach for their combination. The question of vulnerability mitigation has also been considered but the development of methods for vulnerability assessment has been outside of the scope of the work. This report provides a high-level overview of the work with references to the main reports and publications produced within the project. For more details the interested reader is referred to these documents.

The analysis of different weather warnings confirms that multiple hazards occur in different parts of Sweden in both geographical and temporal proximity at certain locations and times of year. While the present indication is that wildfires and flooding are often temporally spread, i.e. they are not both in the same place at the same time, there are indications that they can nonetheless occur in the same area with some temporal overlap in the north of Sweden during the late spring. As the method has presently only been applied to Ljungby where the hazard of both flooding and wildfires has little temporal overlap, this has not been confirmed in detail.

Further work is needed to apply the methodology in detail to additional municipalities to confirm its utility in areas both with and without overlapping hazards. In addition, further work is needed to apply the connect hazard and exposure analysis and vulnerability assessment in Sweden using a similar methodology to that developed in Canada. Finally, the *Extreme-Index*, which can be calculated by analysing the relative importance of each hazard has been proposed as a proof-of-concept and requires additional development to establish the method combinatorial practices.

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