THE DEVELOPMENT OF A VULNERABILITY ASSESSMENT METHOD FOR WILDFIRES

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Lund 2020

English Title
The development of a Vulnerability Assessment Method for wildfires

Swedish Title
Utveckling av en sårbarhetsanalysmetod för skogsbränder

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Report 5616
ISRN: LUTVDG/TVBB--5616--SE

Antal sidor/Number of pages: 89, including appendices
Illustrationer/Illustrations: 24

Sökord/Keywords
vulnerability assessment, wildfire, fire risk assessment, fire danger, rating system, fire, wildland urban interface

Abstract
Wildfires pose a serious threat to communities in different parts of the world, mostly in regions with a warmer climate. Due to the increased urbanization next to the forest and climate change, they are currently an issue to be addressed also in other parts of the world. The purpose of this thesis is to provide a first step in the direction of creating a holistic Vulnerability Assessment Method (VAM) regarding wildfires, applicable for Sweden. The aim of this thesis is to review existing wildfire risk assessment tools and look at the factors they consider and determine the most important ones to use in a VAM for the Swedish context. The method is developed with three different modes, namely 1) preventive, 2) operational and 3) evaluative. Each factor in the VAM has five rating levels, a correlation variable and a weight variable. A hypothetical application of the VAM is exemplified through a case study on a municipality in Sweden for the Preventive and Operational modes. The results from the case study show that individual factors can have a great impact on the outcome, and both the overall result and the individual factors should be carefully considered. An advantage of the proposed method is the flexibility in use given the different modes of applications. This makes the method useful for several actors.

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Summary

Wildfires pose a serious threat to communities around the world, so far mostly (but not exclusively) in regions with a warmer climate, such as Australia, southern Europe and North America. In Sweden, the summer of 2018 was warmer, dryer and windier than normal, leading to severe conditions regarding number of ignitions of wildfires. Wildfires were scattered over the whole country and the worst fires were situated in the middle of the country. With the large wildfire in Västmanland 2014 and the wildfires during the summer of 2018, a demand for a holistic methodology to assess vulnerability to wildfires increased in Sweden.

The purpose of this thesis was to provide a first step in the direction of developing a holistic Vulnerability Assessment Method (VAM) regarding wildfires, applicable for Sweden. The aim of this thesis was to review existing wildfire risk assessment tools (including those for wildland-urban interface fires) and look at the factors they consider and determine the most relevant ones to the Swedish context. The selected factors were then used as the basis when developing a VAM. The VAM resulted in an equation calculating the vulnerability and three modes were developed for different usages, with each mode including different factors. The modes are preventive, operational, and evaluative. The use of the VAM was exemplified through a hypothetical case study on a municipality in Sweden. The chosen case study area was Ljusdal municipality, this location was considered suitable because of its exposure to wildfires in 2018. Modifications had to be done before the method could be used, mainly due to inability to determine correlation between the factors and the inability to retrieve all the required data. While not all needed data could be retrieved, this example is deemed to provide a useful starting point for understanding the applicability of the VAM. Another simplification consisted in making the calculations on a number of communities within Ljusdal municipality rather than considering the whole municipality using a grid. The results from the case study show a percentage of vulnerability for each community in Ljusdal, with the preventive and operational mode as well as data from the summer of 2018 during the wildfires in the municipality.

The results from the case study showed, in general, a higher vulnerability in the largest communities. This is not surprising, as they include a larger population (thus potentially threatening a higher number of people), and higher number of assets and hazardous objects were situated where more people live in. Nevertheless, these results should be considered indicative rather than conclusive, as many assumptions employed in the calibration of the VAM inputs require a deeper analysis, and further sensitivity analyses are needed to improve the reliability of the VAM. The literature review of existing methods showed that a holistic approach does not exist today, thus such a method would be useful for many actors, including land use planners and rescue service personnel etc. Several suggestions for future method improvements and topics for future research are also presented.

Sammanfattning

Skogsbränder utgör ett allvarligt hot mot samhällen runt om i världen, hittills främst (men inte uteslutande) i regioner med ett varmare klimat som Australien, södra Europa och Nordamerika. I Sverige blev sommaren 2018 varmare, torrare och blåsigare än normalt, vilket ledde till svåra förhållanden kring skogsbränder som var spridda över hela landet. De värsta bränderna härjade i de mellersta delarna av Sverige, kring Gävleborg och Dalarna. Efter den stora branden i Västmanland 2014 samt alla bränder sommaren 2018 uppkom en efterfrågan för en metod som kan bedöma sårbarheten för skogsbränder i Sverige.

Syftet med detta examensarbete var att tillhandahålla ett första steg i riktning för att skapa en helhetlig sårbarhetsanalys för skogsbränder och även bränder i gränssnittet mellan vegetation och samhälle, tillämpad just för Sverige. En inventering av befintliga system i världen, tillsammans med en litteraturstudie, gjordes för att identifiera de viktigaste faktorerna som bör inkluderas och undersöka hur de kan användas i en sådan metod. Denna information användes sedan för att utveckla en sårbarhetsanalysmetod, som resulterade i en ekvation för att beräkna sårbarheten. Metoden konstruerades med tre primära lägen, förebyggande, operativ och utvärderande, för olika användningsområden. En fallstudie genomfördes för att visa hur den konstruerade metoden kan användas. Det område som valdes för fallstudien var Ljusdal kommun, denna plats ansågs lämplig på grund av de skogsbränder som härjade där 2018. Modifieringar behövdes göras innan metoden kunde användas, de främsta på grund av svårigheter att uppskatta korrelation mellan faktorer och begränsad möjlighet att ta fram data. En annan svårighet var att göra beräkningarna för ett komplett rutnätsystem och istället användes ett antal samhällen inom Ljusdal kommun för att tillämpa metoden och inte hela kommunen. Resultaten från fallstudien visar en procentuell sårbarhet för varje område i Ljusdal, med det förebyggande och operativa läget samt data från sommaren 2018 då bränderna härjade i kommunen.

Resultaten från fallstudien visade i allmänhet en högre sårbarhet i de största samhällena i Ljusdal. Detta berodde troligen på den större befolkningen och det högre antalet egendomar, samt riskfyllda objekt, så som bensinstationer, där fler människor befinner sig. Trots detta bör resultaten ses som vägledande snarare än avgörande, eftersom många antaganden behövdes göras vid appliceringen av metoden. Mer arbete och fler känslighetsanalyser behövs för att förbättra tillförlitligheten. Litteraturstudien av befintliga modeller visade att någon helhetlig metod inte finns i dag och att en sådan metod kan vara användbar för flera aktörer, till exempel samhällsplanerare och räddningstjänsten. Ett antal förslag på forskningsområden och förbättringspotentialer för metoden presenterades slutligen.

Acknowledgements

The authors would like to express their gratitude and thanks to Enrico Ronchi at the Department of Fire Safety Engineering at Lund University for his patience, guidance and support during the process of this thesis project.

Terminology

Brush fire - Brush fire is a term used for fires in vegetation dominated by bushes, scrubs and brushes, primarily in the United States (US) (USDA Forest Service, 2019).

Bush fire - Bush fire is a term for vegetation fires that is used in Australia. It can be divided into grass fires and forest fires depending on the fuel burning, but the commonly used term is bush fire. (United Nations Office for Disaster Risk Reduction, 2020)

Forest fire - Forest fire is the common term for unwanted fires in forests and wildland used in Europe (Paton et al., 2015).

Hazard - Hazard is defined as "*A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation*" according to the United Nations Office for Disaster Risk Reduction (UNDRR) (United Nations Office for Disaster Risk Reduction, 2017a).

Holistic – According to Cambridge dictionary, holistic means "dealing with or treating the whole of something or someone and not just a part" (Cambridge, 2020). In this thesis, holistic refers to an approach that looks at vulnerability that includes factors from multiple categories like topography, climate, fire characteristics and community. Focus is not only on fire behaviour but also on the people, evacuation possibilities and mitigation resources.

Hälsingland farms - Hälsingland farms are a number of 36 farms in Hälsingland, Sweden, that are well preserved from the 19th century. They are considered a valuable world heritage and protected by United Nations Educational Scientific and Cultural Organization (UNESCO). (Gävleborgs län, 2020)

Lane reversal – Lane reversal can be defined as "The reversal of lanes in order to temporarily increase the capacity of congested roads - can effectively mitigate traffic congestion during rush hour and emergency evacuation." (M. Hausknecht et al., 2011). One or more lanes are reversed into the other direction in order to increase the available road capacity.

Occluded Wildland Urban Interface - Occluded Wildland Urban Interface (WUI) often occurs within cities where vegetation and wildland is surrounded by structures, for example parks and green open spaces (USDA Forest Service et al., 2001). The only numerous limitation for occluded WUI, is that it cannot exceed 400 ha (Mell et al., 2010).

RAKEL - RAKEL is a radio communication system used in Sweden by employees for actors within societally important services, for instance the police departments and rescue services. RAKEL stands for RAdioKommunikation för Effektiv Ledning which translates to radio communication for efficient management. (MSB, 2020c)

Risk - Risk is defined as a result of likelihood and severity of an incident combined, also depending on hazard and vulnerability (Fire Safety Advice Centre, 2011).

Vulnerability - Vulnerability is defined as "*The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards*" according to the UNDRR (United Nations Office for Disaster Risk Reduction, 2017b).

Wildfire - Common term for uncontrolled fires burning in wildland vegetation, can be used for all types of natural fuels and fire characteristics. Primarily used in the US but a well-known term in the whole world.

Wildland fire - Another word for wildfire which is mainly used in the US (USDA Forest Service, 2019).

Wildland Urban Interface - The definition of WUI is according to the US government, *"The line, area or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetative fuels"* (USDA Forest Service, 2019). To be specified as a WUI community there has to be 1 house per 16 ha, have less than 50 % vegetation, and are within 2,4 km of an area (made up of one or more contiguous Census blocks) over 500 ha that is more than 75 % vegetated (Mell et al., 2010).

Wildland Urban Intermix - In the wildland urban intermix structures are scattered within the wildland (USDA Forest Service et al., 2001). The numerical definition of the wildland urban intermix is that there has to be more than 1 house per 16 ha, have more than 50 % vegetation, and are within 2,4 km of an area (made up of one or more contiguous Census blocks) over 500 ha that is more than 75 % vegetated (Mell et al., 2010).

Acronyms

ASET - Available Safe Egress Time
CFFDRS - Canadian Forest Fire Danger Rating System
Co-WRAP - Colorado Wildfire Risk Assessment Portal
CWFIS - Canadian Wildland Fire Information System
FFDI - The Forest Fire Danger Index
FOFEM - First Order Fire Effects Model
FWI - Fire Weather Index
GIS – Geographical Information System
HVRA - High Value Resource and Asset
MSB - The Swedish Civil Contingencies Agency
NFDRS - National Fire Danger Rating System
No-HARM - National Hazard and Risk Model
RSET - Required Safe Egress Time
SMHI - Swedish Meteorological and Hydrological Institute
UNDRR - United Nations Office for Disaster Risk Reduction
UNESCO - United Nations Educational Scientific and Cultural Organization
US - United States
VAM - Vulnerability Assessment Method
VMA - "Important Message to the Public", Swedish national alert system
WRAF - A Wildfire Risk Assessment Framework
WUI - Wildland Urban Interface
WUI in B.C. - WUI wildfire threat assessment in B.C.

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1 Introduction

Wildfires are an issue around different parts of the world, so far mostly (but not exclusively) in regions with a warmer climate, such as Australia, Southern Europe and parts of the United States (Kottek et al., 2006). However, there are exceptions, Canada is one of those with massive wildfires occurring annually. Statistics shows that 3 % of the annual fires between 1959-1997 burned on average 2 million ha. (Stocks et al., 2002)

In this report, the term wildfire will be used to describe fires in all types of vegetation, as this is a renowned term globally. There are a number of terms globally which are used to describe these fires. In Australia, the term bushfire is mainly used, while in Sweden it is often described as forest fire. In the United States (US) the term wildfire or wildland fire is used but they also have terms that describe fires in a specific vegetation type. For definitions of these terms see the Terminology section.

According to the Swedish Meteorological and Hydrological Institute (SMHI), the summer of 2018 became warmer, dryer and windier than normal in most parts of Sweden, leading to severe conditions regarding ignition and spread rates of wildfires. The heat and drought were most severe in the southern parts of Sweden (SMHI, 2018), the wildfires were scattered over the whole country and the worst wildfires were situated in the middle parts of the country (Justitiedepartementet, 2019). The counties of Dalarna, Gävleborg and Jämtland were the most affected ones. Dalarna had the fire in Trängslet which burned a total of 2 500 ha. Gävleborg had the Enskogen, Nötberget and the Ängra fires burning more than 8 000 ha combined. Jämtland had a 3 500 ha fire in Lillåsen. (Eriksson et al., 2018) All of these fires were occurring at the same time. This matches well with previous research regarding wildfires in Sweden, which predicted a higher risk for wildfires in the future, mainly in the southern parts of the country (Tinghai Ou, 2017; Yang et al., 2015).

The year of 2018, most primarily the summer, displayed a peak, both in the number of wildfire incidents (see Figure 1. Diagram on number of incidents related to wildfires in Sweden 1998-2018) and area burned (see Figure 2. Diagram of area burned in wildfires in Sweden 1998-2018 measured in hectares). Before this year, the last peak that could be observed in number of incidents was in 2003. Also, only 2014 can compare to the area burned, exclusively due to the fire in Västmanland which burned over 13 000 ha (Skogsstyrelsen, 2019).

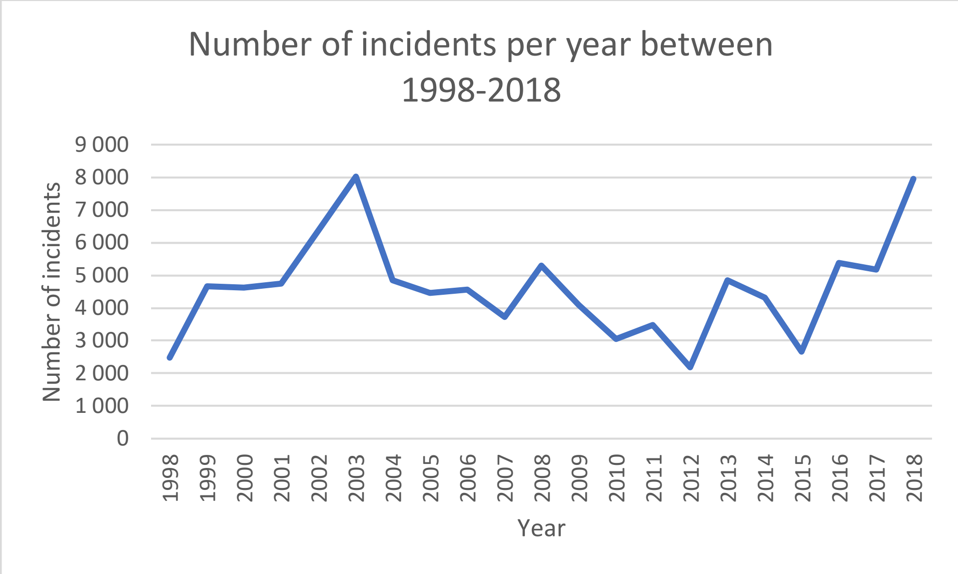

Figure 1. Diagram on number of incidents related to wildfires in Sweden 1998-2018 (MSB, 2020b)

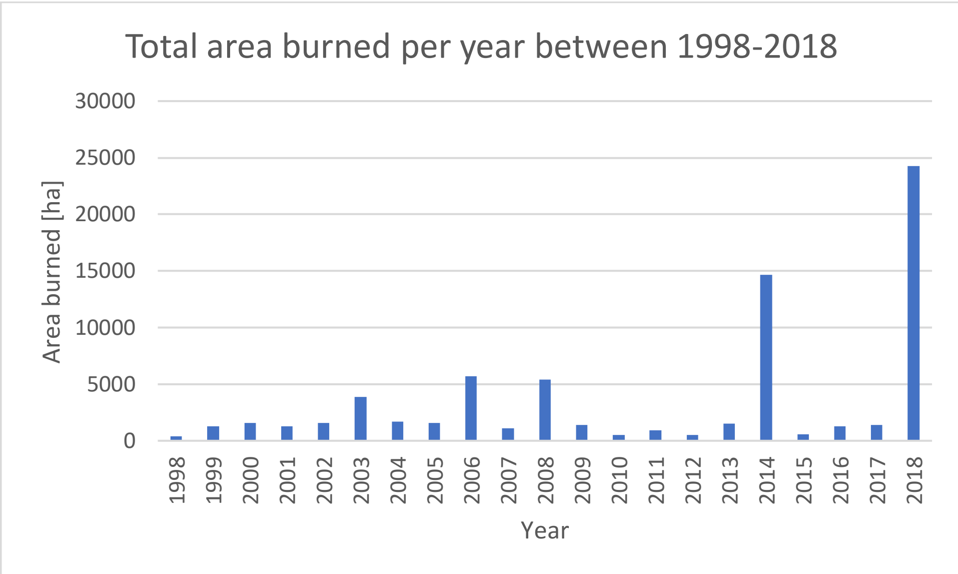

Figure 2. Diagram of area burned in wildfires in Sweden 1998-2018 measured in hectares (MSB, 2020b)

Several measures have been implemented to minimize the risk of wildfires in Sweden over the years. Sweden uses the Fire Weather Index (FWI) (Canada, 2020c) to perform forecasts of the fire risk all over the country with a resolution of 11 km×11 km. The forecasts are made during the whole fire season, April to October. (Yang et al., 2015) The FWI is based on four input parameters; relative humidity, temperature, precipitation and wind, calculated with codes resulting in an index translated to a fire risk index (1-5E), where 5E implies the highest risk (MSB, 2020a).

When the fire risk index is high, Sweden attempts to enter a higher state of readiness to be more prepared for eventual wildfires. This includes wildfire flights, patrolling and looking out for new wildfires, extra tank vehicles in vulnerable areas, etc. There can also be extended contact with the Swedish armed forces and helicopter agencies that are able to help in emergencies (MSB, 2019a). On a local level, municipalities are able to issue a fire/barbeque ban on different levels. Stores can decide to stop the sale of disposable grills since they have been seen to constitute a great fire risk historically (Brandskyddsföreningen, 2018).

While climate can play an important role when it comes to wildfires, there are other factors to keep in mind, such as urbanization closer to the forests. These are two factors that both have an impact on the hazards and vulnerabilities and thereby risk of wildfires (Ronchi et al., 2017). Fires in Wildland Urban Interface (WUI) areas tend to exhibit a different fire behaviour than urban fires. The main fire spread in WUI fires has been seen to occur through embers in the wind possibly leading to new ignitions (Thompson, 2011). This fire spread pattern and the amount of people that can be present within the area may lead to difficult evacuations (Ronchi et al., 2017).

Given the risk with fires in wildland and WUI areas, countries around the world have developed methodologies to map areas that are prone to wildfires. These methodologies consist of tools such as Geographic Information System (GIS) tools, risk assessment tools, etc. (Ronchi et al., 2017). Nevertheless, only few attempts to develop holistic methodologies are available worldwide and systems to be adopted in Sweden are object of debates (Sinclair, 2018). To date, there are tools that look at different aspects associated to wildfires and evacuation during WUI fires in isolation, like fire behaviour, pedestrian movement, and traffic movement. But there is no system today that considers all aspects in a holistic approach which could be beneficial in a decision-making process. (Ronchi et al., 2017)

The Swedish Civil Contingencies Agency (MSB) states that, "*A monitoring system as well as an assessing system, which could provide a potential fire size, is needed for rescue agency. The information can help to decide how much and what kind of efforts is needed to control the fires*." (Tinghai Ou, 2017). Enrico Ronchi, senior lecturer at the department of fire safety engineering at Lund university states that "*The debate is currently centred around the amount of resources, but it should rather focus on increasing the understanding regarding Sweden's vulnerability towards wildfires*." (Sinclair, 2018) With the large wildfire in Västmanland during 2014 (Skogsstyrelsen, 2019) and the wildfires during the summer of 2018 in Sweden, a demand for a holistic methodology to assess wildfire and WUI fire vulnerability has increased.

1.1 Purpose and aim

The purpose of this thesis is to provide a first step in the direction of creating a holistic Vulnerability Assessment Method (VAM) regarding wildland and WUI fires, applicable for Sweden. The VAM should be useful for various actors through different modes. Results from this thesis should inform future research on the topic and the development of a method to be implemented in Sweden.

The aim of this thesis is to review existing wildfire risk assessment tools and look at the factors they consider. An inventory of existing systems in the world, together with a literature review is performed to identify the most important factors to include in the method and how they can be used. Factors regarding fire behaviour as well as factors regarding evacuation are considered relevant for a holistic method. The selected factors are used to develop a VAM that will be applied through a case study, using data which the authors are able to retrieve. Beyond this, will an inventory be carried out to assess which modes are useful for this type of method. The developed version will be discussed and suggestions for future improvements provided.

1.2 Delimitations and limitations

The project was limited to focus on wildfires. The perspective was societal so there were little to no consideration of individual differences with regard to people and structures. A limited number of systems were identified and analysed, to keep the work within a reasonable size. Focus was on risk assessment tools that considered wildfires but also the WUI. In the case study, a simplified version of the VAM was used, mainly due to the authors inability to retrieve the required data. The case study was applied to one selected area of Sweden only. There was also a limitation in the assessment of the correlation between factors, due to the difficulty to determine these correlations in the given timeframe. A few factors were related to size or population but no correlation between factors was considered.

2 Method

Based on the purpose and aim of the work, a general literature review regarding wildfires and WUI was executed. Information that was desirable to retrieve consisted of, among other, why WUI areas are considered to be more vulnerable than the remaining urban area, what challenges exist with fires within the WUI, what trends can be observed regarding wildfires and WUI fires and what factors affect them. Keywords used to find information consisted of; Brushfire, Bushfire, Fire, Forest fire, Wildfire, Wildland fire, Wildland Urban Interface fire, Wildfire trends, Wildland Urban Interface, Wildland Urban Interface in Sweden, Swedish wildfires and Wildfire behaviour. This was made to enable the authors to gain background knowledge on the topic.

A second literature review was executed to locate risk-, vulnerability assessment methods as well as danger rating tools regarding fires in wildland and WUI and related information to this subject. Desirable information to locate consisted of, among other things, which systems and methodologies exist worldwide today, what approach are they using i.e. hazard, risk, vulnerability, danger etc., how are the different tools constructed with input/output parameters and where are the tools used today. Keywords were, among other; Brushfire, Bushfire, Fire, Forest fire, Wildfire, Wildland fire, Wildland Urban Interface fire, Risk assessment, Vulnerability assessment, Danger rating and Fire system. This was made to enable the development of a preliminary VAM (for details, see 2.1). Databases and search engines which were used to locate information during the search for relevant literature consisted of, among others: Google, Google Scholar, ResearchGate, ScienceDirect, Academia.

The selection process of collected literature consisted of three steps. The initial step was to perform a title analysis in order to eliminate literature whose focus was outside the scope of the thesis. Then the abstract was analysed to create a deeper understanding of the content of the literature and thus eliminate further literature. In step three, a final selection was made to eliminate literature that had similar or the same content. This was mainly the case when selecting literature for factor collection and then the literature that was considered to give a wide range of factors was selected. The number of sources which were included in the selection process was initially approximately 100 papers or reports.

In order to get an overview on the procedure and execution of the VAM and to be able to assess the strengths and weaknesses of this method, a case study was carried out. The case study was limited to one municipality in Sweden that was exposed to the wildfires during the summer of 2018. In addition, the choice of municipality was based on availability of data which is required to apply the method (for details, see 0). Results from the case study were then presented and evaluated. This was used to provide suggestions for improvements of the VAM and assess the benefits of its use. Figure 3 displays the steps in the general method.

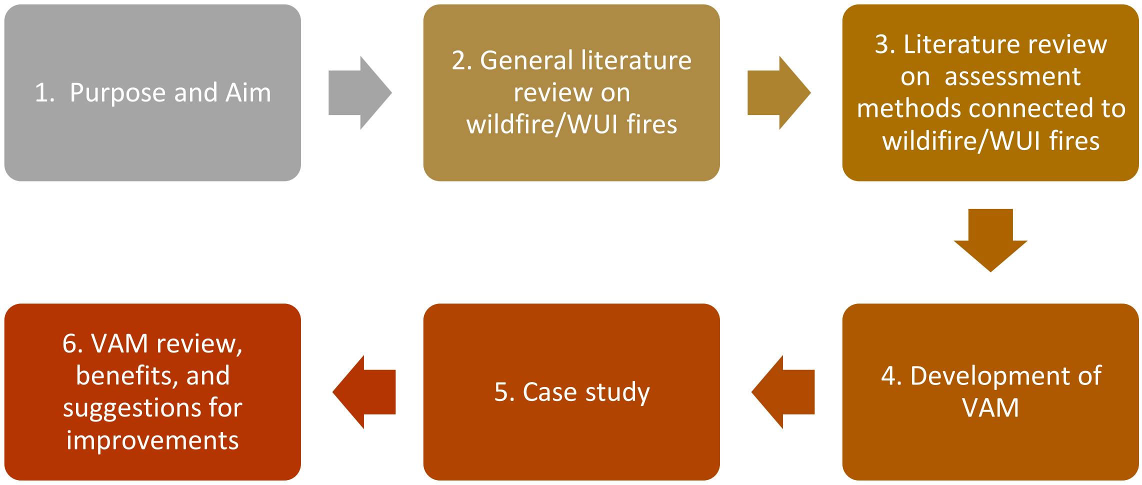

Figure 3. Flow chart of general method for the development of a Vulnerability Assessment Method (VAM) for wildfires

2.1 Review of assessment methods and related information

A set of factors which could impact wildfire vulnerability were identified in the review of assessment methods and rating tools. An example of such a factor could be *Precipitation*. These factors were defined and categorized according to their type. There were eight categories of factors, *Climate*, *Fuel*, *Topography*, *Fire Characteristics*, *Structure*, *Community*, *Population* and *Mitigation*.

Factors which related to the weather or climate were included in the category labelled *Climate*. The category labelled Fuel consisted of factors which referred to the natural fuel, e.g. type of vegetation. The category labelled *Topography* contained factors that were related to the properties of the natural landscape while factors which described the behaviour and properties of a fire were in the category labelled *Fire Characteristics*. Any factor that related to the individual buildings of the built landscape fell under the category labelled *Structure* and factors which referred to multiple structures or an entire community were in the category labelled *Community*. *Population* was the label of the category which contained all factors that described the properties of the population. Finally, the *Mitigation* category included any factor which could have a positive impact on the vulnerability, e.g. location or presence of fire stations.

The categories were created to get a better overview of the factors. The names were based on the types of the factors and the categorization was used to merge factors which were considered similar. Retrieved systems were briefly described and a number of systems were chosen for a comparison to observe which systems considered which factors out of all the identified factors.

The selection of systems was based on their scope, usage, and availability of data. Scope is intended here as whether the system took fires in the WUI into consideration or exclusively observed wildfires. Usage relates to what extent the system was used worldwide. Finally, availability of data relates to how difficult it was to retrieve information about the system structure, i.e., primarily considering which factors the system included. Systems were chosen both on the basis of their usage or their scope, but all were chosen with regard to the ability to retrieve information regarding their components, i.e. the factors they consider.

Factors considered to have a large impact on wildfire vulnerability were selected for the VAM through the review of retrieved systems as well as studies of previous reports and research regarding the topic. Finally, a VAM based on the selected factors was then developed to give a certain area a vulnerability rating. This included an equation which was used to calculate the vulnerability. Figure 4 displays the construction process for the VAM. For more information see Section 3.

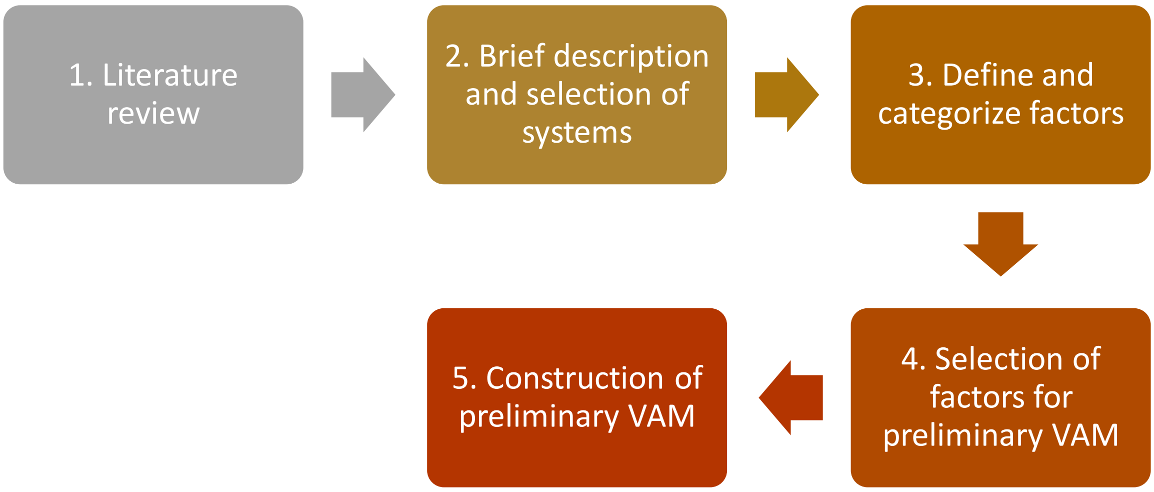

Figure 4. Flow chart of method for development of VAM for wildfires

For a more detailed overview of the construction of the VAM, see Figure 5

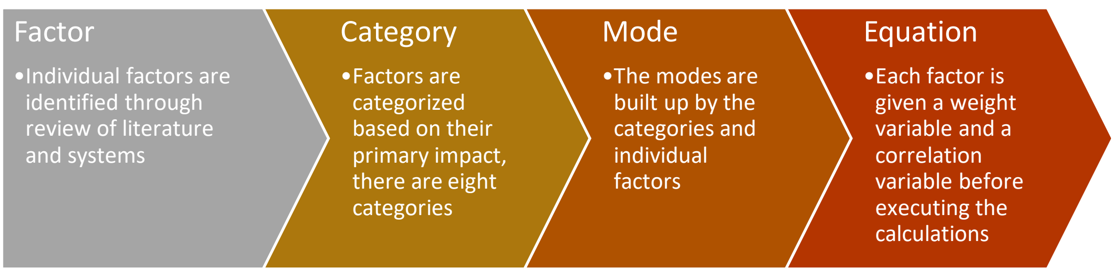

Figure 5. Construction process for the VAM

2.2 Case study

A case study was conducted to show how the VAM could be applied. The purpose of this case study was not to analyse a specific location, but to show how the VAM could be applied. The initial part of the case study consisted of making simplifications to the VAM in order to enable its application. Modifications consisted of either removing a factor completely or consider the factor in a different way, due to the authors' inability to retrieve the required data.

The next step was to rank the impact of the selected factors and determine an example of weight to each factor, which corresponds to the level of impact and results in a weight variable. The weights of the factors are by no means valid for all cases and should at this stage in the development of the VAM be determined for each specific case study. In the case study, those have a purely exemplary purpose.

Limit values were determined for each rating level, 1-5, for all factors. Sources that consisted of, among others; existing systems, e.g. the Canadian Wildland Fire Information System (CWFIS) (Canada, 2020c) was used to establish the limit values. Another type of source was reports that described which values a factor could vary between, e.g. SMHI (SMHI, 2012). Another of the most used sources to retrieve useful information was statistics from Statistics Sweden (Statistiska Central Byrån, 2019).

A municipality was selected and a number of areas within this municipality were chosen to carry out the calculations on. The goal was to select an area where most of the required data for the VAM was available. The data were collected for the selected areas and the calculations were then carried out on the selected areas within the municipality and the results were reported. Figure 6 displays the process of the case study.

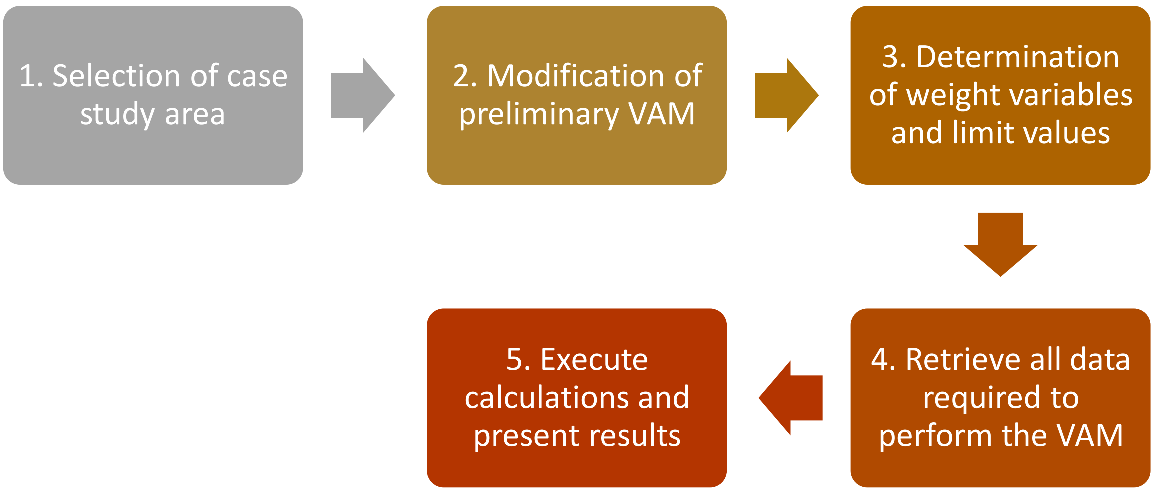

Figure 6. Flow chart of method to test the developed VAM in the case study under consideration.

3 Vulnerability Assessment Method

The method is developed with three primary modes, preventive, operational and evaluative. The reason why there is more than one mode is because the VAM aims at providing decision support to multiple different actors. The preventive mode is divided into three sub-modes, Preventive 1 (P1)-Historical trends, Preventive 2 (P2)-Current data and Preventive 3 (P3)-Future forecast. The operational mode (O) looks at active fires while the evaluative mode (E) observes historical fires.

The preventive mode is primarily aimed towards actors who operate within land use planning in a municipality or similar sectors. Factors in this mode can be retrieved by historical data (P1), present data (P2) and forecasts (P3). The purpose of the preventive mode is as the name states; to prevent wildfires. The difference between P1, P2 and P3 is only from which time the data is collected. An example of when the preventive mode can be used is when making a prediction of an area's vulnerability towards wildfires. The operational mode is primarily aimed towards the rescue services and similar agencies which can use it as a base for decision making in an operational stage, e.g. decision support during an ongoing wildfire for tactics and evacuation orders. The operational mode utilizes current values for the factors and forecasts for some variables to make predictions of the following days. Finally, the evaluative mode is primarily aimed towards actors within rescue services, insurance agencies and similar sectors that may have an interest of evaluating a historical event. Factors here are exclusively retrieved from historical values.

3.1 Existing danger rating and risk assessment systems

The systems that are of interest to identify are fire danger rating- and risk assessment systems that look at wildland and WUI fires. The purpose of this collection is to retrieve systems to use in a comparison (see Appendix 2. Comparison of systems, for full comparison) with the identified factors (see Section 3.3), as well as gaining an overview on how systems are designed. The identified systems are listed below along with a brief description. The scope of the systems, i.e. which factors they consider, are described through the categories.

3.1.1 Canadian Wildland Fire Information System (CWFIS)

Website: https://cwfis.cfs.nrcan.gc.ca/home
Examples of regions of usage: Canada, New Zealand, Malaysia, Indonesia
Brief description: CWFIS is built up by two modules, Canadian Forest Fire Danger Rating System (CFFDRS) and fire-M3. The system observes factors which can be included in the categories *Climate, Fuel, Topography* and *Fire Characteristics.* Information that can be retrieved from the system consists of fire danger and fire behaviour, fire and smoke locations, weekly statistics and links to provincial agencies. The system can be used both for preventive and operational purposes. Results are displayed on a map, that contains a colour code which corresponds to different levels of fire danger. The CFFDRS module displays the results through indexes, while the fire-M3 module uses maps. (Canada, 2019, 2020a).

3.1.2 McArthur Forest Fire Danger Index (FFDI)

Website: http://www.bom.gov.au/nsw/forecasts/fire-map.shtml
Examples of regions of usage: Australia
Brief description: FFDI is built up by four interacting modules, drought factor module, fuel moisture module, rate of spread module and suppression difficulty module. The system observes factors which can be included in the category *Climate* and provides information

regarding fire danger. The primary usage of the system is preventive. Results are given as an index. (Meteorology, 2020).

3.1.3 National Fire Danger Rating System (NFDRS)

Website: https://www.firelab.org/project/national-fire-danger-rating-system
Examples of regions of usage: The US
Brief description: NFDRS is built up by four modules, the first describes the characteristics of the geographical area with parameters such as *Topography, Climate* and *Fuel type*. Module number two and three describe the weather with parameters such as wind speed, temperature, relative humidity and rainfall. The fourth module tries to estimate the fuel moisture content by using data from previous days. The system can be used both for preventive and operational purposes. The results are given as four indexes. (Jolly & Bradshaw, 2018).

3.1.4 National Hazard and Risk Model (No-HARM)

Website: https://www.anchorpointgroup.com/services
Examples of regions of usage: The US
Brief description: No-HARM consists of three modules, the wildland-, the urban interface- and the ember module. The system observes factors which can be included in all categories except *Structure*. Information which can be retrieved from the system consist of hazard and risk ratings. The primary usage for the system is preventive and the results are displayed as a colour coded map. (White, 2015)

3.1.5 WUI wildfire threat assessment in B.C. (WUI in B.C.)

Website: https://www.fness.bc.ca/resources/library/forest-fuel-management/2017-wildfire-threat-assessment-guide
Examples of regions of usage: Canada
Brief description: WUI in BC consists of four modules, fuel, weather, topography and structure. The system observes factors which can be included in the categories *Climate, Fuel, Topography* and *Community*. The reason for why the names of the categories do not correspond to the modules of the system is the different perspectives. Information which can be retrieved consist of fire risk assessments. The usage of the system is preventive and performed on location. Results are displayed as colour coded indexes. (Morrow et al., 2017).

3.1.6 Wildland risk assessment framework (WRAF)

Website: https://www.fs.usda.gov/treesearch/pubs/56265
Examples of regions of usage: The US
Brief description: WRAF has four modules, wildfire simulation, HVRA characterization, exposure analysis and effects analysis. The system observes factors which can be included in the categories *Climate, Fuel, Topography, Fire Characteristics* and *Community*. Information which can be retrieved consist of fire risk. The usage of the system is preventive. Final output consists of tables and charts describing the exposure and effects. (Scott et al., 2013).

3.1.7 Fireharm

Website: https://www.firelab.org/project/fireharm
Examples of regions of usage: The US
Brief description: Fireharm is a platform which utilizes data from various systems, such as First Order Fire Effects Model (FOFEM) and NFDRS. Fireharm observes factors which can be included in the categories *Climate*, *Fuel* and *Topography*. Information which can be retrieved consist of fire effects, fire behaviour and fire danger components. The platform can

be used for both preventive and operational purposes. The results are displayed with indexes. (USDA Forest Service, 2020).

3.1.8 Colorado Wildfire Risk Assessment Portal (Co-WRAP)

Website: https://www.coloradowildfirerisk.com/
Examples of regions of usage: The US
Brief description: Co-WRAP assesses wildfire risk based on two components, hazard and vulnerability. The system observes factors which can be included in the categories *Climate, Fuel, Topography, Fire Characteristics* and *Community*. Information which can be retrieved consist of wildfire risk, burn probability and fire intensity. The usage of the system is preventive. The results are displayed with maps. (Colorado state Forest Service, 2020).

3.2 Selection of systems for comparison

To aid in the determination of the significance of a factor, five risk analysis systems are chosen for comparison with the identified factors. The selection was made based on three criteria, their scope, extent of usage around the world and possibility to retrieve information about the inputs and outputs of the system, for details see 2.1. Three out of five systems are chosen because they are considered the most used fire danger rating systems globally. The remaining two systems are chosen due to their scope that not only includes wildfires, but also fires in the WUI. Listed below are the chosen systems.

- Canadian Wildland Fire Information System
- McArthur Forest Fire Danger Index
- National Fire Danger Rating System
- No-HARM
- WUI Wildfire threat assessment in BC

3.3 Identification of factors

Five main sources were eventually used to identify the key factors for the VAM. The sources consisted of a Swedish book on wildfire extinguishing called Skogsbrand -Släckning (Hansen et al., 2003). Three different systems, two from the US and one from Canada. The ones from the US were the No-HARM (White, 2015) and the WRAF (Scott et al., 2013). WUI in B.C. (Morrow et al., 2017) was the Canadian system. These systems were chosen since they all look at WUI but with slightly different perspectives and therefore presented some difference in the factors included. Finally, a report was used that contained an overview of factors that affect the outcome of a fire in the WUI. The name of the report is e-Sanctuary Open Multi Physics Framework for Modelling Wildfire Urban Evacuation (Ronchi et al., 2017). There are also factors in the list that have no source, and these are factors that the authors have identified as relevant to a VAM but are not included in any of the above sources.

To clearly display in which sources each factor is included, all sources are given a label in form of a number between 1-6. Table 1 displays the labelling of the various sources.

Table 1. Sources used to identify the factors, with their reference and label

Source	**Reference**	**Label**
Skogsbrand -Släckning	(Hansen et al., 2003)	1
WUI in B.C.	(Morrow et al., 2017)	2
No-HARM	(White, 2015)	3
WRAF	(Scott et al., 2013)	4
e-Sanctuary Open Multi Physics Framework for Modelling Wildfire Urban Evacuation	(Ronchi et al., 2017)	5
Factor identified by the authors		6

The tables below show all factors sorted by categories and labelled with numbers depending on which sources they are retrieved from. The tables also include a description of each factor which is specific for this thesis and might be described in another way depending on source. Primary perspective and which modes, preventive (P1, P2, P3), operational (O), evaluative (E), a factor can be used in, is also presented in the tables.

Fel! Hittar inte referenskälla. displays the factors which are included in the category *Climate* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 2. Identified factors from category Climate with descriptions, perspectives and modes

Climate			
Name (source in **Fel! Hittar inte referenskälla.**)	Description	Perspective	Modes
Relative humidity (1)(5)	The proportion of water vapour in air compared to the saturation vapour density (Lexico, 2019a).	Societal	All modes
Wind speed (1)(5)	The speed of the air movement (Lexico, 2019c).	Societal	All modes
Wind direction (1)(5)	The direction from which the wind blows (Meteoblue, 2019).	Societal	All modes
Precipitation (1)(5)	Water that falls from the atmosphere in shape of rain, hail or snow (SMHI, 2019).	Societal	All modes
Dry days (6)	The number of consecutive days with a daily precipitation of less than two millimetres (Chen et al., 2014).	Societal	All modes
Temperature (1)(5)	The amount of heat in air, measured in degrees Celsius, degrees Fahrenheit or degrees Kelvin (Lexico, 2019b).	Societal	All modes
Bio geoclimatic zone (2)	A geographical area with a similar macroclimate that contains similar vegetation and wildlife (Edgell, 2015).	Societal	All modes

Table 3 displays the factors which are included in the category *Fuel* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 3. Identified factors from category Fuel with descriptions, perspectives and modes

Fuel			
Name (source)	Description	Perspective	Modes
Fuel moisture content (1)(3)(5)	The amount of available water within a fuel compared to the dry weight of the fuel, specified in percent (Fridholm, 2019).	Individual	P2, O, E
Fuel characteristics (1)	Factors that affect the fuel´s fire behaviour, such as, height, size, age and porosity.	Individual	All modes
Fuel load (1)	Fuel available within a certain area, usually expressed in fuel weight per unit area (USDA Forest Service, 2019).	Societal	All modes
Fuel Type (3)(5)	A group of fuel consisting of a distinctive species, shape, size and other characteristics which predicts a certain rate of spread (USDA Forest Service, 2019).	Individual	All modes
Continuity (1)	Fuel that is located at a distance so that fire spread through conduction, convection and radiation can be enabled. The fire spread can be both vertical and horizontal (Wooten Twist, 2019).	Societal	All modes

Table 4 displays the factors which are included in the category *Topography* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 4. Identified factors from category Topography with descriptions, perspectives and modes

Topography			
Name (source)	Description	Perspective	Modes
Aspect (1)(2)(3)(5)	The direction the slope is facing, specified in cardinal and intercardinal points (USDA Forest Service, 2019).	Individual	All modes
Slope (1)(2)(3)(5)	The incline of the slope expressed in degrees (Government of Scotland, 2013).	Individual	All modes
Elevation (1)(3)(5)	The altitude above sea-level (Lexico, 2019d).	Individual	All modes
Special land formations (1)	Formation in nature that contribute to a changed fire behaviour, such as ravines (Hansen et al., 2003).	Individual	All modes
Fire barriers (1)	Natural and constructed objects that creates a barrier towards the fire, such as deciduous forest, water streams and roads (USDA Forest Service, 2019).	Individual	All modes

Table 5 displays the factors which are included in the category *Fire Characteristics* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 5. Identified factors from category Fire Characteristics with descriptions, perspectives and modes

Fire characteristics			
Name (source)	Description	Perspective	Modes
Fire size (1)	The relative extent of the fire from back to front i.e. the area which is burning (Hansen et al., 2003).	Societal	O, E
Fire type (1)(5)	Four main fire categories, ground fires, crawling/surface fires, ladder fires and crown fires, that describe the fire behaviour based on available fuel and spread rate (National History Museum of Utah, 2019).	Societal	O, E
Fireline intensity (1)	The heat release rate per metre (National Wildfire Coordinating Group, 2019a).	Societal	O, E
Mode of fire development (5)	With what type of heat transfer a fire spreads, such as conduction, convection, radiation and spotting through embers.	Societal	O, E
Wildfire occurrence (2)(4)(5)	The frequency at which a fire occurs in an area over time (National Wildfire Coordinating Group, 2019a).	Societal	All modes
Fire duration (3)	The length of time that a fire occurs.	Societal	O, E
Rate of spread (3)(5)	The speed at which a fire extends its horizontal dimensions (USDA Forest Service, 2019).	Societal	O, E
Ignition source (5)	The cause of the fire (National Wildfire Coordinating Group, 2019a).	Societal	O, E
Fire fronts (5)	An area of the fire where continuous combustion takes place (USDA Forest Service, 2019).	Societal	O, E
Wind produced by fire (5)	The winds that a fire produces when it reaches adequate size (Hansen et al., 2003).	Societal	O, E
Materials involved in fire (3)(5)	The materials which are consumed in the fire.	Societal	O, E
Smoke distribution (5)	The surface on which the smoke spreads.	Societal	O, E
Smoke toxicity (5)	The amount of poisonous substances that exist within the smoke.	Societal	O, E
Smoke visibility (5)	Limitation of the visibility due to smoke from wildfires (Stone et al., 2019).	Societal	O, E

Table 6 displays the factors which are included in the category *Structure* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 6. Identified factors from category Structure with descriptions, perspectives and modes

Structure			
Name (source)	Description	Perspective	Modes
Building material (5)	The primary material which is used in the construction of the building, such as steel, concrete and wood etc.	Individual	All modes
Height of structure (5)	The measurement of a building from base to top.	Individual	All modes
Size of structure (5)	The bottom area of a building.	Individual	All modes
Building type (5)	Division of a building according to the protection needs, referred to in Swedish as "byggnadsklass" (Boverkets Byggregler (2011:6) - Föreskrifter Och Allmänna Råd, 2011).	Individual	All modes
Building functionality (5)	Division of a building´s spaces according to their primary functionality, referred to in Swedish as "verksamhetsklass". A building can have more than one functionality (Boverkets Byggregler (2011:6) - Föreskrifter Och Allmänna Råd, 2011).	Individual	All modes
Specific components (5)	Components that affects a building´s ability to withstand a fire or limit fire spread. Specific components include doors, windows, walls, roofs and other parts of a building.	Individual	All modes
Landscape maintenance (6)	The work of ensuring that the landscape stays safe, healthy and clean.	Individual	All modes

Table 7 displays the factors which are included in the category *Community* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 7. Identified factors from category Community with descriptions, perspectives and modes

Community			
Name (source)	Description	Perspective	Modes
Placement on slope (5)	The location of a community in relation to a slope (Hansen et al., 2003).	Societal	All modes
Development density (5)	The number of structures within an area compared to the size of the area (Metropolitan Council, 2019).	Societal	All modes
Wildland urban interface (5)	There is a clear line of demarcation between urban development and wildland fuels in a wildland urban interface community (USDA Forest Service et al., 2001).	Societal	All modes
Wildland urban intermix (5)	The structures are scattered throughout a wildland area in a wildland urban intermix	Societal	All modes

	community (USDA Forest Service et al., 2001).		
Occluded Wildland urban interface (5)	An island of wildland fuel is surrounded by structures, such as parks, in a wildland urban occluded community (USDA Forest Service et al., 2001).	Societal	All modes
Distance to fire (6)	Distance between a fire front and the observation area.	Societal	O, E
High hazard objects (5)	Objects that contain a high fuel load or other substances that can injure the population if affected by fire (Sur & Sokhi, 2006).	Societal	All modes
Road capacity (5)	The maximum traffic flow obtainable on a given roadway using all available lanes (Dictionary of Military and Associated Terms, 2019).	Societal	All modes
Status of road (5)	To what extent the road capacity can be used.	Societal	P2, O, E
Traffic management (5)	Traffic management refers to the work of achieving balance between the available and needed traffic capacity (Jiménez, 2018). A type of traffic management can be a sign that conveys information, an instruction or a warning (Lexico, 2019e).	Societal	All modes
Occupancy rate community (6)	Ratio between expected population and actual population of a community.	Societal	All modes
HVRA (3)(4)	Highly Valued Resources and Assets (HVRA) refer to stocks of money, objects or persons that are highly valued to the community for any particular reason.	Societal	All modes

Table 8 displays the factors which are included in the category *Population* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 8. Identified factors from category Population with descriptions, perspectives and modes

Population			
Name (source)	Description	Perspective	Modes
Population (5)	All the people or animals of a particular type or group who live in one country, area, or place.	Societal	All modes
Population density (5)	The number of people in each unit area.	Societal	All modes
Households (5)	All people in a family or group who live together in a house.	Societal	All modes
People with limited ability to self-evacuate (5)	This factor includes people who have a permanent or temporary mental, physical or material limitation that will affect the ability to self-evacuate. A material limitation could be the lack of vehicles in an emergency.	Societal	All modes

Occupancy rate structures (5)	Ratio between the actual number of people within a building compared to the allowed maximum level.	Individual	All modes

Table 9 displays the factors which are included in the category *Mitigation* together with a description of the factor, its primary perspective, and which modes it can be used in.

Table 9. Identified factors from category Mitigation with descriptions, perspectives and modes

Mitigation			
Name (source)	Description	Perspective	Modes
Protective actions (5)	Any action taken to protect the wellbeing of a population.	Societal	All modes
Means of communication (5)	The tools and technology which facilitate for exchanging information, ideas and opinions between people or organisations of different places. VMA or “Important Message to the Public” is also included. VMA is a Swedish national alert system, sending a signal through signal horns placed in most of the populated places of Sweden. Messages are also reported through radio, television and other social medias (MSB, 2019c)	Societal	All modes
Rescue service response time (5)	The time it takes for the rescue service to arrive to the scene after the alarm is received.	Societal	All modes
Responders (5)	Number of available responders.	Societal	All modes
Special competencies (6)	Available people that possess special competencies with regard to wildfires.	Societal	All modes
Fire stations (5)	The distance between the nearest fire station and the affected area.	Societal	All modes
Proximity to water (5)	The distance between a water source of sufficient size and the location of the affected area.	Societal	All modes
Water sources (5)	The amount of water sources of sufficient size within a selected area.	Societal	All modes
Water capacity (5)	The maximum amount that a water source can provide.	Societal	All modes
Training (5)	Teaching people how to act and react in an emergency, such as evacuation drills.	Societal	All modes
MSB forest fire depots (5)	The depot is a reinforcement resource provided by MSB, there are 24 depots in the country (Sverige & MSB, 2016). This factor is only applicable in Sweden.	Societal	All modes

How a factor is practically taken into account is dependent on the type of factor. Many factors can be considered using the actual value, maximum, minimum, or average value over time or for a specific event, e.g. temperature. Other factors can be considered as the dominant feature or species, e.g. fuel type, where the factor can be simplified to only one fuel type if most fuels are of that type. If a factor like fuel type is considered in more detail, then the variation can be displayed using the proportion of the fuel types. A factor like fuel load can be considered as a proportion, volume, mass or energy. Finally, certain factors are constant or change very little over time, e.g. elevation. This can be observed for single events where a factor like ignition source is constant. Spatial factors can also be considered in the same ways as non-spatial factors, however, the time window where they are observed needs to be determined.

3.4 Selection of factors

In this section the selection process of factors is performed. The selected factors should include the most important factors to use in a VAM for wildfires with a holistic approach considering evacuation as well as fire behaviour. Which factors that are and are not selected for the VAM is displayed in tables, one table for each category. The content of the tables consists of the factors name, impact, the result from the comparison and whether it is selected. The impact refers to how a factor impact the vulnerability (based on literature and historical information). The comparison refers to a comparison between the selected system (see Section 3.2) which displays how many systems consider a certain factor. The complete comparison can be found in Appendix 2. Both the information regarding a factor's impact and the results of the comparison form the basis for the selection of factors together with a subjective judgment by the authors based on the following three parameters, Scope, Effect and Overlap. The Scope displays the factors that may be included within the limitations specified for the report, for details regarding the limitations, see section 1.2. Effect describes both the degree to which a factor affects vulnerability and whether it is measurable or not. Overlap describes that certain factors are not selected due to double consideration since they are similar e.g. households and population.

Table 10 shows the selection for the *Climate* factors, including their impact and results from comparison of systems.

Table 10. Selection of Climate factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Climate			
Name	Impact	Comparison of systems	Selected for VAM
Relative humidity	Relative humidity is found to be one of the most important weather variables to influence the spread and burn severity of a fire, a lower humidity makes the fuel drier and fire growth quicker (Wu et al., 2018).	4/5	Yes
Wind speed	Just as for relative humidity, wind speed is one of the most important weather variables regarding spred and burn severity (Wu et al., 2018). Wind gives the fire more oxygen, dries the fuel and helps push the fire further accelerating its spread rate. Wind can also transport embers leading to new ignitions and fires, a higher wind speed can transport embers longer distances. (Hansen et al., 2003)	4/5	Yes
Wind direction	The wind direction impacts the direction of the fire spread (Hansen et al., 2003). The vulnerability	4/5	Yes

	increases if the fire spreads towards valuable assets like populated areas.		
Precipitation	Precipitation has shown to make a great impact on the fire season. A study made in the US shows that the precipitation during the summer months is highly associated with the range of fire-affected forest areas (Holden et al., 2018).	4/5	Yes
Dry days	The lack of precipitation for a long period of time allows the fuel to dry out and enabling ideal fire conditions (Blumberg, 2019).	0/5	Yes
Temperature	The heat dries the fuel and makes it easier for ignitions to occur and the spread rate is also considered to increase with higher temperatures. (Hansen et al., 2003)	4/5	Yes
Bio geoclimatic zone	The bio geoclimatic zone provides an overview of the climate and vegetation that can be found in an area (Government of British Columbia, 2019), and is relevant to know to predict which areas are prone to wildfires. Not selected due to overlap.	1/5	No

Table 11 shows the selection for the *Fuel* factors, including arguments and results from comparison of systems.

Table 11. Selection of Fuel factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Fuel			
Name	Impact	Comparison of systems	Selected for VAM
Fuel moisture content	The fuel moisture content affects how much energy that is needed for the fuel to dry enough to ignite. How fast the fuel moisture content change in the fuel is dependent on the fuel characteristics like height, size, age and porosity. Dead fuels are always easier to dry than living fuels. (Hansen et al., 2003)	4/5	Yes
Fuel characteristics	A fire is more likely to occur in a young forest since older trees are bigger and releases moisture continually, also a faster fire progress is likely in a younger forest. Fuel height matters, since taller trees cause a higher fire plume and can transport embers further away, thus enabling fire spread. (Hansen et al., 2003)	0/5	Yes
Fuel load	As one of the three components, both in the fire triangle and the wildland fire triangle, fuel is necessary for a fire to occur and the amount will impact its behaviour. A higher fuel load leads to, in general, a higher fire load and more energy released in the fire. (Hansen et al., 2003)	0/5	Yes
Fuel type	Moss, grass, bushes and trees are the four largest groups of fuel, all of which contributes to a certain	3/5	Yes

	fire behaviour (Hansen et al., 2003). Moss and grass, the fine fuels, usually have a higher spread rate than the heavy fuels which are bushes and trees (USDA Forest Service, 2019). Deciduous trees contain more moisture and will ignite slower than coniferous trees. When a wildfire occurs in deciduous forests, it is usually mostly the ground vegetation that is burning, and the trees will still stand afterwards. Fires in forest vegetation is therefore associated with coniferous forests. (Hansen et al., 2003) Because of this, information about the composition of the various fuel types is important.		
Continuity	The level of continuity affects the fire intensity that is needed to enable fire spread, more discontinuity within the fuel requires a greater fire intensity. (Wooten Twist, 2019) Continuity can be both horizontal and vertical, vertically the fire can spread from the ground to crowns if there are vegetation connecting all parts together. Horizontal continuity makes the fire spread on larger areas, if there are gaps in the vegetation restricting the continuity, the fire spread will also decrease. (Morrow et al., 2017)	1/5	Yes

Table 12 shows the selection for the *Topography* factors, including arguments and results from comparison of systems.

Table 12. Selection of Topography factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Topography			
Name	Impact	Comparison of systems	Selected for VAM
Aspect	The moisture levels will be lower and the temperature higher on south-facing slopes because the sun heats up the fuel more. This will give a higher spread rate for fires on south-facing slopes (Government of Scotland, 2013)	3/5	Yes
Slope	The fire spread will be faster uphill since the fuel above the fire is pre-heated. The wind will also help push the flames up along the slope. It is said that a 10° increase of slope will double the spread rate upwards. (The Bushfire Foundation, 2019)	5/5	Yes
Elevation	Fires at sea level tend to be more severe than in the mountains due to a lower fuel moisture content and higher fuel load (Hansen et al., 2003).	3/5	Yes
Special land formations	In valleys, the fire can spread from one side to the other through radiation and embers. In a ravine there can be a chimney effect making the wildfire	0/5	Yes

	drastically more intense and severe. (Hansen et al., 2003)		
Fire barriers	A fire barrier can stop or slow down a fire and even make it change direction. The usage of fire barriers is crucial during firefighting operations to create fire gates and fire boundary lines. (Hansen et al., 2003)	1/5	Yes

Table 13 shows the selection for the *Fire Characteristics* factors, including arguments and results from comparison of systems.

Table 13. Selection of Fire Characteristic factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Fire characteristics			
Name	Impact	Comparison of systems	Selected for VAM
Fire size	If a wildfire grows large enough, it can create its own behaviours, and the external factors will not affect as much anymore. A large wildfire can create its own weather and produce very strong winds. Phenomenon like fire storms and tornados might occur. When a wildfire is large it can also split into several flame fronts, making it harder and more dangerous to put out. (Hansen et al., 2003)	1/5	Yes
Fire type	There are four main fire types, ground fires, surface or crawling fires, ladder fires and crown fires. In groundfires the main fuel is usually roots, duff and buried organic materials underground. The fire can be smouldering for days and even months. A crawling or surface fire is usually fuel burning in the lower vegetation layers like leaves, timbers, debris and grass on the ground. (National History Museum of Utah, 2019) A crawling fire is estimated to move about 0-10 meters per minute (Hansen et al., 2003). Ladder fires are burning in the layers between the low surface layers and the high crowns, the fuels are typically logs, small trees, larger bushes and other plants. (National History Museum of Utah, 2019) The characteristic fire spread for ladder fires is vertical from the lower layers to the higher and the spread rate is about 10-20 meters per minute (Hansen et al., 2003). A crown fire is burning in the top layers (National History Museum of Utah, 2019). A crown fire can spread quickly from crown to crown, with spread rates up to 20-50 meters per minute and perhaps even quicker in specific conditions (Hansen et al., 2003).	1/5	Yes

Fireline intensity	The fireline intensity enables the prediction of the likelihood of fire spread and the difficulties in suppression (National Wildfire Coordinating Group, 2019a).	1/5	Yes
Mode of fire development	Convection makes smoke and hot gases from low burning fuels pre-heat higher leaves and branches above the fire, making them more likely the ignite. Conduction can make the fuel adjacent to the fire ignite. Radiation is energy released from the fire as heat. Radiation from a wildfire can potentially ignite fuel on a distance up to 10 meters. The wind can transport embers a long distance, starting new fires, making the fire spread can increase significantly. (Randall, 2001) Embers can also make the fire spread past a fire barrier where other modes of fire development are impossible. (Hansen et al., 2003) Not selected due to scope and effect.	1/5	No
Wildfire occurrence	Previous wildfire occurrence can be used to predict where new wildfires might be more likely to occur. This information can also be used to see where measures like fuel treatments can be more effective. (Plucinski, 2012)	2/5	Yes
Fire duration	A fire that lasts for a long period of time, demands more resources, and leads to higher costs for the rescue operations. Not selected due to overlap.	2/5	No
Rate of spread	During the large wildfire in Västmanland in 2014, the fire spread from 30×30m to 300×1000m in one hour. This fire came to be one of the most severe fires in Swedish history. Four days after ignition, came a day referred to as the black Monday. (Skogsstyrelsen, 2019) On this day, temperatures were estimated to 34 °C in combination with winds of 15 m/s. The result, the fire spread was too rapid and time and time again the fire breached the borderlines. It was not only wildland fuel that was burning at this stage, everything was on fire.(Gustavsson, 2014)	2/5	Yes
Ignition source	The ignition of a wildfire can be natural, human caused or a result of failing components, which can create sparks. Natural ignitions occur randomly, and there is no way to predict where a fire might start. Failing components can only ignite certain areas, where these components are located, but there is no way to predict which component will fail. Finally, human caused ignitions can be placed strategically, in order to create as much damage as possible. Not selected due to scope.	1/5	No
Fire fronts	When a flame front reaches a different type of terrain, it can be divided into various flame fronts, going in different directions. The area between	0/5	No

	different flame fronts can be very dangerous to be in, actions should be taken to extinguish the new fronts, as soon as possible. (Hansen et al., 2003) Not selected due to effect.		
Wind produced by fire	When a fire is large enough, it can produce its own winds. In severe conditions, fire tornados might occur, making the fire hard to extinguish. (Hansen et al., 2003) Fire tornados can be very dangerous, and make the fire spread extremely fast. Examples of fire tornados historically can be found in California, where several fire tornados occurred during a fire in San Luis, Obispo, 1926. Another example is the wildfire in Canberra, Australia, 2003, that created a massive fire tornado, where almost 500 people were injured, and 4 people lost their lives. (Migiro, 2018) Not selected due to effect.	1/5	No
Materials involved in fire	Different materials behave differently when exposed to a fire (Östman, 1988),and the heat release rate varies, depending on the material (B. Karlsson & Quintiere, 1999). Smoke production rate, and carbon monoxide production, is also dependant on the material (Östman, 1988).	2/5	Yes
Smoke distribution	Decreased visibility and irritating effects from the fire smoke, makes the evacuation harder and more time inefficient. Studies show that even a relatively thin smoke layer, can make people unwilling to evacuate. However, familiarity with the surroundings, is another factor which impacts that decision. The study also shows that the heat and smoke, decrease the ability to think and make rational decisions. (Jin, 2016) There are also health problems, both short- and long-term, associated with fire smoke. A study shows that wildfire smoke can be especially associated with respiratory infections and is also expected to be related to cardiovascular effects. (Reid et al., 2016)	0/5	Yes
Smoke toxicity		0/5	Yes
Smoke visibility		0/5	Yes

Table 14 shows the selection for the *Structure* factors, including arguments and results from comparison of systems.

Table 14. Selection of Structure factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Structure			
Name	Impact	Comparison of systems	Selected for VAM
Building material	Building materials affect how resistant a building is to fires, and how the fire will behave. If the materials are combustible, non-combustible or fire resistant, will affect the Available Safe Egress Time (ASET). (Laranjeira & Cruz, 2014) Not selected due to overlap.	0/5	No
Height of structure	Tall buildings usually take longer to evacuate since they can fit many people, creating a higher flow. Elevators are not always designed to be used in case of fire, and evacuation through stairs can be time consuming. (Rubens, 2016) Similarly, a larger structure may lead to longer escape routes and evacuation times. Larger structures are also able to house more people. Not selected due to scope.	0/5	No
Size of structure		0/5	No
Building type	The assessment of the protection needs for a building should consider likely fire development scenarios, their consequences and the complexity of the building. The classification should take factors regarding evacuation and consequences from building collapse into account. (Boverkets Byggregler (2011:6) - Föreskrifter Och Allmänna Råd, 2011)	0/5	Yes
Building functionality	The division into a functionality class depends on; To what extent people have knowledge regarding the building layout and evacuation possibilities. If the people within the building are able to self-evacuate for the bigger part, if the people can be expected to be awake. Finally, if there is a heightened risk for fire or where a fire can have a very rapid and extensive course. Depending on which functionality a building has, the knowledge regarding the building layout varies. (Boverkets Byggregler (2011:6) - Föreskrifter Och Allmänna Råd, 2011)	0/5	Yes
Specific components	According to Swedish building codes, building components are divided into different classes based on their primary function combined with a time scale. The time scale describes how long the component is expected to withstand a fire. (Boverkets Byggregler (2011:6) - Föreskrifter Och Allmänna Råd, 2011) Not selected due to scope.	0/5	No

Table 15 shows the selection for the *Community* factors, including arguments and results from comparison of systems.

Table 15. Selection of Community factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Community			
Name	Impact	Comparison of systems	Selected for VAM
Placement on slope	The risk level varies depending on the community´s placement on the slope. A community which is at the bottom of a slope is exposed to the same fire behaviour as on flat ground. The worst location for a community is on the upper part of a continuous slope. (Morrow et al., 2017)	1/5	Yes
Development density	A higher development density means more people on the same area, but also a higher risk of fire spread between buildings (Laranjeira & Cruz, 2014). Not selected due to overlap.	0/5	No
Wildland Urban Interface	Wildland urban interface, intermix and occluded, are all different forms of areas where humans and development meet, or intermix, with the wildland fuel (Stein et al., 2013). Fires in wildland urban interface areas tend to become very complex and severe. The fire spread is different from other urban fires and wildfires, the main fire spread is seen to occur through embers. The different type of WUI will induce different difficulties. (Materese, 2017) Approximately 32% of all housings in the US are located in the WUI, on 10% of the country's total area (Stein et al., 2013). To date, there is no specific number on the amount of homes in WUI areas in Sweden. However, 69% of the country consists of forestland, so it can be assumed that many housings in Sweden are within, or close to these areas. (SkogsSverige, 2019)	1/5	Yes
Wildland Urban Intermix		1/5	Yes
Occluded Wildland Urban Interface		1/5	Yes
Distance to fire	The distance towards a fire affects many variables such as Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET), the risk of ignition etc. The closer a fire is to a community, the more it will affect the community.	0/5	Yes
High hazard objects	During the Woolsey fire in California, there were concerns that the fire had released toxic substances from the former test facility, which used radioactive and hazardous materials. This did not occur, but a similar scenario could have had long-term severe consequences for surrounding areas and population. (Osborne, 2018)	0/5	Yes
Road capacity	If evacuation is needed in a WUI fire, it is important that there are enough available roads to manage the	0/5	Yes

	traffic load. In cases where the available roads have not been enough, traffic stocking occurred, and people were stuck in severe conditions. (Wyloge, 2019)		
Status of road	During the Camp fire in California in 2018, the status of roads had a large impact on the road capacity. In the evacuation of Paradise, were three out of five outgoing routes closed due to fire, which lead to further clogging on the remaining routes, and longer evacuation time. (Wyloge, 2019)	0/5	Yes
Traffic management	Out of different types of traffic managements, studies show that the adaptive signs can affect the traffic by reducing the driving times and congestion. (Sätterlund, 2012) Not selected due to effect.	0/5	No
Occupancy rate community	The local population is expected to have a greater knowledge about their surroundings and may be more prepared if something were to happen, compared to tourists who visit (Eriksen & Prior, 2011). Tourists also temporary impact the population within the community, especially during the high season or a special event. Not seleted due to effect.	0/5	No
HVRA	HVRA´s need to be protected and their presence within a community raise the level of vulnerability, it is therefore important to know their location. (Scott et al., 2013)	1/5	Yes
Landscape maintenance	Maintenance of the garden has shown to make a great impact on whether a building is still standing after a WUI-fire or not. The most important thing is to mow the grass and it is more likely for a house to last if it is done around the whole garden and not only parts of it. (Schroeder & Wennerlund, 2016) Not selected due to effect.	0/5	No

Table 16 shows the selection for the *Population* factors, including arguments and results from comparison of systems.

Table 16. Selection of Population factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Population			
Name	Impact	Comparison of systems	Selected for VAM
Population	More people in a certain area means more people vulnerable to fire. Evacuation times will increase when the flow decreases, both in buildings and on roads, with a higher risk of stockings. (Friberg & Hjelm, 2014) Households is not selected due to overlap.	0/5	Yes
Population density		1/5	Yes
Households		0/5	No
People with limited ability to self-evacuate	People who do not have the ability to self-evacuate, or possess a reduced mobility, are expected to have a longer evacuation time. This was observed in California, when a hospital received an evacuation order. In that particular case, it took 12 hours to evacuate 86 patients. (Kelly et al., 2019) Statistics show that elderly (>84) is one of the more exposed groups within a community and stands for the majority of the fatalities connected to fires (Frontline, 2018).	0/5	Yes
Occupancy rate structures	According to codes and standards, there is a maximum occupancy set based on, among other, building type, size and number of emergency exits (Boverkets Byggregler (2011:6) - Föreskrifter Och Allmänna Råd, 2011). If the maximum occupancy is exceeded, it can lead to an obstructed evacuation, and in some cases have severe consequences. This was observed during the fire in Gothenburg, on the Herkules street, in 1998. During the time of the fire, there were approximately 370 people within a building that was designed to hold a maximum occupancy of 150, which resulted in 63 casualties. (Statens haverikommission et al., 2001) Not selected due to effect.	0/5	No

Table 17 shows the selection for the *Mitigation* factors, including arguments and results from comparison of systems.

Table 17. Selection of Mitigation factors, including arguments and number of systems in the comparison that consider the factor, labelled here as comparison of systems

Mitigation			
Name	Impact	Comparison of systems	Selected for VAM
Protective actions	A protective action can be evacuation, land use planning or prescribed fires, which are either preventive or operational (Cova et al., 2009). No	0/5	No

	matter which protective action is taken, it is expected to mitigate the outcome, and lower the vulnerability. Not selected due to effect.		
Means of communication	There are many different ways to communicate, such as, internet, telephone or radio systems. It is important that these systems function properly. During the wildfires in Sweden in 2018, there were many incidents where communication did not function as expected. This led to wasteful use of personnel. (Mannberg, 2019) Another channel of communication which was used during the wildfires was the VMA system. VMA was used several times to alert people and inform them about evacuation orders as an attempt to shorten the evacuation time, since people got information earlier (Sönnert, 2018). Not selected due to scope.	0/5	No
Rescue service response time	The rescue service response time and location of the fire station affects the time it takes for rescue operations to begin. A short distance and response time at the scene of a wildfire has shown to increase the possibility to save structures. (White, 2015) An example of when the response time for the rescue service was crucial, is the Västmanland fire in Sweden 2014. The fire grew big because the first responders got the wrong directions, and when arriving to the scene the fire had grown to such size that reinforcement was needed immediately. (Skogsstyrelsen, 2019)	0/5	Yes
Fire station		1/5	Yes
Responders	It is crucial to have enough personnel working on containing wildfires. During the wildfires in Sweden 2018, all available fire fighters in the affected area had to assist in some way. When that was not enough, fire fighters had to quit their vacations to come back to work. They also had to get help from other rescue services in Sweden, as well as, international help from the European Union. (Justitiedepartementet, 2019)	0/5	Yes
Special competencies	In the US, there are special rescue service units that are trained for wildfires. These special units can be expected to have a greater knowledge regarding the wildfire behaviour and can fight these fires more efficiently. (National Wildfire Coordinating Group, 2019b) Not selected due to scope.	0/5	No
Proximity to water	When extinguishing a wildfire or WUI fire, the water supply is of big importance and can often be problematic (Hansen et al., 2003). Water	0/5	Yes
Water sources		0/5	Yes

Water capacity	deficiency has occurred during several fires in Sweden. During the big fires in Ljusdal 2018, water supply for the fire trucks was problematic since the distance was long to the closest refill location. (Eirefelt, 2018) During another fire in Skåne, in 2019, the water deficiency was due to poor water supply in the water conduits. People in the area were told to limit their use of water during the firefighting operations (Eriksson/TT, 2019).	0/5	Yes
Training	There are different types of training on different levels, it can be table-top exercises or full-scale drills. These affect different groups within the community and will impact the level on vulnerability in various ways. (Ready, 2019) Not selected due to scope and effect.	0/5	No
MSB forest fire depot	Each depot contains equipment that are an aid to the firefighters, when battling with wildfires. Examples of equipment are chainsaws, hoses of various size and a six wheeled terrain vehicle. (MSB, 2019b) Between the 21st of May and the 23rd of July 2018, 24 depots were sent out to 16 counties. (MSB, 2018) Not selected due to effect.	0/5	No

3.5 Development of a vulnerability assessment method

Based on the selected factors in Section 3.4 (for a complete list, see Appendix 4.) a preliminary VAM is constructed. The factors included in the modes, preventive 1, 2 and 3, operational and evaluative are presented in Table 18.

Table 18. List of which selected factors for the VAM are included in each mode

	Prevent. 1	**Prevent. 2**	**Prevent. 3**	**Operational**	**Evaluative**
Climate	All factors	All factors	All factors	All factors	All factors
Fuel	All factors except fuel moisture content	All factors	All factors except fuel moisture content	All factors	All factors
Topography	All factors	All factors	All factors	All factors	All factors
Fire Characteristics	Only wildfire occurrence	Only wildfire occurrence	Only wildfire occurrence	All factors	All factors
Structure	All factors	All factors	All factors	All factors	All factors
Community	All factors except status of road and distance to fire	All factors except distance to fire	All factors except status of road and distance to fire	All factors	All factors
Population	All factors	All factors	All factors	All factors	All factors
Mitigation	All factors	All factors	All factors	All factors	All factors

The method is built up with five rating levels where the limit values for these levels are determined for each factor, based on facts and statistics. When deciding how many rating levels were appropriate, the authors discussed different options. The initial idea was to keep it simple with only 2 rating levels, yes or no, but this was discarded because it did not enable a display of the variations of a factor. The next idea was to have 10 rating levels, but this made it too detailed for this thesis. Finally, the authors decided on 5 rating levels, after observing the number of rating levels used in other systems, where 5 was common. Table 19 shows an example of the rating levels with corresponding limit values for a factor, in this case temperature.

Table 19. Example of limit values for rating levels

Rating level	1	2	3	4	5
Temperature [°C]	< 0	0-10	10-20	20-30	> 30

Data is collected for all factors for each cell in a grid, where the size of the grid depends on the total area of the selected region. Based on the collected data, each factor receives a rating of 1-5, dependant on the limit values. The given rating of the factor is then multiplied by that factor's specific correlation variable and weight variable. The correlation variable describes how much correlation there is between the different factors.

The weight variable describes how much a factor affects the vulnerability. Aspects to consider during the determination of weight variables are local conditions, human impact, size of affected area and rate of change. Local conditions refer to what interval a factor can be expected to vary between in that area and which rating levels this corresponds to. If the interval is located on the higher rating levels will the weight variable be determined higher. E.g. a location which has many slopes with a large incline will give a higher weight variable for Slope. Human impact refers to what extent people can impact a factor. E.g. the fuel load can be controlled by fuel maintenance operations like prescribed burning or the factors related to weather which people cannot impact at all. Size of affected area refers to the extent of a factor’s impact. E.g. HVRA can be limited to a single building or an entire community. The rate of change refers to a factor’s ability to shift rapidly. E.g. wind direction can change momentaneous, while the road capacity is more constant. All aspects should be considered since they interact with one another.

The rating can be 0, 0,5 or 1 where 0 corresponds to the lowest impact on vulnerability, and 1 the highest. The local conditions are labelled A, Human impact is B, Size of affected area is C and Rate of change is D. Table 20 presents an example on the rating or a weight variable for the factor temperature.

Table 20. Example of weight variable

Factor	**A**	**B**	**C**	**D**	**Weight Variable**
Temperature	0.5	1	1	1	0.875

All values obtained from the rating of the factors with respect to correlation and weight, by means of an equation, result in the percentage vulnerability for each cell compared to the maximum vulnerability, shown in Equation 1.

$$\sum \frac{(A_1 \times C_1 \times D_1)+(A_2 \times C_2 \times D_2)+\cdots+(A_x \times C_x \times D_x)}{(B_1 \times C_1 \times D_1)+(B_2 \times C_2 \times D_2)+\cdots+(B_x \times C_x \times D_x)} \times 100 = \%\, Vulnerability$$

Equation 1. Equation to calculate the vulnerability in the VAM

A_1, A_2, …, A_x – The rating (1-5) a factor receives based on the collected data for that factor
B_1, B_2, …, B_x – The maximum rating (5) a factor can receive
C_1, C_2, …, C_x – Correlation variable for a specific factor
D_1, D_2, …, D_x – Weight variable for a specific factor

The equation is exclusively developed by the authors, where the idea during the development was to create a simple equation that does not require much computer capacity. At the same time, the equation provides a holistic approach where many factors are taken into account.

The result displays the vulnerability with the help of a digital map of the specific region. This map contains a colour scale with five levels that illustrates the vulnerability of each cell in the grid. Blue represents 0-20 %, green 20-40 %, yellow 40-60 %, orange 60-80 % and red 80-100 % vulnerability. Clicking on a cell on the map gives you an exact percentage of the vulnerability. At this stage, the scale of vulnerability is relative, 100 % vulnerability does not necessarily correspond to worst credible scenario. Figure 7 shows the complete flow chart for the VAM application.

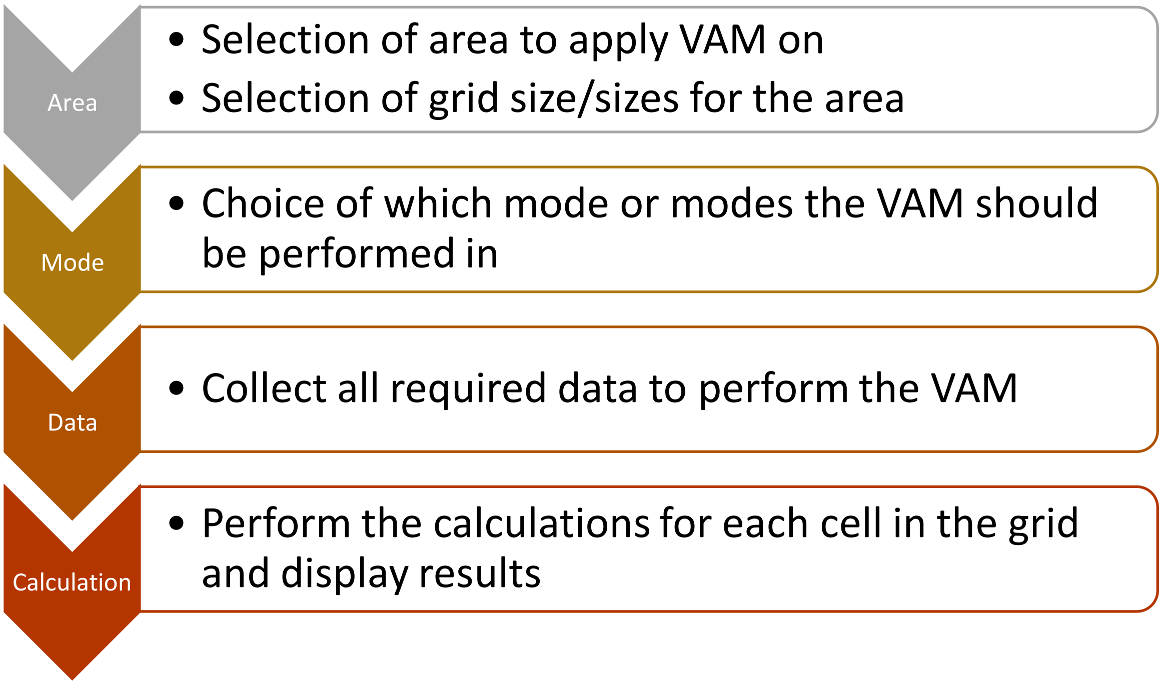

Figure 7. Flow chart for application of the developed Vulnerability Assessment Method (VAM)

4 Case study

The case study is carried out to give an idea of how the method can be applied in the future, while showing how the impact of the factors varies. The case study is conducted in two modes, preventive 1 and operational. The information provided includes choice of case study area, modifications performed to apply the VAM, determination of weight variables and limit values, collection of data and execution of VAM calculations.

4.1 Case study area

The area chosen for this case study is Ljusdal municipality. This location is considered suitable because of the exposure to wildfires in 2018. The total area burned during that summer was over 8 700 ha which made Ljusdal one of the most affected areas. Figure 8 shows a picture from Ljusdal during the fires.

Figure 8. Picture of Ljusdal 2018 during wildfires, retrieved from (Von Walden, 2020)

Ljusdal, the 20th largest municipality to size in Sweden belongs to Gävleborg county and is situated with the midpoint of Sweden within the municipality (Ljusdals Kommun, 2010a). In 2018 the population of Ljusdal was estimated to 19 033 (Statistiska Central Byrån, 2020b), the proportion of families is lower than the average in Sweden and proportion of elderly is higher than the average (Ljusdals Kommun, 2010a). The urban areas Ljusdal, Färila and Järvsö, located in the south east include most of the population in the municipality, this is also where the rescue services are located. Ljusdal municipality has four part-time fire stations, Ljusdal, Färila and Järvsö all have one team each on call all the time and a capacity to handle most types of accidents. Ramsjö has two fire fighters on call evenings, nights and weekends, being able to handle minor emergencies on their own. Beyond this, there are voluntary fire stations located in Ramsjö, Kårböle, Los and Tandsjöborg with equipment to handle minor accidents and support other fire fighters. Voluntary fire fighters are never on call and can never be expected to respond in the event of an accident. (Ljusdals Kommun, 2016) Figure 9 displays the municipality of Ljusdal with the location of fire stations by red marks. The large red marks are full part-time fire stations while the small red marks are voluntary fire stations.

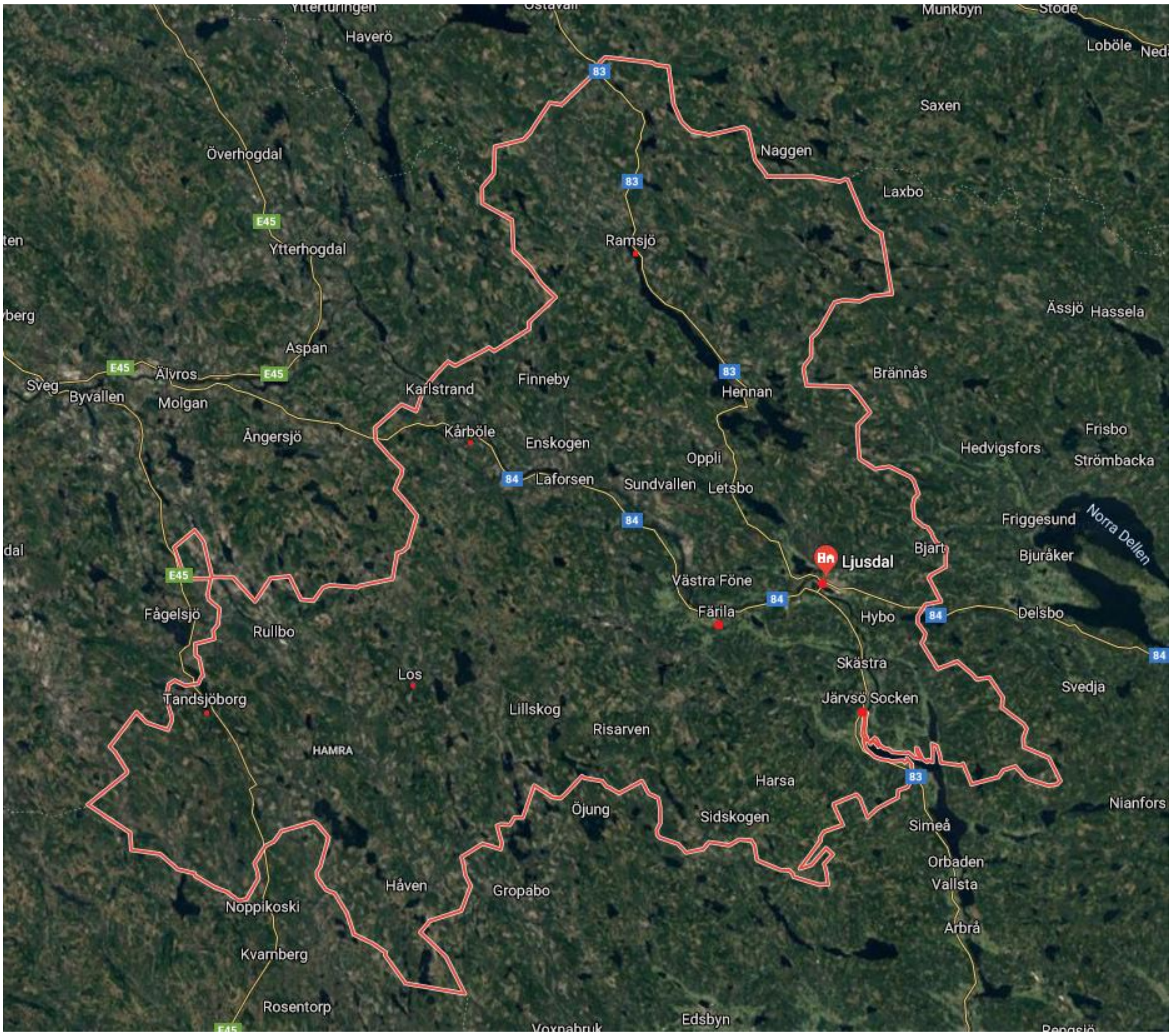

Figure 9. Map of Ljusdal with positions of fire stations, retrieved from (Google, 2020)

The largest business in the municipality is elderly care, reflecting the high proportion of elderly people that also is expected to increase the following years. There is a vision within the municipality that elderly should be able to live at home longer with help from home care and other means.(Ljusdals Kommun, 2010a) Statistics show that 80 % of Ljusdal consist of productive forestland and 10 % of Ljusdal is unproductive forestland. In total, 90 % of Ljusdal is forestland. (Ljusdals Kommun, 2020a; Statistiska Central Byrån, 2020c). Ljusdal also has many water courses and lakes, together they add up to about 40 000 hectares. 29 water and nature areas in the municipality are protected and considered as national interests. (Ljusdals Kommun, 2010a) Other large businesses in the area except elderly care, are tourism with ski resort, hiking paths and many other outdoor activities all year around (Hälsingland, 2020). With the large amount of forest in Ljusdal, the forestry accounts for a large part of the industry and is protected by the Swedish Environmental Code (Ljusdals Kommun, 2010a).

Located in the middle of Sweden, Ljusdal is an important connection for transport through the country. There are three roads of national interest in the municipality, E45 which extends through the west part of the municipality and road 83 and 84, both going through the centre of

Ljusdal. There is also a railway in the east, of national interest with high speed trains to the capital and other parts of Sweden as well as transportation of goods. (Ljusdals Kommun, 2010a). The areas of Ljusdal municipality which will be observed in the case study are the communities of; Ljusdal, Färila, Järvsö, Hybo, Lillhaga, Los, Tallåsen, Hamra, Kårböle, Ramsjö and Tandsjöborg. Nothing outside of the communities will be considered.

The case study will be carried out in two modes, Preventive 1 and Operational. All data for the operational mode will be retrieved for the 18th of July 2018 as this was the day when Kårböle was evacuated.

4.2 Simplifications of the method

The following modifications are made for mode Preventive 1 (P1) and Operational (O). In this case study, due to the inability to retrieve certain data, a set of factors are excluded from the P1 and O mode. The complete list of factors included in the modes can be found in Table 18.

The excluded factors for the P1 mode, sorted by category are;
Climate - Wind direction, Relative humidity
Fuel - Fuel characteristics, Fuel type, Continuity
Topography - Special land formations
Structure - Building type, Building functionality
Community - Wildland Urban Interface, Wildland Urban Intermix, Wildland Urban Occluded
Mitigation - Number of responders, Water capacity

The excluded factors for the O mode, sorted by category are;
Fuel - Fuel moisture content, Fuel characteristics, Fuel type, Continuity
Topography - Special land formations
Fire Characteristics - Fire type, Fireline intensity, Rate of spread, Smoke distribution, Smoke toxicity, Smoke visibility
Structure - Building type, Building functionality
Community - Wildland Urban Interface, Wildland Urban Intermix, Wildland Urban Occluded
Mitigation - Number of responders, Water capacity

Table 21 shows each factor included in the case study, considering both modes. It also shows how, and in what unit it is measured. It is also stated if the factor is considered for the whole municipality or each area individually.

Table 21. Presentation of how each factor is considered in the case study and if the value applies for the entire municipality

Name	**Unit**	**Comment**	**Applies for entire municipality**
Temperature	°C	Maximum temperature	x
Wind speed	m/s	Average wind speed	x
Wind direction	-		x
Precipitation	mm	Daily precipitation	x
Dry days	Number of days	Consecutive days	x
Relative humidity	%		x
Fuel load	%		x
Slope	%	Average incline	
Aspect	-		
Placement on slope	%		
Distance to fire	km		
Fire barriers	Number/ km^2		
High hazard objects	Number/km^2		
HVRA	Number/ km^2		
Road capacity	People/lane and hour	In this thesis will the road capacity be observed as the population of a community divided by outgoing lanes	
Status of road	%	Maximum percentage of 200% if lane reversal is applied	
Population	Number		
Population density	People/ km^2		
People with limited ability to self-evacuate	%	People aged below 18 and above 84 to represent the material limitation (no driving license) and the physical limitation (elderly).	x
Fire size	m^2		
Wildfire occurrence	Operations/ km^2 and year		x
Rescue service response time	min		
Proximity to water	min		
Water sources	%		x

For the correlation, there is only a relation to community size and/or population. The correlation between factors is excluded in this case study. The weight variable gives an estimated indication on how large the impact of a certain factor is, compared to the others.

In this example, rather than using a grid and conduct calculations for each cell in the grid, calculations are only carried out once per community. For some of the factors the same value is applied to the entire municipality, i.e. the same value applies for all communities. This is dependent on the ability to retrieve data for the factors.

4.3 Determination of weight variables

Table 22 displays the weight variables for each factor in the case study together with a rating for each of the four aspects to consider. The local conditions are labelled A, Human impact is B, Size of affected area is C and Rate of change is D. . In this example each rating is based on subjective assessments by the authors' knowledge regarding the subject and the weight variables are fictitious and specific for this exemplary case study. This should by no means be considered as an indication of an actual weight variable.

Table 22. Determination of weight variables

Name of factor	**A**	**B**	**C**	**D**	**Weight variable**
Temperature	0.5	1	1	1	0.875
Wind speed	0.5	1	1	1	0.875
Wind direction	0.5	1	1	1	0.875
Precipitation	0.5	1	1	1	0.875
Dry days	0.5	1	1	1	0.875
Relative humidity	0.5	1	1	1	0.875
Fuel load	1	0.5	1	0	0.625
Slope	0.5	1	1	0	0.625
Aspect	0.5	1	1	0	0.625
Placement on slope	0.5	0.5	1	0	0.5
Distance to fire	0.5	0.5	1	0.5	0.625
Fire barriers	0.5	0.5	0.5	0	0.375
High hazard objects	0.5	0.5	0.5	0	0.375
HVRA	0.5	0.5	0.5	0	0.375
Road capacity	0.5	0	1	0	0.375
Status of road	0.5	0.5	0.5	1	0.625
Population	0.5	1	1	0.5	0.75
Population density	0.5	0.5	0.5	0.5	0.5
People with limited ability to self-evacuate	1	1	1	0.5	0.875
Fire size	1	0.5	1	1	0.875
Wildfire occurrence	0.5	1	0.5	0	0.5
Rescue service response time	0.5	0.5	1	0	0.5
Proximity to water	0.5	0.5	1	0	0.5
Water sources	0.5	0.5	1	0	0.5

4.4 Determination of limit values

This section presents the limit values for each rating level for every factor in the case study. Several approaches are used to determine the limit values. Some factors have the same limit values as an existing system, e.g. relative humidity, while other limit values from an existing system have been modified to fit the five rating levels in the case study, e.g. temperature. Limit values for a few factors are determined based on statistics, e.g. population. In the cases where a benchmark can be retrieved in the form of an average value, this is used to set the boundaries for rating level three. The determination of the limit values for the following factors in this case study are exclusively based on subjective assessments; wind direction, placement on slope, fire barriers, HVRA, high hazard objects, status of road, proximity to water and water sources. All limit values which are presented in the following section should be evaluated before their usage, note that this is only an example for this specific case study.

Temperature - The CWFIS daily weather maps has selected the following division to display the temperature (Canada, 2020b), shown in Table 23.

Table 23. Limit values for temperature from CWFIS

Rating level	1	2	3	4	5	6
Temperature [°C]	< 0	0-10	10-20	20-25	25-30	> 30

In order to create a scale with five rating levels for the case study, level four (20-25 °C) and five (25-30 °C) are grouped together. These levels are chosen to have even intervals in the limit values, see Table 24.

Table 24. Limit values for temperature

Rating level	1	2	3	4	5
Temperature [°C]	< 0	0-10	10-20	20-30	> 30

Wind speed - SMHI utilizes a seven graded rating scale to define the wind speed (SMHI, 2012), see Table 25.

Table 25. Limit values for wind speed from SMHI

Rating level	Calm	Soft	Moderate	Fresh	Hard	Storm	Hurricane
Wind speed [m/s]	< 0,3	0.3-3.3	3.3-8	8-13.8	13.8-24.4	24.4-32.6	> 32.6

In this case study, calm and soft winds will be grouped together as well as storm and hurricane winds. A weather wane in good condition can show the wind direction during soft winds, so the effects are assumed to be small from these winds (SMHI, 2012). Storm and hurricane wind speeds are grouped together since the effects of storm winds are considered sufficiently extensive to be included in the highest rating level. Limit values are presented in Table 26.

Table 26. Limit values for wind speed

Rating level	1	2	3	4	5
Wind speed [m/s]	< 3.3	3.3-8	8-13.8	13.8-24.4	> 24.4

Wind Direction - The limit values in this case study for wind direction are determined to cardinal and intercardinal points in relation to position of community and fire. Cardinal and intercardinal points are not directly specified since they vary depending on the position of community and fire. Limit values are presented in Table 27. For further clarification see Figure 10.

Table 27. Limit values for wind direction

Rating level	1	2	3	4	5
Wind direction	Straight away from community	135° angle from community	90° angle from community	45° angle from community	Straight towards community

The modified compass rose is centred around a fire which is being observed in the specific scenario and shows the wind direction. The position of the community in relation to fire and wind direction gives the rating level for the community. Assuming there is a fire which is situated south of a community which is being observed, the wind is blowing from the south, i.e. the wind is blowing straight from the fire towards the community. This would then correspond to rating level 5.

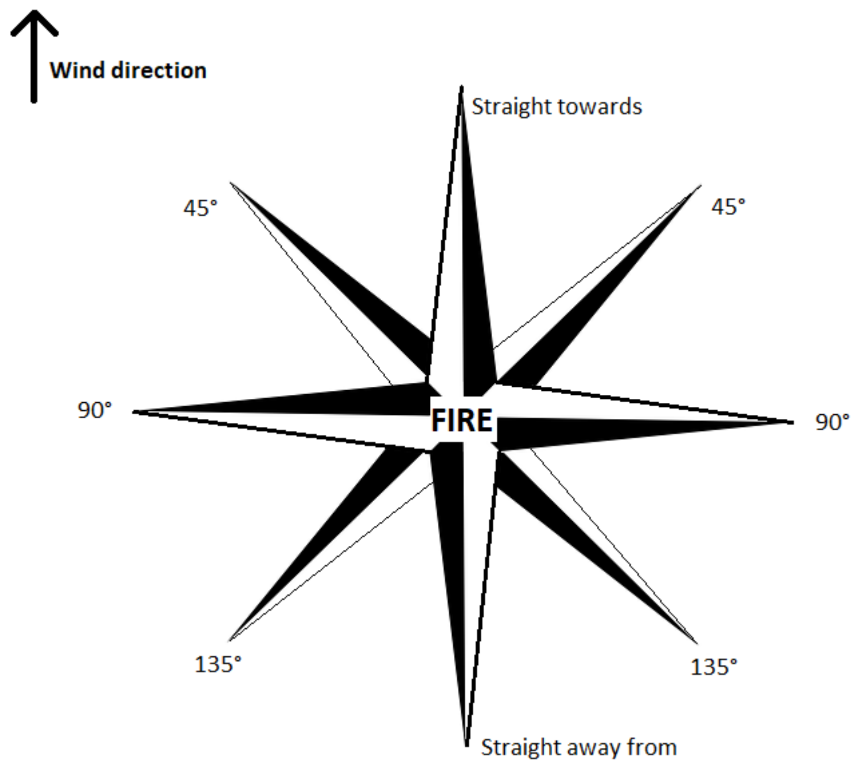

Figure 10. Compass rose with wind directions, original photo retrieved from (Pixabay, 2013)

Precipitation - The amount of precipitation observed is divided into six rating levels in the CWFIS daily weather maps (Canada, 2020b), see Table 28.

Table 28. Limit values for precipitation from CWFIS

Rating level	1	2	3	4	5	6
Precipitation [mm]	> 30	20-30	10-20	5-10	0-5	0

The limit values for precipitation in this case study are determined to the same as the CWFIS daily weather maps for rating levels 1-3. For rating level 4, the limit values are 9-2 mm and less than 2 mm for rating level 5. A dry day is defined as a precipitation less than 2 mm during a day (Chen et al., 2014), hence the limit value for rating level 5. Rating level 4 fills the gap between rating level three and five. Limit values are presented in Table 29.

Table 29. Limit values for precipitation

Rating level	1	2	3	4	5
Precipitation [mm]	> 30	20-30	10-20	2-10	< 2

Dry Days - Fires in vegetation, primarily grass can occur as soon as the day after precipitation (Olofsson, 2012). Based on this report the limit values for dry days in this case study are determined to less than 2 days for rating level 1. In order to set a limit value for the highest rating level, a few locations in Sweden are chosen to act as a benchmark for consecutive dry days that occur during a Swedish summer. Precipitation data for these locations from June to August between the years of 2010-2018 is used to create the benchmark. The benchmark shows an average of 13 consecutive dry days during the summer when the fire season is at its peak, hence why it is chosen for the limit value of rating level 5. The limit values for the remaining rating levels increase evenly. Limit values are presented in Table 30.

Table 30. Limit values for dry days

Rating level	1	2	3	4	5
Dry Days	< 2	2-5	5-9	9-13	> 13

Relative Humidity - The CWFIS daily weather maps observe the relative humidity, there are five rating levels for this factor (Canada, 2020b). The limit values for relative humidity in this case study are determined to the same as the CWFIS daily weather maps except for the overlaps between rating levels. Limit values are presented in Table 31.

Table 31. Limit values for relative humidity

Rating level	1	2	3	4	5
Relative humidity [%]	> 80	60-80	40-60	20-40	< 20

Fuel Load - When observing the proportion of forest land fuel for different Swedish communities it is seen to vary from 1 % in Staffanstorp, to 92 % in Uppvidinge (L. Karlsson, 2018). The scale for the rating levels is therefore divided into even intervals between 0- and 100 %. Limit values are presented in Table 32.

Table 32. Limit values for fuel load

Rating level	1	2	3	4	5
Fuel load [%]	< 20	20-40	40-60	60-80	> 80

Slope - For every 10° increase of incline the spread rate is doubled (The Bushfire Foundation, 2019). The limit values in this case study are determined to 0° incline for rating level one, followed by even steps of 10° intervals to account for the doubled spread rate. Limit values are presented in Table 33.

Table 33. Limit values for slope

Rating level	1	2	3	4	5
Slope [°]	0	0.1-10	10-20	20-30	> 30

Aspect - The 2012 version of the WUI in B.C. rating system, utilizes a five graded rating level to assess aspect. In this case study, aspect will have the same five rating levels as in the 2012 version of the WUI Wildfire threat assessments in B.C. (Johnston et al., 2013). Limit values are presented in Table 34.

Table 34. Limit values for aspect

Rating level	1	2	3	4	5
Aspect (> 15°)	North	East	< 16° incline, all aspects	West	South

Placement on Slope - The limit values for placement on slope are determined to the proportion of the community which is located on a slope. The levels are divided into even intervals between 0- and 100 %. Limit values are presented in Table 35.

Table 35. Limit values for placement on slope

Rating level	1	2	3	4	5
Placement on slope [%]	< 20	20-40	40-60	60-80	> 80

Distance to fire - Embers can travel up to 40 km and start new ignitions (The Bushfire Foundation, 2019), this is assumed to be a reasonable limit value between rating level 3 and 4four. The rest of the limit values are divided into steps of 20 km to make the rating levels even. Limit values are presents in Table 36.

Table 36. Limit values for distance to fire

Rating level	1	2	3	4	5
Distance to fire [km]	> 80	60-80	40-60	20-40	<20

Fire barriers, High hazard objects and HVRA's - In order to retrieve reasonable limit values for fire barriers, high hazard objects and HVRA's in this case study, several communities in Ljusdal municipality are observed. The results are related to the community size and show a variation between 0 and 5 for the different factors. The limit values are divided into even intervals starting from 0 and a maximum of more than 3. Limit values are presented in Table 37.

Table 37. Limit values for fire barriers, high hazard objects and HVRA's

Rating level	1	2	3	4	5
Fire barriers [per km^2]	> 3	2-3	1-2	0.1-1	0
High hazard objects [per km^2]	0	0.1-1	1-2	2-3	> 3
HVRA´s [per km^2]	0	0.1-1	1-2	2-3	> 3

Road Capacity - A critical flow of vehicles in the core of communities is observed to be around 1 000 cars per hour (Trafikverket, 2018). The road which has been observed is a 40 km/h road with one lane in each direction. For details, see figure 4-23 in the report issued by Trafikverket (Trafikverket, 2018). With the assumption that there is one person in each private vehicle (conservative assumption, as it assumes the highest number of vehicles in the system) and relating the factor with the population in each community. The car occupancy rate can be adjusted to be more accurate if it is based on actual values of number of vehicles from the car registry and compare this with household information. However, the conservative assumption is used in this case study. Limit values for rating level 5 is determined to more than 1000 people per outgoing lane. The remaining limit values are constructed with even intervals from 1000 down to 0. Limit values are presented in Table 38.

Table 38. Limit values for road capacity

Rating level	1	2	3	4	5
Road capacity [people /lane × h]	< 250	250-500	500-750	750-1 000	> 1 000

Status of road - When all outgoing lanes are open, the status of road is at 100 % which is used to set the limit values for rating level three. If lane reversal is considered, the status of road can increase to 200 % when the number of ingoing lanes is the same as the number of outgoing lanes. The limit values are determined to even intervals of 40 % starting from 200 % going down to 0 %. Limit values are presented in Table 39.

Table 39. Limit values for status of road

Rating level	1	2	3	4	5
Status of road [%]	> 160	120-160	80-120	40-80	< 40

Population - In Swedish urban areas (> 200 people), the median value for the population of an urban area for 2018 is between 500-999 (Statistiska Central Byrån, 2019). This is used to set the limit value for rating level 3. Since most of the Swedish population live in urban areas with a population above the median, the intervals for the higher rating levels are wider than for the lower ones. All small urban areas, defined as area with a population below 200, are included in rating level 1. Limit values are presented in Table 40.

Table 40. Limit values for population

Rating level	1	2	3	4	5
Population	< 200	200-500	500-2 000	2 000-10 000	> 10 000

Population density - A few Swedish communities are used to observe the variation in population density. It shows that most areas are around or below the national average which is approximately 1 400 people/km^2. (Statistiska Central Byrån, 2019) There are less areas with a high population density, this leads to a smaller interval for the lower rating levels and a wider for the higher ones. Limit values are presented in Table 41.

Table 41. Limit values for population density

Rating level	1	2	3	4	5
Population density [people/km^2]	< 100	100-500	500-1500	1500-2500	> 2500

People with limited ability to self-evacuate - The limit values for this factor is divided into one for children and one for elderly. This is made so that the two groups are looked at equally. A few Swedish communities are used to observe the variation in the proportion of children and elderly. The proportion of children in Sweden is 21 %, the proportion of elderly is 2,5 % and is used to set the limit values for rating level 3. (Statistiska Central Byrån, 2020a) The scales increase evenly and limit values for rating level 1 and 5 is set due to examinations of several municipalities with an unusually high or low average age. Limit values are presented in Table 42.

Table 42. Limit values for children and elderly

Rating level	1	2	3	4	5
Children [%]	< 12	12-18	18-24	24-30	> 30
Elderly [%]	< 1	1-2	2-3	3-4	> 4

Fire size - The average size of wildfires in Sweden, specified as forest or terrain fires, where rescue service is needed, is 6 000 m^2 (MSB, 2020b). The impact on the surroundings and the need of resources is considered when the limit values are created. The scale increases exponentially since most fires are relatively small while it is the large fires that have the highest impact. Limit values are presented in Table 43.

Table 43. Limit values for fire size

Rating level	1	2	3	4	5
Fire size	< 1 000 m^2	1 000 m^2-1 ha	1 ha-10 ha	10 ha-1 km^2	> 1 km^2

Wildfire occurrence - The total number of reported wildfire incidents in Sweden between 1998 and 2018 is 96 992. This provides an average number of 4 619 wildfires in Sweden per year. (MSB, 2020b). The average number is divided with the number of Swedish municipalities (290) to retrieve an average per municipality which is 16 fires/year. This average is used to set the limit values for rating level 3. The scale increases evenly with the same interval width for every rating level. Limit values are presented in Table 44.

Table 44. Limit values for wildfire occurrence

Rating level	1	2	3	4	5
Wildfire occurrence [operations/km^2 × year]	< 7	7-13	13-19	19-24	> 24

Rescue service response time - A study shows that the goal for many Swedish rescue services is to reach their entire population within 20-30 minutes (Blomqvist et al., 2012). This is used to set the limit value rating level 3. The remaining limit values are set with the same interval width as rating level 3. Limit values are presented in Table 45.

Table 45. Limit values for rescue service response time

Rating level	1	2	3	4	5
Rescue service response time [min]	< 10	10-20	20-30	30-40	> 40

Proximity to Water - The limit values for proximity to water is set to the same as for rescue service response time since it seems reasonable that the time it takes to get water to a wildfire scene is as important as the arrival of fire fighters. Limit values are presented in Table 46.

Table 46. Limit values for proximity to water

Rating level	1	2	3	4	5
Proximity to water [min]	< 10	10-20	20-30	30-40	> 40

Water sources - The proportion of Sweden's area which is covered in water is 9,85 % (Statistiska Central Byrån, 2020c). This is used to set the limit values for rating level 3. The remaining rating levels increase and decrease with even interval width. Limit values are presented in Table 47.

Table 47. Limit values for water sources

Rating level	1	2	3	4	5
Water sources [%]	> 16	12-16	8-12	4-8	< 4

4.5 Collection of data

The data was retrieved by various sources depending on the factor. Some were retrieved through statistics while others were in documents from the municipality. Detailed descriptions over how the data was retrieved can be found in

Appendix 3.

Weather factors - The same weather data applies for the entire municipality. Since there is no specific weather data for Ljusdal, the data for Delsbo is used for all factors except the relative humidity and the wind direction, because the factors are not recorded for this station. The relative humidity and wind direction values are retrieved from the measuring station in Sveg between 13:20 and 15:40, when the temperature was peaking, in the afternoon on the 18th of July 2018. Delsbo is located 25 km to the east of Ljusdal and Sveg is located 110 km to the west of Ljusdal.

For the preventive weather data, values are retrieved for June to August from 2010 to 2018. The data is used to create a mean value over the summer months. All operational weather data is retrieved for the 18th of July 2018 as this was the day when Kårböle was evacuated. All data is retrieved from the same source (Larsson, 2020) and is presented in Table 48.

Table 48. Weather data for case study

	Temperature	**Wind speed**	**Wind direction**	**Precipitation**	**Dry days**	**Relative Humidity**
Prevention	20.6	4	-	< 2	14	-
Operative	30.6	6	Southeast	< 2	18	32

Fuel load - The same data applies for the entire municipality. Measurements of the land use for the municipality show that 80.00 % of Ljusdal consist of productive forestland and 10.31 % of Ljusdal is unproductive forestland. In total, 90.31 % of Ljusdal is forestland. (Statistiska Central Byrån, 2020c)

Placement on slope - A topographic map (see Appendix 1) is used to assess the percentage of the community located on a slope (e.g., > 0° incline) (OpenStreetMap, 2020). The assessment is not precise, but an estimation of the community´s location is performed. The procedure is as follows: 1) Go to the topographic map which displays the community that is being observed. 2) Look if the community has more than one colour on the map, the colours correspond to different elevations. 3) Make an estimation of the area proportion located on a slope.

Slope - A topographic map (see Appendix 1) is used to retrieve the mean slope incline (OpenStreetMap, 2020). Only topographic maps which display different colours within the observed community are investigated. The mean incline is taken on the same slope that is used when analysing the placement on slope factor.

Aspect - A topographic map (see Appendix 1) is used to determine which direction the slope is facing (OpenStreetMap, 2020). The mean slope incline that is retrieved for the slope factor is taken under consideration for the assessment.

Distance to fire - The data is retrieved for the 18th of July 2018. Two separate maps are used to retrieve the information, one map displays the outline of the fire day by day while the other displays the location of each community. (Google, 2020; Ljusdals Kommun, 2020b) The distance is measured as the shortest distance between the outline of the fire and the community. The assessment is not precise, but an estimation.

Table 49 show data retrieved regarding placement on slope, slope, aspect and distance to fire for all areas.

Table 49. Data for case study: placement on slope, slope, aspect and distance to fire

Community	**Placement on slope**	**Slope**	**Aspect**	**Distance to fire [km]**
Ljusdal	40 %	15°	Less than 16° incline	35
Färila	80 %	9°	Less than 16° incline	26
Järvsö	10 %	33°	East	46
Hybo	0 %	-	Less than 16° incline	42
Lillhaga	0 %	-	Less than 16° incline	34
Los	100 %	21°	South	31
Tallåsen	80 %	23°	South-west (South)	29
Hamra	0 %	-	Less than 16° incline	42
Kårböle	0 %	-	Less than 16° incline	4
Ramsjö	0 %	-	Less than 16° incline	22
Tandsjöborg	100 %	35°	East	48

Fire barriers/ High hazard objects - A map is used to locate any natural or constructed fire barriers as well as any high hazard objects within each community (Google, 2020). Roads, lakes and watercourses are the fire barriers that are observed while gas stations and railways are the high hazard objects. The number of identified fire barriers or high hazard objects are put in relation with the size of the community.

HVRA - A map that displays national interests within the municipality (see Figure 11) is used to retrieve the information regarding the presence of HVRA's in each community (Ljusdals Kommun, 2010a). The national interests on the map are identified by the municipality of Ljusdal. Only the amount of identified HVRA´s in the map is of interest and no consideration is taken to the type of HVRA. Above the HVRA's that are identified on the map, the location of Hälsingland farms is also vital information as that is observed as an HVRA (Hälsingland, 2012). The number of identified HVRA's are put in relation with the size of the community.

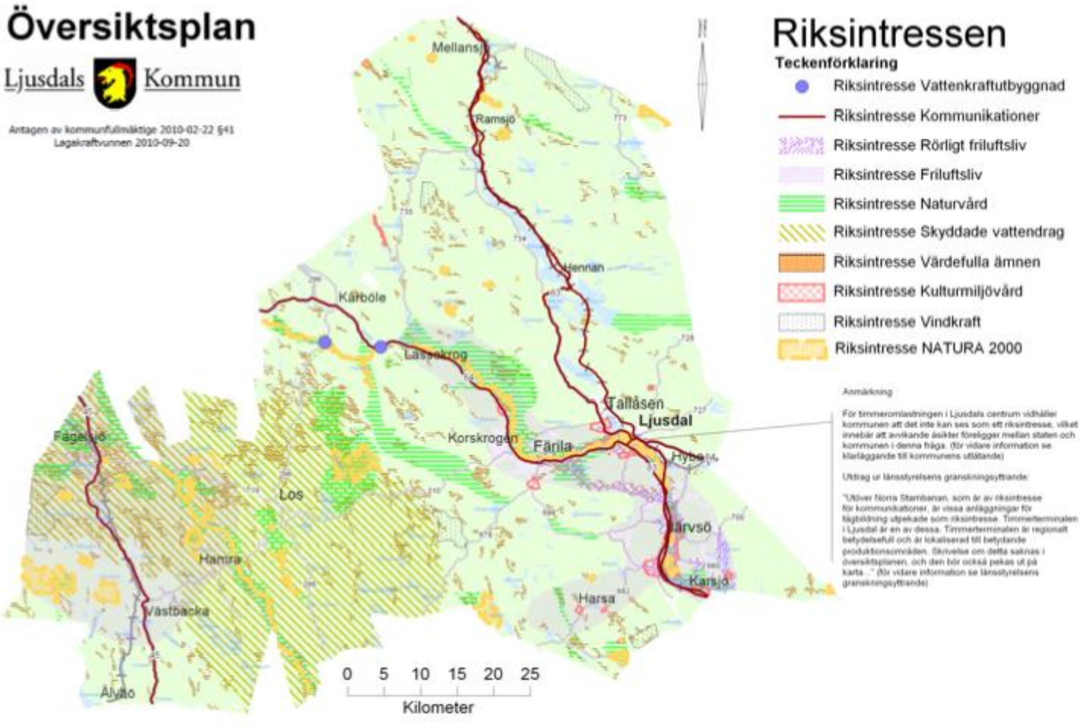

Figure 11. Map of HVRA´s in Ljusdal municipality, retrieved and used with permission from (Ljusdals Kommun, 2010b).

Table 50 shows data retrieved regarding area, fire barriers, high hazard objects and HVRA´s for all areas.

Table 50. Data for case study: area, fire barriers, high hazard objects and HVRA's

Community	**Area [ha]**	**Fire barrier**	**Fire barrier /km^2**	**High hazard object**	**High hazard object /km^2**	**HVRA´s**	**HVRA´s /km^2**
Ljusdal	729	5	0.69	4	0.55	7	0.96
Färila	291	4	1.37	1	0.34	6	2.06
Järvsö	345	3	0.87	1	0.29	7	2.03
Hybo	50	2	4	1	2	2	4
Lillhaga	75	3	4	2	2.67	4	5.33
Los	158	2	1.27	0	0	1	0.63
Tallåsen	160	2	1.25	2	1.25	1	0.63
Hamra	98	2	2.04	0	0	2	2.04
Kårböle	86	3	3.49	0	0	1	1.16
Ramsjö	64	3	4.69	0	0	1	1.56
Tandsjöborg	87	3	3.45	1	1.15	3	3.45

Road capacity - A map is used to locate all roads that lead out of each community (Google, 2020). The number of outgoing lanes for each road is observed and divided by the population for each community, to retrieve the number of people that use each outgoing lane. One person is estimated to use each car, which is a conservative assumption.

Status of road - All values are retrieved for the 18th of July 2018. Traffic information from that day for the municipality of Ljusdal is observed to retrieve information regarding which roads and lanes are partially or completely closed. (Gävleborg, 2018) Any information regarding the usage of lane reversal is not found and it is therefore assumed that lane reversal was not used on that day.

Table 51 shows all data retrieved regarding number of outgoing lanes, population and status of road for all areas.

Table 51. Data for case study: road capacity, status of road

Community	Outgoing lanes	Population	Road capacity [People/ Outgoing lane]	Status of road
Ljusdal	5	7 309	1 462	All outgoing lanes open
Färila	5	1 376	275	All outgoing lanes open
Järvsö	3	1 508	503	All outgoing lanes open
Hybo	3	218	73	All outgoing lanes open
Lillhaga	2	403	202	All outgoing lanes open
Los	4	340	85	All outgoing lanes open
Tallåsen	4	590	148	All outgoing lanes open
Hamra	2	114	57	All outgoing lanes open
Kårböle	4	124	31	One outgoing lane closed
Ramsjö	3	177	59	All outgoing lanes open
Tandsjöborg	3	80	27	All outgoing lanes open

Population/Population density - The population and community size for each urban area is retrieved from statistics for 2018 (Statistiska Central Byrån, 2020d), while the same data for the small urban areas is retrieved for 2010 (Statistiska Central Byrån, 2020e). The population density is calculated using the retrieved values of population and community size, see Table 52.

Table 52. Data for case study: population, population density

Community	Area [ha]	Population	Population density
Ljusdal	729	7 309	1 002
Färila	291	1 376	472
Järvsö	345	1 508	437
Hybo	50	218	438
Lillhaga	75	403	540
Los	158	340	216
Tallåsen	160	590	369
Hamra	98	114	116
Kårböle	86	124	145
Ramsjö	64	177	276
Tandsjöborg	87	80	92

People with limited ability to self-evacuate - Statistics from 2018 is used to retrieve information regarding the number of children (< 18) and elderly (85 and above) people in the municipality of Ljusdal (Statistiska Central Byrån, 2020a). The number of children for 2018 is 3 635 and the number of elderlies for 2018 is 676. The proportion of children and elderly is calculated using the numbers retrieved divided by the population for Ljusdals municipality in 2018 which was 19 033. The proportion of children is 19 % and the proportion of elderly is 3.5 %.

Fire size - Since there is no value for the fire size on the 18th of July 2018 for the fires in Ljusdals municipality, the final fire size is retrieved. There were three larger fires within the municipality. The largest one, the fire in Enskogen, covered 4 137 ha, the fire in Ängra covered 3 437 ha and the fire on Nötberget covered 848 ha. This adds up to a total size of 8 422 ha. (Eriksson et al., 2018).

Wildfire occurrence - Statistics from old firefighting operations for wildfires in the municipality of Ljusdal, between 1998-2018, show that the average number of fires is 24 fires/year (MSB, 2020b). The statistics only covers wildfires where a firefighting operation occurred but is assumed to be an adequate estimation of the wildfire occurrence.

Rescue service response time - There are three part time fire stations located in the municipality of Ljusdal. The stations are in Ljusdal, Färila and Järvsö (Ljusdals Kommun, 2016). These are the only stations with a 24-hour preparedness time and is therefore used as a starting point in the calculations for the response time for the rescue service. Values regarding the driving time between communities is retrieved from a map on the 11th of November 2019 during rush-hour at 16:30. (Google, 2020) 7 minutes is added to the driving times since this is the set preparedness time for the firefighters.

All data retrieved regarding rescue service response time is presented in Table 53 with the shortest time marked by a bold font and underscored.

Table 53. Data for case study: rescue service response time

Community	Ljusdal fire station	Färila fire station	Järvsö fire station
Ljusdal	**<u>10</u>**	20	25
Färila	20	**<u>10</u>**	30
Järvsö	20	30	**<u>10</u>**
Hybo	**<u>15</u>**	30	20
Lillhaga	**<u>15</u>**	20	20
Los	60	**<u>40</u>**	60
Tallåsen	**<u>20</u>**	30	30
Hamra	60	**<u>50</u>**	70
Kårböle	50	**<u>40</u>**	60
Ramsjö	**<u>55</u>**	60	65
Tandsjöborg	85	**<u>70</u>**	90

Proximity to water - The proximity to water applies to each community. Locations of fire hydrants are retrieved from Räddningstjänsten Ljusdal. (Ljusdals Kommun, 2016) Fire hydrants are located within each urban area, and all the small urban areas are located next to natural water sources of sufficient size, therefore the proximity to water is assumed to be below 10 minutes for every urban area as well as the small urban areas.

Water sources - Statistics displaying the land use of Ljusdals municipality shows that the municipality consists of 35 342 ha water. This is related to the entire size of the municipality, which is 525 637 ha. (Statistiska Central Byrån, 2020c) The proportion of water is 6.7 % of the municipality.

5 Results of Case Study

The results are organized in tables and maps for the two different modes, namely 1) preventive (P1) and 2) operational (O). The results for urban areas and small urban areas are also divided into different tables for each mode.

Table 54 shows the results for urban areas with the preventive mode. The table shows all factors included in the preventive mode and their rating level in each urban area. In the bottom the percentages of vulnerability are calculated for each urban area using Equation 1.

Table 54. Results preventive mode urban areas

Factor\Urban Area	**Ljusdal**	**Färila**	**Järvsö**	**Hybo**	**Lillhaga**	**Los**	**Tallåsen**
Temperature	4	4	4	4	4	4	4
Wind speed	2	2	2	2	2	2	2
Precipitation	5	5	5	5	5	5	5
Dry days	5	5	5	5	5	5	5
Fuel load	5	5	5	5	5	5	5
Slope	3	2	5	1	1	4	4
Aspect	3	3	2	3	3	5	5
Placement on slope	3	4	1	1	1	5	4
Fire barriers	4	3	4	1	1	3	3
High hazard objects	2	2	2	4	4	1	3
HVRA's	2	4	4	5	5	2	2
Road capacity	5	2	3	1	1	1	1
Population	4	3	3	2	2	2	3
Population density	3	2	2	2	3	2	2
Children	3	3	3	3	3	3	3
Elderly	4	4	4	4	4	4	4
Wildfire occurrence	2	2	2	2	2	2	2
Rescue service response time	2	2	2	2	2	4	3
Proximity to water	1	1	1	1	1	1	1
Water sources	4	4	4	4	4	4	4
Percentage of vulnerability	**68 %**	**65 %**	**66 %**	**60 %**	**61 %**	**68 %**	**69 %**

Table 55 shows the results for small urban areas with the preventive mode. The table shows all factors included in the preventive mode and their rating level in each small urban area. In the bottom the percentages of vulnerability are calculated for each small urban area.

Table 55. Results preventive mode small urban areas

Factor\Small Urban Area	**Hamra**	**Kårböle**	**Ramsjö**	**Tandsjöborg**
Temperature	4	4	4	4
Wind speed	2	2	2	2
Precipitation	5	5	5	5
Dry days	5	5	5	5
Fuel load	5	5	5	5
Slope	1	1	1	5
Aspect	3	3	3	2
Placement on slope	1	1	1	5
Fire barriers	2	1	1	1
High hazard objects	1	1	1	3
HVRA's	4	3	3	5
Road capacity	1	1	1	1
Population	1	1	1	1
Population density	2	2	2	1
Children	3	3	3	3
Elderly	4	4	4	4
Wildfire occurrence	2	2	2	2
Rescue service response time	5	4	5	5
Proximity to water	1	1	1	1
Water sources	4	4	4	4
Percentage of vulnerability	**60 %**	**58 %**	**59 %**	**66 %**

Figure 12 displays the results for the preventive mode on a map, using the colour scale. Lillhaga is the only community, which is not displayed in the figure, but the community is located directly to the west of Ljusdal and received the same colour as Ljusdal.

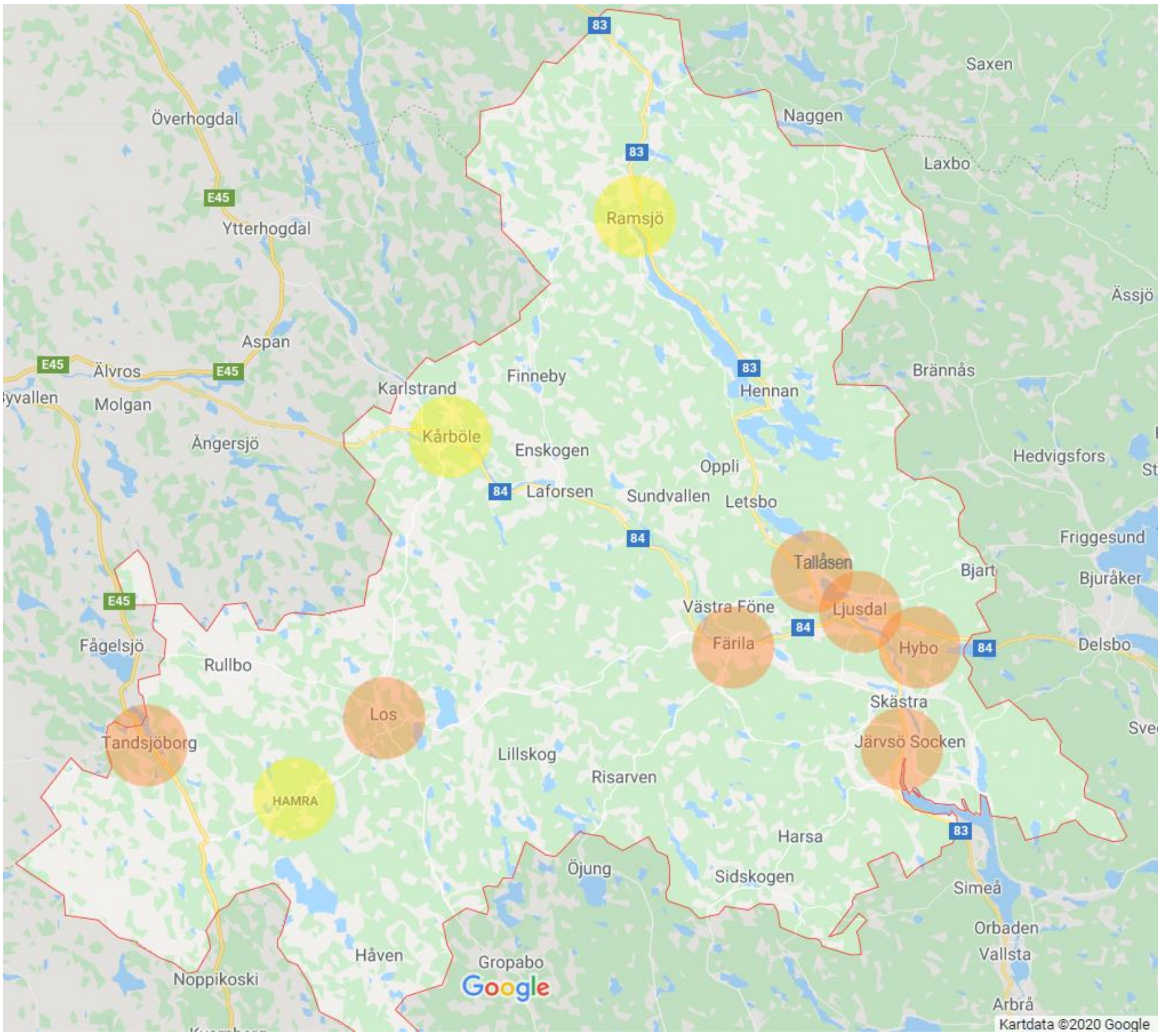

Figure 12. Results from the preventive mode displayed on map

Table 56 shows the results for urban areas with the operational mode. The table shows all factors included in the operational mode and their rating level in each urban area. In the bottom there are the calculated percentages of vulnerability for each urban area.

Table 56. Results operational mode urban areas

Factor\Urban Area	**Ljusdal**	**Färila**	**Järvsö**	**Hybo**	**Lillhaga**	**Los**	**Tallåsen**
Temperature	5	5	5	5	5	5	5
Wind speed	2	2	2	2	2	2	2
Wind direction	1	1	1	1	1	3	1
Precipitation	5	5	5	5	5	5	5
Dry days	5	5	5	5	5	5	5
Relative humidity	4	4	4	4	4	4	4
Fuel load	5	5	5	5	5	5	5
Slope	3	2	5	1	1	4	4
Aspect	3	3	2	3	3	5	5
Placement on slope	3	4	1	1	1	5	4
Fire barriers	4	3	4	1	1	3	3
High hazard objects	2	2	2	4	4	1	3
HVRA	2	4	4	5	5	2	2
Road capacity	5	2	3	1	1	1	1
Status of road	3	3	3	3	3	3	3
Population	4	3	3	2	2	2	3
Population density	3	2	2	2	3	2	2
Children	3	3	3	3	3	3	3
Elderly	4	4	4	4	4	4	4
Fire size	5	5	5	5	5	5	5
Distance to fire	4	4	3	3	4	4	4
Rescue service response time	2	2	2	2	2	4	3
Proximity to water	1	1	1	1	1	1	1
Water sources	4	4	4	4	4	4	4
Percentage of vulnerability	**69 %**	**66 %**	**66 %**	**62 %**	**63 %**	**70 %**	**69 %**

Table 57 shows the results for small urban areas with the operational mode. The table shows all factors included in the operational mode and their rating level in each small urban area. In the bottom there are the calculated percentages of vulnerability for each small urban area.

Table 57. Results operational mode small urban areas

Factor\Small Urban Area	**Hamra**	**Kårböle**	**Ramsjö**	**Tandsjöborg**
Temperature	5	5	5	5
Wind speed	2	2	2	2
Wind direction	3	5	3	3
Precipitation	5	5	5	5
Dry days	5	5	5	5
Relative humidity	4	4	4	4
Fuel load	5	5	5	5
Slope	1	1	1	5
Aspect	3	3	3	2
Placement on slope	1	1	1	5
Fire barriers	2	1	1	1
High hazard objects	1	1	1	3
HVRA	4	3	3	5
Road capacity	1	1	1	1
Status of road	3	4	3	3
Population	1	1	1	1
Population density	2	2	2	1
Children	3	3	3	3
Elderly	4	4	4	4
Fire size	5	5	5	5
Distance to fire	3	5	4	3
Rescue service response time	5	4	5	5
Proximity to water	1	1	1	1
Water sources	4	4	4	4
Percentage of vulnerability	**65 %**	**68 %**	**65 %**	**70 %**

Figure 13 displays the results for the operational mode on a map, using the colour scale. Lillhaga is the only community, which is not displayed in the figure, but the community is located directly to the west of Ljusdal and received the same colour as Ljusdal.

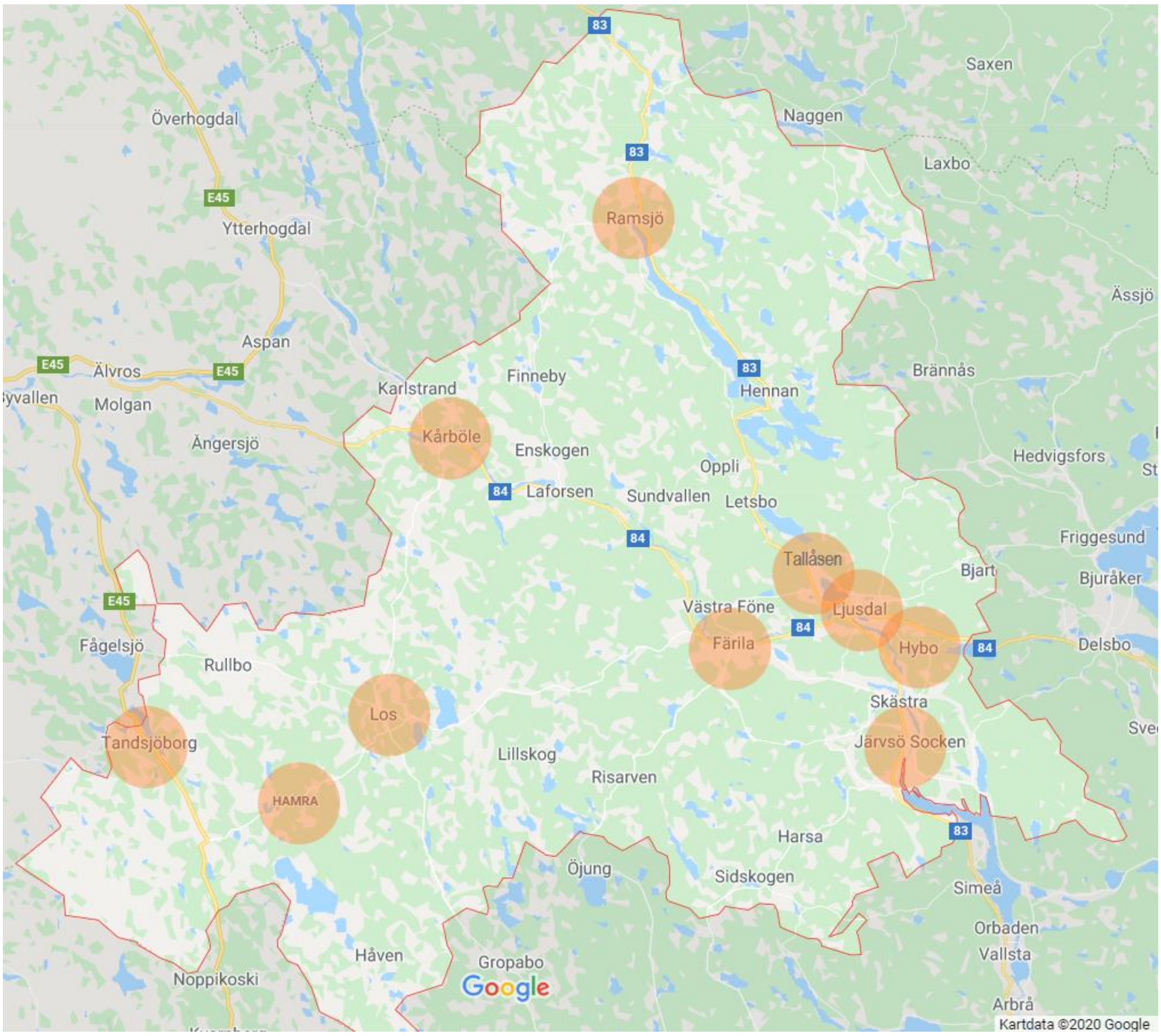

Figure 13. Results from the operational mode displayed on map

6 Discussion

The discussion is divided into three sections which cover the case study, the VAM, and the availability of data. It is again important to state that the results are based on assessments by the authors with their knowledge regarding the subject and available information. Therefore, these results should not be used for other analyses without further research.

6.1 Case study

Observations of the results from the case study show that, in general, the larger communities are more vulnerable in the municipality of Ljusdal. This is probably due to a higher number of inhabitants combined with a high weight variable for population. Other factors also come into play but the factors with high values vary depending on which community is observed.

In the preventive mode, it is seen that Tandsjöborg stands out compared to the other small urban areas. The reasons behind this are the factors Slope, Placement on slope, High hazard objects and HVRA. Kårböle received the lowest vulnerability percentage in the preventive mode and landed on 58 %, with Tallåsen highest at 69 %. In the operational mode, Hybo was at a low of 62 % and Tandsjöborg and Los at a maximum of 70 %.

It can be observed that Kårböle was the community that had the greatest difference between preventive and operational mode, with an increase of ten percentage points. The location of the fire used as reference in this example played a major role in this as it was situated closest to Kårböle. The increase could have been greater if more fire factors were included in the case study.

Looking at the individual factors, it can be observed in this example that the weather factors weigh heavily, and they are generally high, except for wind speed and wind direction in both modes. The low wind speed depends on the municipality's location in relation to the coast, as it lies inland. Factors that were low are Wildfire occurrence, Proximity to water, Population density and Road capacity and Population for all communities except Ljusdal. Finally, it can be observed that the Rescue service response time is higher for small towns than agglomerations.

The results show that individual factors can have a great impact on the outcome, and both the overall result and the individual factors should be considered. This can be used as a basis for, among other issues, community planning. For example, based on this exemplary case study, if Ljusdal municipality was to build a new fire station, it should be located in the western part of the municipality, perhaps in Los. The entire municipality is within level three and level four on the rating and, the vulnerability percentage lies between 55-70 %. The operational mode did not give the indications as expected, in the case study the fires were situated close to Kårböle, and even if the results increased by 10 % it only reached 68 % vulnerability. Due to this, more factors regarding the fire might be needed in the operational mode.

At this stage in the case study, the only "correlation" between factors that has been considered is the relation to community size or population. Also, this is only done for a few factors and not all. The fictitious assessment of the weight variables with the four aspects, the local conditions, possibility to impact, size of affected and rate of change was a simplification. The weight variables would most likely be different, if the assessments were based on facts and results from one or several sensitivity analyses. How this affected the results, and to what extent is hard to estimate without further research.

Instead of employing a grid over the entire municipality of Ljusdal, a simplification was made where 11 communities were selected to be included in the VAM. No additional communities outside these were considered. Each community was observed as a cell, which meant that the data collected for each community was valid for the entire community. Thus, variations of a certain factor within each community were not considered, and only a result that applied to the whole community was calculated. Certain factors could not be considered in more detail than for the entire municipality, in these cases, the data for the municipality was used for all communities.

For the rating levels and limit values, some were employed so that level three on the scale would correspond to the mean of the vulnerability. Others, whose limit values were based solely on subjective judgments, or that the limit values were taken straight from another system could show a different scale. In other words, level three might not correspond to the mean of vulnerability. This issue occurred for all factors since vulnerability is used to a limited extent and it is difficult for the authors to find systems, data and so on which is adapted to this type of VAM.

Improvements to the limit values can be made by basing the values on statistics, trends and studies that are site-specific, in this case for Sweden. Ideally, all boundaries should be able to have an argument that strengthens the boundary value and that all boundaries must be able to correspond to a certain amount of vulnerability. In this case study, all limit values are linear, which might not always be the case in reality.

Table 58 is used to, in the clearest way possible, present how each factor was considered compared with each factor´s desirable information.

Table 58. Presentation of actual consideration of factors in case study, and desirable

Name	**Actual consideration**	**Desirable information**
Temperature	Maximum temperature, either by trends or for a specific date and time	The actual temperature for modes that look at present data and daily maximum temperature either to create trends for modes or to look at historical data
Wind speed	Average wind speed.	Average wind speed with regard to wind gusts
Wind direction	Position of the fire in relation to the community compared to the wind direction	Position of the fire in relation to the community compared to the wind direction. Wind roses are also desirable to use to predict trends
Precipitation	Daily precipitation	Daily precipitation, actual precipitation at the moment or precipitation trends
Dry days	Number of consecutive days with a precipitation of less than 2 mm	Number of consecutive days with a precipitation of less than 2 mm
Relative humidity	Percent	Percent
Fuel load	Percent of area covered by forest fuel	Percent of area covered by forest fuel in combination with the fire load of the fuel
Slope	Average incline	Average incline
Aspect	Taken straight from WUI in B.C.	Taken straight from WUI in B.C.

Placement on slope	Percentage of community located on the slope	Position of community on slope combined with the percentage of the community located on the slope
Distance to fire	Kilometres	Kilometres
Fire barriers	Number/km^2	The number of fire barriers, their size and efficiency in relation to the other barriers
High hazard objects	Number/km^2	The number of high hazard objects, their size, the safety measures taken and the impact of the object in relation to the other objects
HVRA's	Number/km^2	Economical losses for different HVRA´s
Road capacity	People/lane and hour	Number of vehicles per hour that can obtain a specific road type without congestion
Status of road	Percentage of road open	Percentage of road open
Population	Number	Number
Population density	People/km^2	People/km^2
People with limited ability to self-evacuate	Percentage of children and elderly	People who have a permanent or temporary mental, physical or material limitation that will affect the ability to self-evacuate and their location
Fire size	m^2	m^2
Wildfire occurrence	Operations/km^2 and year	Operations/year for the specific area
Rescue service response time	Minutes	Minutes
Proximity to water	Minutes	Minutes
Water sources	Percentage	The capacity of water sources for, primarily, airborne resources and their usability

How a factor was considered in the case study is one of the simplifications that was required to be able to carry out the case study. Out of the selected factors for the VAM, several were excluded, mainly due to the authors inability to retrieve the required data. In addition, the equation changed when the correlation variable was excluded. The modifications made to enable the execution of the case study does not affect the results considerably according to the authors. As previously mentioned, the purpose of the case study was to test the method and the results should not be taken for facts. This should not be confused with the impact the modifications have on the method itself, which is negatively affected when the required data is excluded.

6.2 Vulnerability Assessment Method

The VAM includes six components, the included factors, the equation, the grid, rating levels, limit values and display of results. All components have deficiencies, for the constituent factors these are primarily how the factor is taken into account. Some factors may need to be replaced with other, similar factors that include richer information.

The equation is simple and gives an overview of the situation but can be developed further and include more variables which might improve the results. It could also be expanded to perform multiple vulnerability calculations, at least one calculation per cell in the grid, to give a more comprehensive result. Having a simple equation that does not require a lot of computer capacity, can be seen as an advantage as the calculations do not become as time consuming, but at the same time the need for information to perform the calculations will increase. This can be compared to systems today that use results from one module that acts as input to another module which requires more computer capacity. However, the equation takes this into account to some extent through the correlation variable. Which method that provides the best results cannot be determined without a deeper analysis.

In the future, it is desirable to be able to check the correlation and interaction between different cells in the grid as well as correlation between factors. To date, there is no clear way to consider the correlation between factors, and this issue should be examined further. Rating levels and limit values should reflect the vulnerability and should not simply use the average as level three but be based on facts, statistics, trends, and experiments. At this stage, will the weight variables most likely be determined for each specific case, but the goal in the future is to start from set weight variables which are altered depending on the local conditions. The four aspects which the authors display, are only an example, and should be evaluated and further developed.

The size of the grid could be varied based on what is found in the cell. For example, if it is a large area of homogeneous vegetation, that area may be included in the same cell. If the cell is placed in the middle of a community that has a lot of variation, the size of the cell should be smaller. However, the size should not be too small then you lose the variations in the whole and look too much at the details. Finally, it is important to look at the factors that have a distance or time from a specific starting point and decide how to take these into account. Average or worst possible outcomes are two approaches.

The result should be displayed in such a way that it is clear and easy to read. One idea is to use a map that contains the grid. Each cell in the grid is given a colour that reflects the result of that cell. If you click on a cell, it is desirable to get all the values of the individual factors with the corresponding colour to facilitate reading along with the final percentage of vulnerability for the cell. It is important to display both the individual factors and the results, not just in pictures since valuable information such as which factors presented a high vulnerability may be lost.

At the moment, the method is built for a societal perspective. It can be good to create a method that can work on a more individual perspective but can be combined with the societal perspective. For example, each cell has a value, then the value of the society is added up by the individual cells to be able to read the overview. The individual cells are added to see where the major vulnerabilities are in that society. Important to think about what is in adjacent cells and not just to look at the cell which is currently being observed. Mitigation should perhaps reduce vulnerability and not increase vulnerability as it does now.

The method is currently constructed with three different modes, where the preventive mode has several sub-modes. The idea behind this is to be able to make the method useful for the needs of several actors. The preventive mode´s main task is to map the vulnerable areas in different ways and then be able to implement measures based on the results. This mode is primarily aimed towards actors who may be working with land use planning. As previously mentioned regarding the municipality of Ljusdal, one could read that the rescue service response time for the small urban areas was considerably longer than in the urban areas. If you look at the map of the municipality you can observe that the existing part time stations were all located in the eastern parts of the municipality. This shows a good example of how to use the method in the preventive mode.

For the operational mode, the primary actor is intended to be the rescue service. Just as other systems in the world today provide a decision basis for operational situations, this method should also be able to provide the rescue service with such documentation. It is important to point out that this method is aimed at the vulnerability and not the hazard or risk that many existing systems do. This will probably give a different picture in some cases where the vulnerability is dependent on how susceptible the community or area is to the hazards and risks that are present.

Finally, there is the evaluative mode aimed at those actors who want to be able to evaluate a historical fire in order to draw conclusions from which measures worked and which did not. The desire with this mode is to be able to provide a basis for development mainly within the operational work. It may be observed that a decision taken in the context of a historical fire led to an unfavourable outcome and people can then use that information in the future if they are facing a similar situation and hopefully make another decision.

When the VAM was tested in the case study it could be seen that many factors can have a large impact on the result. This can for example, be the grid size, limit values and correlation or weight variables. To minimize this error, a sensitivity analysis can be useful in the future. There needs to be a balance between the number of factors used in the method and how detailed the factors are. To use too many factors would make the impact of every factor too small and the results misleading. The same applies for using too few factors, this would give each factor a very big impact on the vulnerability. If an area of interest is located within, adjacent or close to a specific topographical attribute, then the factor special land formations is of great importance to be able to include the variation which will occur. This could not be observed in the case study as the factor was excluded due to inability to retrieve the required data.

If this method is compared with systems that exist today, three main issues can be pointed out. The first is, as mentioned earlier, the choice of vulnerability rather than the hazard or risk which is often used in other systems. An attempt was made to integrate many parameters in addition to fire behaviour (that is generally the most prevalent aspect considered in existing systems).

Considering the system comparison that was made, factors which affected fire behaviour existed in almost all systems, while there were few systems that took into account factors within a category that did not affect fire behaviour, An example is the category population, where only one system considers population density and then it is empty in that category. The reason behind this, is likely due to the scope of the existing systems. Most of the systems we observed, were aimed towards fire behaviour and their primary user was the rescue service. The manner adopted to display the results in the present VAM, is used in other systems to some extent. There are systems that use maps and colour scales to display the results.

In summary, the results of the literature studies and the system evaluation were useful in the development of the VAM. The results of the case study did not meet the expectations. Determination of weight variables and limit values was more difficult than expected and had a large impact on the results, just like the exclusion of correlation variables. It is therefore difficult to draw any conclusions from the results in the case study. Nevertheless, this example can still be considered informative to display the challenges that may occur in applying such type of VAM. In addition, many valuable insights arose about the needed further developments of the method. These resulted in several suggestions for improvements for the VAM, as well as ideas for future research. However, it is important to take into consideration that the method is far from fully developed but can give a possible strategy for how this type of method can be developed.

6.3 Data required for desirable application of VAM

A large recurring issue in this thesis was the inability to retrieve required data regarding factors in Sweden. In what way the method is affected by the lack of required information is not determined to date. However, it is still possible to use the method, but it is important to reflect on what information the results are based on. Factors or parts that we consider necessary to be able to implement this method as it is constructed today, are many in number, these are presented according to each category.

Climate - All data for weather factors can be easily located for the current weather situation. However, it is desirable to find old weather data to see trends, or to check the weather at a certain point in history, which is quite difficult today. It is important to ensure that coverage is good, there should be at least one measurement value per municipality, more if the municipality is large to the surface.

Fuel – The presence of maps of vegetation types and specific plant species are desirable. It is important to be able to read if there are deciduous or coniferous forests in the area as they behave very differently in fire. Information regarding age, size, moisture content etc. of the fuels is also desirable.

Topography - Detailed topographic maps which display the variations of the land is necessary to provide good estimations of the topographic factors. This would make it possible to identify if there were any special land formations present in the area.

Fire characteristics - Information regarding historical fires in the wildland and WUI. Preferably reports which contain maps that display affected area and information regarding fire behaviour.

Structure - Maps over building specifications, such as type, functionality, materials, year of construction etc. for the different blocks within the community.

Community - Maps over the WUI areas in Sweden, as they are more exposed than the other parts of the community in the event of a fire in the wildland. More data regarding status of road, which disruptions are currently active, to what extent does this affect the road capacity and is the use of lane reversal applicable.

Population - More detailed data regarding population demographics, primarily for the vulnerable groups, which are people with limited ability to self-evacuate. This information should preferably be displayed on a map which illustrates locations of the community where these groups reside.

Mitigation - Information about rescue service and fire stations varies between different municipalities. It is desirable to be able to retrieve the same information regarding the rescue service response time and personnel resources, preferably displayed by maps. Data on which water sources that are available to the rescue services in the event of a fire in the wildland or WUI. Preferably displayed by a map which states the capacity of the water source.

7 Future research

More research is required to develop the various parts of the VAM to make it useful. Examples on subjects for future research are listed below.

- A review of the selected factors is needed to assess whether they provide an adequate overview of the vulnerability or if factors need to be included or excluded.
- A sensitivity analysis is required to assess the correlation between factors and their impact.
- The availability of the data, which is needed for the method must be inspected, and information that does not yet exist should be obtained.
- The impact of the grid size should be investigated.
- The equation should be reviewed to establish whether it provides adequate results.
- Rating levels and limit values should be reviewed so they correspond to the same level of vulnerability for all factors.
- Development of all modes is needed in order to be able to implement them.
- The desirably way to display the results needs to be developed.
- More case studies to test the VAM should be performed.

8 Conclusions

The systems identified in the review look at a sub-set of aspects which affect wildfires and WUI fires and therefore they could be expanded to allow a holistic approach. The majority of the systems consider similar factors, foremost in the categories of climate, fuel, topography and fire characteristics. The factors in the remaining categories are considered to a very limited extent. The scope of the systems were almost exclusively risk or danger, and no system looked at vulnerability. Therefore, it is observed that there is a need for a method similar to the one which was developed in this thesis which uses a vulnerability approach. There is no clear definition for how vulnerability should be measured and assessed, which causes difficulties in the development of the VAM.

A case study was performed to test the VAM, but due to inability to retrieve information only parts of the method was tested. In the equation, which was used for the case study, there is room for improvements to enable a higher consistency in the assessments. The calculations are connected to the limit values which are determined and should be reviewed.

An advantage that is observed with this type of method is in which aspects it can be applied as the authors have examined different modes, preventive, operational and evaluative. This makes the method useful for several actors, such as land use planners and rescue service personnel.

At this stage, the method used in the case study would need to be carefully reviewed to perform an adequate assessment of a given area. This is mainly due to the simplifications which were required to be able to apply the method in the case study, when necessary data was not retrieved. When the VAM was tested in the case study it could be seen that many factors can have a large impact on the result. This could for example be the grid size, limit values and correlation or weight variables. To minimize this error a sensitivity analysis could be useful in the future.

9 References

Blomqvist, J., Cesar, F., & Lejonklou, L. (2012). *Lagkrav på insatstider för räddningstjänst i Skandinavien*. http://lejonklou.se/lina/reports/lina_lejonklou_legal_requirements_for_response_time.pdf

Blumberg, S. (2019, July 9). *A Drier Future Sets the Stage for More Wildfires* [Text]. NASA. http://www.nasa.gov/feature/goddard/2019/a-drier-future-sets-the-stage-for-more-wildfires

Boverkets byggregler (2011:6)—Föreskrifter och allmänna råd, (2011). https://www.boverket.se/sv/lag--ratt/forfattningssamling/gallande/bbr---bfs-20116

Brandskyddsföreningen. (2018). *Inför tillfälligt försäljningsstopp av engångsgrillar under eldningsförbudet!* https://www.brandskyddsforeningen.se/om-oss/pressrum/pressmeddelanden2/infor-tillfalligt-forsaljningsstopp-av-engangsgrillar-under-eldningsforbudet/

Cambridge. (2020, April 7). *HOLISTIC | meaning in the Cambridge English Dictionary*. https://dictionary.cambridge.org/dictionary/english/holistic

Canada, N. R. (2019, May 14). *Canadian Wildland Fire Information System*. http://cwfis.cfs.nrcan.gc.ca/home

Canada, N. R. (2020a, January 16). *Canadian Forest Fire Danger Rating System*. https://www.nrcan.gc.ca/our-natural-resources/forests-forestry/wildland-fires-insects-disturban/forest-fire-danger-rating-tool/14470

Canada, N. R. (2020b, January 20). *Canadian Wildland Fire Information System | Weather Maps*. https://cwfis.cfs.nrcan.gc.ca/maps/wx

Canada, N. R. (2020c, February 4). *Canadian Wildland Fire Information System | Canadian Forest Fire Weather Index (FWI) System*. https://cwfis.cfs.nrcan.gc.ca/background/summary/fwi

Chen, F., Niu, S., Tong, X., Zhao, J., Sun, Y., & He, T. (2014). The Impact of Precipitation Regimes on Forest Fires in Yunnan Province, Southwest China. *The Scientific World Journal*, *2014*, 9.

Colorado state Forest Service. (2020, February 17). *CO-WRAP Home*. https://www.coloradowildfirerisk.com/

Cova, T., Drews, F., Siebeneck, L., & Musters, A. (2009). Protective Actions in Wildfires: Evacuate or Shelter-in-Place? *Natural Hazards Review*, *10*, 151–162. https://doi.org/10.1061/(ASCE)1527-6988(2009)10:4(151)

Dictionary of Military and Associated Terms. (2019, December 12). *Road Capacity*. https://www.thefreedictionary.com/road+capacity

Edgell, M. C. r. (2015). *Biogeoclimatic Zone | The Canadian Encyclopedia*. https://www.thecanadianencyclopedia.ca/en/article/biogeoclimatic-zone

Eirefelt, M. (2018, July 16). Vattenbrist för räddningstjänsten. *SVT Nyheter*. https://www.svt.se/nyheter/lokalt/gavleborg/vattenbrist-till-skogsbranderna

Eriksen, C., & Prior, T. (2011). *The art of learning: Wildfire, amenity migration and local environmental knowledge*. https://www.academia.edu/3633030/The_art_of_learning_wildfire_amenity_migration_and_local_environmental_knowledge

Eriksson, A., Frisk, A., Hansson, L., & Nilsson, L. (2018). *Förslag till åtgärder för att kompensera drabbade i skogsbruket för skador med anledning av skogsbränderna sommaren 2018*. https://www.skogsstyrelsen.se/globalassets/om-oss/publikationer/2018/rapport-2018-15-forslag-till-stod-efter-skogsbranderna-sommaren-2018.pdf

Eriksson/TT, A. K. (2019, April 23). *Branden begränsad men inte under kontroll*. Kristianstadsbladet. http://www.kristianstadsbladet.se/nyheter/forsvarsmakten-vattenbombar-skogsbrand/

Fire Safety Advice Centre. (2011, March 28). *Fire Risk Assessment Overview: Firesafe.org.uk*. https://www.firesafe.org.uk/fire-risk-assessment/

Friberg, M., & Hjelm, M. (2014). *Mass evacuation—Human behavior and crowd dynamics* (p. 71). http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=7766859&fileOId=7766990

Fridholm, M. (2019, November 12). *Moisture content*. Swedish Wood. https://www.swedishwood.com/about_wood/choosing-wood/wood-and-moisture/

Frontline. (2018, January 9). Wildfires and the Elderly: Protecting the Most Vulnerable. *Frontline*. https://www.frontlinewildfire.com/wildfires-elderly-protecting-vulnerable/

Gävleborg, P. (2018, August 23). Uppdateringar om bränderna i Ljusdals kommun. *Sveriges Radio*. https://sverigesradio.se/sida/artikel.aspx?programid=99&artikel=7000514

Gävleborgs län. (2020, February 4). *Hälsingegårdar—Halsingegardar.se*. https://www.regiongavleborg.se/halsingegardar/

Google. (2020, January 23). *Google Maps*. Google Maps. https://www.google.se/maps/place/Ljusdal/@61.8294925,16.0565492,13z/data=!3m1!4b1!4m5!3m4!1s0x46642a62584361f7:0xd31e946fde1cc23f!8m2!3d61.8308392!4d16.0817501

Government of British Columbia. (2019, December 9). *BEC WEB*. https://www.for.gov.bc.ca/hre/becweb/index.html

Government of Scotland. (2013, October 21). *Fire and Rescue Service Wildfire Operational Guidance—Gov.scot*. https://www.gov.scot/publications/fire-rescue-service-wildfire-operational-guidance/

Gustavsson, K. (2014). *Skogsbranden i Västmanland 2014*. https://www.lansstyrelsen.se/download/18.2887c5dd16488fe880d46367/1536585741018/Dokumentation-Skogsbranden-2014.pdf

Hälsingland. (2012, July 2). Hälsingegårdar – Karta över de 7 Världsarvsgårdarna. *halsingebloggen*. https://halsingebloggen.wordpress.com/halsingegardar-karta-over-de-7-varldsarvsgardarna/

Hälsingland. (2020, January 21). Upplevelser i Hälsingland. *Hälsingland*. https://halsingland.se/se_gora/

Hansen, R., Sverige, & Statens räddningsverk. (2003). *Skogsbrandsläckning*. Räddningsverket.

Holden, Z. A., Swanson, A., Luce, C. H., Jolly, W. M., Maneta, M., Oyler, J. W., Warren, D. A., Parsons, R., & Affleck, D. (2018). Decreasing fire season precipitation increased recent western US forest wildfire activity. *Proceedings of the National Academy of Sciences*, *115*(36), E8349–E8357. https://doi.org/10.1073/pnas.1802316115

Jiménez, F. (2018). Chapter 1—Introduction. In F. Jiménez (Ed.), *Intelligent Vehicles* (pp. 1–20). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-812800-8.00001-1

Jin, T. (2016). *Studies on Human Behavior and Tenability in Fire Smoke*. 20.

Johnston, K., Morrow, B., & Davies, J. (2013). *Wildland Urban Interface Wildfire Threat Assessments in B.C.*

Jolly, M., & Bradshaw, L. (2018, April 11). *National Fire Danger Rating System | Fire, Fuel, and Smoke Science Program*. https://www.firelab.org/project/national-fire-danger-rating-system

Justitiedepartementet. (2019). *Skogsbränderna sommaren 2018. SOU 2019: Betänkande från 2018 års skogsbrandsutredning*. Norstedts Juridik AB.

Karlsson, B., & Quintiere, J. (1999). *Enclosure Fire Dynamics* (Vol. 1999). CRC PRESS.

Karlsson, L. (2018, October 17). *Lomma har tredje minst andel skog i landet*.

Kelly, H., Wilson, closeHeather K. reporterEmailEmailBioBioFollowFollowScott, California, closeScott W. national correspondent focusing on, & Lanzendorfer, the W. (2019, October 29). *As fires rage, California refines an important skill: Evacuating*. Washington Post. https://www.washingtonpost.com/nation/2019/10/28/fires-rage-california-refines-an-important-skill-evacuating/

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Laranjeira, J., & Cruz, H. (2014). *Building vulnerabilities to fires at the wildland urban interface* (pp. 673–684). https://doi.org/10.14195/978-989-26-0884-6_76

Larsson, R. (2020, January 23). *Robert Larsson, Göteborg*. https://rl.se/

Lexico. (2019a, November 12). *Relative Humidity | Definition of Relative Humidity by Lexico*. Lexico Dictionaries | English. https://www.lexico.com/en/definition/relative_humidity

Lexico. (2019b, November 12). *Temperature | Definition of Temperature by Lexico*. Lexico Dictionaries | English. https://www.lexico.com/en/definition/temperature

Lexico. (2019c, November 12). *Wind Speed | Definition of Wind Speed by Lexico*. Lexico Dictionaries | English. https://www.lexico.com/en/definition/wind_speed

Lexico. (2019d, December 12). *Elevation | Definition of Elevation by Lexico*. https://www.lexico.com/en/definition/elevation

Lexico. (2019e, December 12). *Traffic Sign | Definition of Traffic Sign by Lexico*. https://www.lexico.com/en/definition/traffic_sign

Ljusdals Kommun. (2010a). *Översiktsplan för Ljusdals kommun*. https://www.ljusdal.se/download/18.7b4b850a15065e32c0fbd82/1444983764935/1%20%C3%96versiktsplan.pdf

Ljusdals Kommun. (2010b). *Översiktsplan Ljusdals Kommun—Riksintressen*. https://ljusdal.se/download/18.7b4b850a15065e32c0fbd88/1444983809036/4%20Karta%20Riksintressen.pdf

Ljusdals Kommun. (2016). *Handlingsprogram för skydd mot olyckor*. https://www.ljusdal.se/download/18.2c212165157062b6c6c6f3/1473333653818/Handlingsprogram%20skydd%20mot%20olyckor%202015-2018%20f%C3%B6r%20publicering.pdf

Ljusdals Kommun. (2020a, January 21). *Natur—Ljusdals kommun* [Text]. https://www.ljusdal.se/upplevagora/natur.4.6bb44e7614c906281006ac31.html

Ljusdals Kommun. (2020b, January 23). *Fakta om bränderna—Ljusdals kommun* [Text]. https://www.ljusdal.se/samhallegator/krisochsakerhet/informationombranderna2018/faktaombranderna.4.12be7f0e165140d0d1895a64.html

M. Hausknecht, T. Au, P. Stone, D. Fajardo, & T. Waller. (2011). Dynamic lane reversal in traffic management. *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 1929–1934. https://doi.org/10.1109/ITSC.2011.6082932

Mannberg, K. (2019, May 23). Efter skogsbränderna – så ska brandmännen kommunicera. *SVT Nyheter*. https://www.svt.se/nyheter/lokalt/varmland/efter-skogsbranderna-msb-storsatsar-pa-battre-kommunikation

Materese, R. (2017, July 5). *Reducing Impact of Wildland-Urban Interface Fires* [Text]. NIST. https://www.nist.gov/industry-impacts/reducing-impact-wildland-urban-interface-fires

Mell, W. E., Manzello, S. L., Maranghides, A., Butry, D., & Rehm, R. G. (2010). The wildland-urban interface fire problem—Current approaches and research needs. *International Journal of Wildland Fire*. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=902804

Meteoblue. (2019, November 12). *Wind*. meteoblue. https://content.meteoblue.com/hu/specifications/weather-variables/wind

Meteorology, corporateName=Bureau of. (2020, February 17). *Australian weather and warnings information*. http://www.bom.gov.au/nsw/forecasts/fire-map.shtml

Metropolitan Council. (2019). *Density of Development*. https://metrocouncil.org/Transportation/Planning-2/Transit-Plans,-Studies-Reports/Other-Studies-Reports/Land-Use-Illustrations/Density-of-Development-Examples.aspx

Migiro, G. (2018, August 20). *What Is a Fire Tornado? - WorldAtlas.com*. https://www.worldatlas.com/articles/what-is-a-fire-tornado.html

Morrow, B., Johnston, K., & Davies, J. (2017). *2017 Wildfire Threat Assessment Guide*. /resources/library/forest-fuel-management/2017-wildfire-threat-assessment-guide

MSB. (2018). *MSB:s arbete med skogsbränderna 2018: Tillsammans kunde vi hantera en extrem skogsbrandssäsong*.

MSB. (2019a). *Så stärkte MSB skogsbrandsberedskapen till sommaren 2019*. https://www.msb.se/sv/aktuellt/pagaende-handelser-och-insatser/skogsbrandssasongen-2019/sa-starker-msb-skogsbrandsberedskapen-till-sommaren-2019/

MSB. (2019b). *Faktablad- Skogsbrandsdepå*. https://www.msb.se/siteassets/dokument/amnesomraden/msbs-arbete-vid-olyckor-kriser-och-krig/forstarkningsresurser/faktablad-skogsbrandsdepa.pdf

MSB. (2019c, December 12). *VMA*. https://www.msb.se/sv/amnesomraden/krisberedskap--civilt-forsvar/befolkningsskydd/varningssystem/vma/

MSB. (2020a). *Brandrisk Skog och Mark- fakta och modeller*. https://www.msb.se/ExternData/SMHI/brand_fakta.pdf

MSB. (2020b, January 23). *IDA - Bränder i skog eller mark*. https://ida.msb.se/ida2#page=f5943eeb-e86c-4342-af56-f2de8c55883d

MSB. (2020c, February 4). *Rakel*. https://www.msb.se/sv/verktyg--tjanster/rakel/

National History Museum of Utah. (2019). *All About Wildfires*. https://nhmu.utah.edu/sites/default/files/attachments/All%20About%20Wildfires.pdf

National Wildfire Coordinating Group. (2019a, December 12). *NWCG Glossary of Wildland Fire, PMS 205 | NWCG*. https://www.nwcg.gov/glossary/a-z

National Wildfire Coordinating Group. (2019b, December 16). *How to Become a Wildland Firefighter | NWCG*. https://www.nwcg.gov/how-to-become-a-wildland-firefighter

Olofsson, B. (2012). *Skogs- och gräsbrand utifrån ett förändrat klimat*. https://www.lansstyrelsen.se/download/18.4e0415ee166afb5932411ca5/1541761688080/Skogs-och-grasbrand-utifran-ett-forandrat-klimat.pdf

OpenStreetMap. (2020, January 23). *Ljusdals kommun topographic map, relief, elevation*. Topographic-Map.Com. https://en-gb.topographic-map.com/maps/e35t/Ljusdals-kommun/

Osborne, S. (2018, November 14). *California wildfires: Fears radioactive waste could be caught in destructive blaze | The Independent*.

https://www.independent.co.uk/news/world/americas/california-wildfires-radioactive-nuclear-toxic-waste-woolsey-santa-susana-field-laboratory-a8633711.html

Östman, B. A.-L. (1988). *Comparison of Smoke Release Rate from Building Products*. https://ri.diva-portal.org/smash/get/diva2:1080254/FULLTEXT01.pdf

Paton, D., Buergelt, P. T., Tedim, F., & McCaffrey, S. (2015). Chapter 1—Wildfires: International Perspectives on Their Social—Ecological Implications. In J. F. Shroder & D. Paton (Eds.), *Wildfire Hazards, Risks and Disasters* (pp. 1–14). Elsevier. https://doi.org/10.1016/B978-0-12-410434-1.00001-4

Pixabay. (2013, October 14). *Free Image on Pixabay—Wind Rose, Compass Rose*. https://pixabay.com/vectors/wind-rose-compass-rose-cartography-151855/

Plucinski, M. P. (2012). *A review of wildfire occurrence research*. http://www.bushfirecrc.com/sites/default/files/managed/resource/attachment_g_fire_occurrence_literature_review_0.pdf

Randall, C. K. (2001). *Fire in the Wildland-Urban Interface: Understanding fire behavior*. https://www.srs.fs.usda.gov/factsheet/pdf/fire-understanding.pdf

Ready. (2019, December 16). *Exercises | Ready.gov*. https://www.ready.gov/business/testing/exercises

Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., & Elliott, C. T. (2016). Critical Review of Health Impacts of Wildfire Smoke Exposure. *Environmental Health Perspectives*, *124*(9), 1334–1343. https://doi.org/10.1289/ehp.1409277

Ronchi, E., Gwynne, S., Rein, G., Wadhwani, R., Intini, P., & Bergstedt, A. (2017). *e-Sanctuary: Open Multi-Physics Framework for Modelling Wildfire Urban Evacuation*.

Rubens, T. (2016, June 28). Vertical Cities: How to Safely Evacuate Tall Buildings. *IFSEC Global | Security and Fire News and Resources*. https://www.ifsecglobal.com/global/vertical-cities-how-to-safely-evacuate-from-tall-buildings/

Sätterlund, M. (2012). *Förstudie Adaptiva trafiksignaler*. http://its-sweden.se/wp-content/uploads/2012/07/forstudie_adaptiva_trafiksignaler_120320_v1.pdf

Schroeder, J., & Wennerlund, L. (2016). *Wildland urban interface in Sweden*. 28.

Scott, J. H., Thompson, M. P., & Calkin, D. E. (2013). *A wildfire risk assessment framework for land and resource management* (RMRS-GTR-315; p. RMRS-GTR-315). U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-315

Sinclair, S. (2018, July 28). Forskare: "Bränderna ett nytt problem för Sverige". *Svenska Dagbladet*. https://www.svd.se/pengar-vantas-stromma-till-forskning-om-skogsbrander

Skogsstyrelsen. (2019, February 12). *Skogsstyrelsen—Skogsbranden i Västmanland 2014*. https://www.skogsstyrelsen.se/mer-om-skog/skogsbranden-i-vastmanland-2014/

SkogsSverige. (2019, December 16). *Fakta om skog*. SkogsSverige. https://www.skogssverige.se/skog/fakta-om-skog

SMHI. (2012, November 22). *Skalor för vindhastighet | SMHI*. https://www.smhi.se/kunskapsbanken/meteorologi/skalor-for-vindhastighet-1.252

SMHI. (2018, August 29). *Sommaren 2018—Extremt varm och solig | SMHI*. https://www.smhi.se/klimat/klimatet-da-och-nu/arets-vader/sommaren-2018-extremt-varm-och-solig-1.138134

SMHI. (2019, November 12). *Nederbörd | SMHI*. https://www.smhi.se/kunskapsbanken/meteorologi/nederbord-1.361

Sönnert, P. (2018, July 18). Trängsletbranden sprider sig och VMA har utfärdats – boende uppmanas att lämna området. *dt.se*. https://www.dt.se/artikel/trangsletbranden-sprider-sig-och-vma-har-utfardats-boende-uppmanas-att-lamna-omradet

Statens haverikommission, Eksborg, A.-L., Sigfridsson, S.-E., Mansfeld, J., Elinder, H., & Widlundh, P. (2001). *Brand på Herkulesgatan i Göteborg, 0 län, den 29-30 oktober 1998*. https://www.havkom.se/assets/reports/Swedish/367137144_ro2001_02.pdf

Statistiska Central Byrån. (2019). *Statistiska tätorter 2018*. https://www.scb.se/contentassets/745b357fd3b74ffd934fc4004ce5cf62/mi0810_2018a01_sm_mi38sm1901.pdf

Statistiska Central Byrån. (2020a, January 21). *Folkmängd efter region, ålder och år*. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE__BE0101__BE0101A/BefolkningNy/table/tableViewLayout1/

Statistiska Central Byrån. (2020b, January 21). *Folkmängd efter region och år*. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE__BE0101__BE0101A/BefolkningNy/table/tableViewLayout1/

Statistiska Central Byrån. (2020c, January 23). *Kommuner i siffror*. Sverige i siffror. http://www.scb.se/hitta-statistik/sverige-i-siffror/kommuner-i-siffror/

Statistiska Central Byrån. (2020d, February 23). *Folkmängd och landareal i tätorter, per tätort. Vart femte år 1960—2018*. Statistikdatabasen. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0810__MI0810A/LandarealTatortN/

Statistiska Central Byrån. (2020e, February 23). *Landareal per småort (orter med 50-199 invånare), folkmängd och invånare per kvadratkilometer. (Uppdateras ej) Vart femte år 1995—2010*. Statistikdatabasen. http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0811/LandarealSmaort/

Stein, S. M., Comas, S. J., Menakis, J. P., Carr, M. A., Stewart, S. I., Cleveland, H., Bramwell, L., & Radeloff, V. C. (2013). *Wildfire, Wildlands, and People: Understanding and Preparing for Wildfire in the Wildland-Urban Interface*. https://www.fs.fed.us/openspace/fote/reports/GTR-299.pdf

Stewart, S. I., Wilmer, B., Hammer, R. B., Aplet, G. H., Hawbaker, T. J., Miller, C., & Radeloff, V. C. (2009). Wildland-urban interface maps vary with purpose and context. *Journal of Forestry*, 6.

Stocks, B. J., Mason, J. A., Todd, J. B., Bosch, E. M., Wotton, B. M., Amiro, B. D., Flannigan, M. D., Hirsch, K. G., Logan, K. A., Martell, D. L., & Skinner, W. R. (2002). *Large forest fires in Canada, 1959-1997*. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2001JD000484%4010.1002/%28ISSN%292169-8996.FFIRE2

Stone, S. L., Anderko, L., Berger, M., Butler, C. R., Cascio, W. E., Clune, A., Damon, S., Garbe, P., Hauptman, M., Haskell, W. E., Hoshiko, S., Lahm, P., Materna, B., Mirabelli, M. C., O´Neill, S., Peterson, J., Riveles, K., Sacks, J., Wayland, M., & Williams, J. R. (2019). *WILDFIRE SMOKE: A GUIDE FOR PUBLIC HEALTH OFFICIALS*. *2019*, 88.

Sur, U., & Sokhi, B. S. (2006). *GIS in city fire hazard: Petrol station vicinity vulnerability assessment*. *20*, 50–51.

Sverige, & MSB. (2016). *MSB:s förstärkningsresurser: Ett stöd när regionens egna resurser inte räcker till.* Myndigheten för samhällsskydd och beredskap (MSB).

The Bushfire Foundation. (2019, December 9). *FIRE BEHAVIOUR – The Bushfire Foundation Inc*. https://www.thebushfirefoundation.org/how-fire-behaves/

Thompson, K. D. (2011, September 27). *Wildland-Urban Interface Fire Group*. NIST. https://www.nist.gov/el/fire-research-division-73300/wildland-urban-interface-fire-73305

Tinghai Ou. (2017). *Droughts and wildfires in Sweden* (No. 978-91-7383-757–6). MSB, Göteborgs Universitet. https://www.msb.se/RibData/Filer/pdf/28280.pdf

Trafikverket. (2018). *Bygg om eller bygg nytt—Kapitel 4 Tillgänglighet*. https://www.trafikverket.se/contentassets/0ebc841761f74f56b31c6eba59511bca/bygg-om/kapitel_4_tillganglighet.pdf

United Nations Office for Disaster Risk Reduction. (2017a, February 2). *Terminology: Hazard | PreventionWeb.net*. https://www.preventionweb.net/terminology/view/488

United Nations Office for Disaster Risk Reduction. (2017b, February 2). *Terminology: Vulnerability | PreventionWeb.net*. https://www.preventionweb.net/terminology/view/508

United Nations Office for Disaster Risk Reduction. (2020). *Wildfire prevention in Australia*. https://www.unisdr.org/2000/campaign/PDF/Articulo_6_Australia_eng.pdf

USDA Forest Service. (2019, November 12). *Fire Terminology*. https://www.fs.fed.us/nwacfire/home/terminology.html

USDA Forest Service. (2020, February 17). *FIREHARM | Fire, Fuel, and Smoke Science Program*. https://www.firelab.org/project/fireharm

USDA Forest Service, Bureau of Indian Affairs, Bureau of Land Management, Fish and Wildlife Service, & USDI National Park Service. (2001). *Urban Wildland Interface Communities Within the Vicinity of Federal Lands That Are at High Risk From Wildfire*. https://www.federalregister.gov/documents/2001/01/04/01-52/urban-wildland-interface-communities-within-the-vicinity-of-federal-lands-that-are-at-high-risk-from

Von Walden, R. (2020, January 23). *Fil:Skogsbrand i Kårböle-området.jpg – Wikipedia*. https://commons.wikimedia.org/wiki/File:Skogsbrand_i_K%C3%A5rb%C3%B6le-omr%C3%A5det.jpg

White, C. (2015). *National Hazard and Risk Model (No-HARM) Wildfire*. https://www.intermap.com/hubfs/pdf/InsitePro-Perils/AnchorPoint_-_White_Paper_-_No_HARM_2015.pdf

Wooten Twist, G. (2019). *Fire and fuels management: Definitions, ambiguous terminology and references*. https://www.nps.gov/olym/learn/management/upload/fire-wildfire-definitions-2.pdf

Wu, Z., He, H., Fang, L., Liang, Y., & Parsons, R. (2018). Wind speed and relative humidity influence spatial patterns of burn severity in boreal forests of northeastern China. *Annals of Forest Science*, *75*. https://doi.org/10.1007/s13595-018-0749-z

Wyloge, E. (2019, April 25). California wildfire evacuation analysis after Camp Fire. *Desertsun*. https://www.desertsun.com/story/news/environment/2019/04/25/california-wildfire-evacuation-road-capacity-traffic-analysis-methodology-camp-fire/3514552002/

Yang, W., Gardelin, M., Olsson, J., & Bosshard, T. (2015). Multi-variable bias correction: Application of forest fire risk in present and future climate in Sweden. *Natural Hazards and Earth System Sciences*, *15*(9), 2037–2057. https://doi.org/10.5194/nhess-15-2037-2015

Appendices

This chapter includes all appendices related to the thesis.

Appendix 1. Topographic maps

This appendix includes all topographic maps used to estimate slope and placement on slope in the case study. The topographic maps are all retrieved from the same source (OpenStreetMap, 2020). Each map displays a selected community with a colour scale on the right that describes the elevation, specified in ft.

Figure 14 displays the topographic map of Ljusdal.
Figure 15 displays the topographic map of Färila.
Figure 16 displays the topographis map of Järvsö.
Figure 17 displays the topographis map of Los.
Figure 18 displays the topographic map of Hybo.
Figure 19 displays the topographic map of Tallåsen.
Figure 20 displays the topographic map of Ramsjö.
Figure 21 displays the topographic map of Kårböle.
Figure 22 displays the topographic map of Tandsjöborg.
Figure 23 displays the topographic map of Hamra.

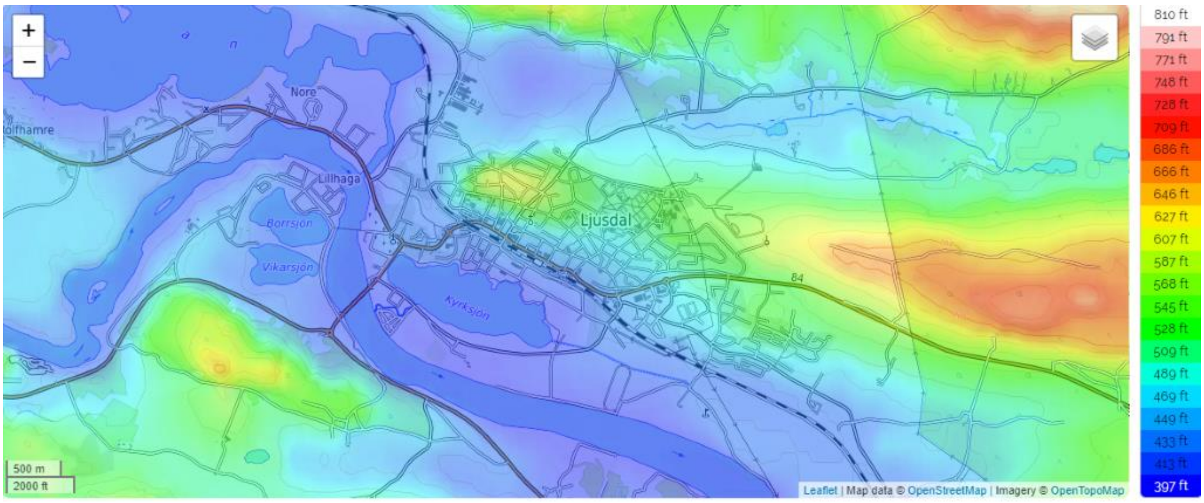

Figure 14. Topographic map of Ljusdal, retrieved from (OpenStreetMap, 2020)

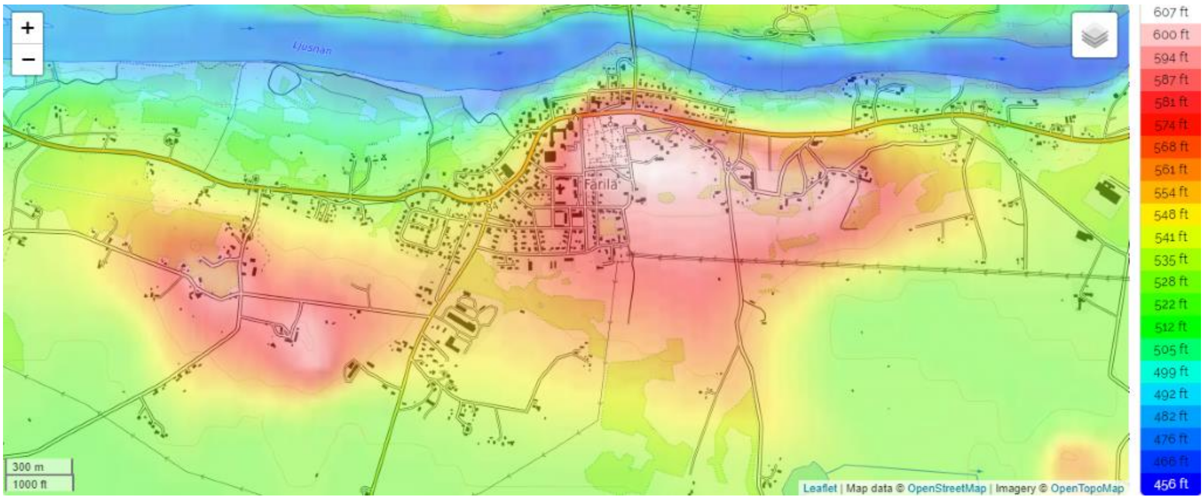

Figure 15. Topographic map of Färila, retrieved from (OpenStreetMap, 2020)

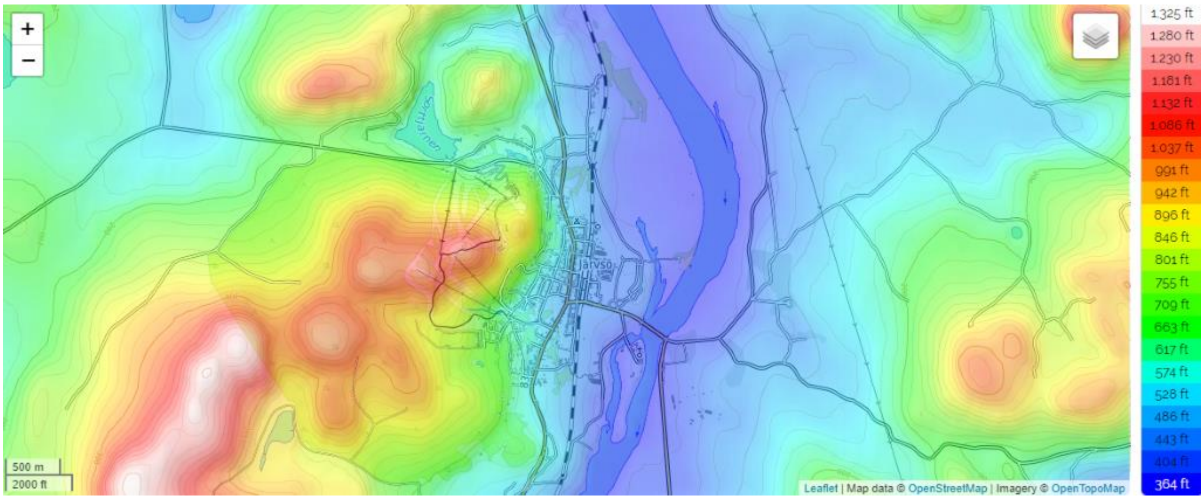

Figure 16. Topographic map of Järvsö, retrieved from (OpenStreetMap, 2020)

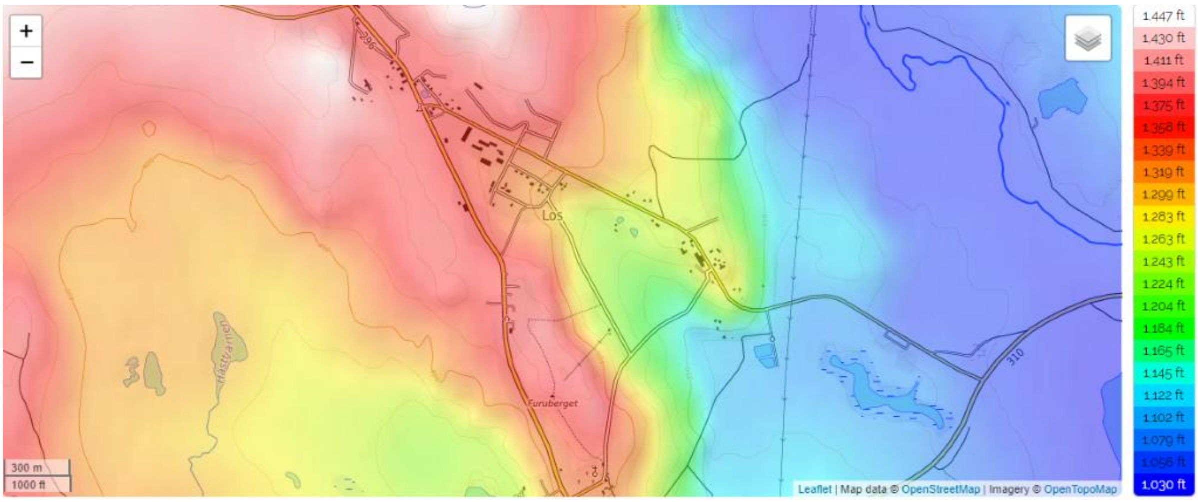

Figure 17. Topographic map of Los, retrieved from (OpenStreetMap, 2020)

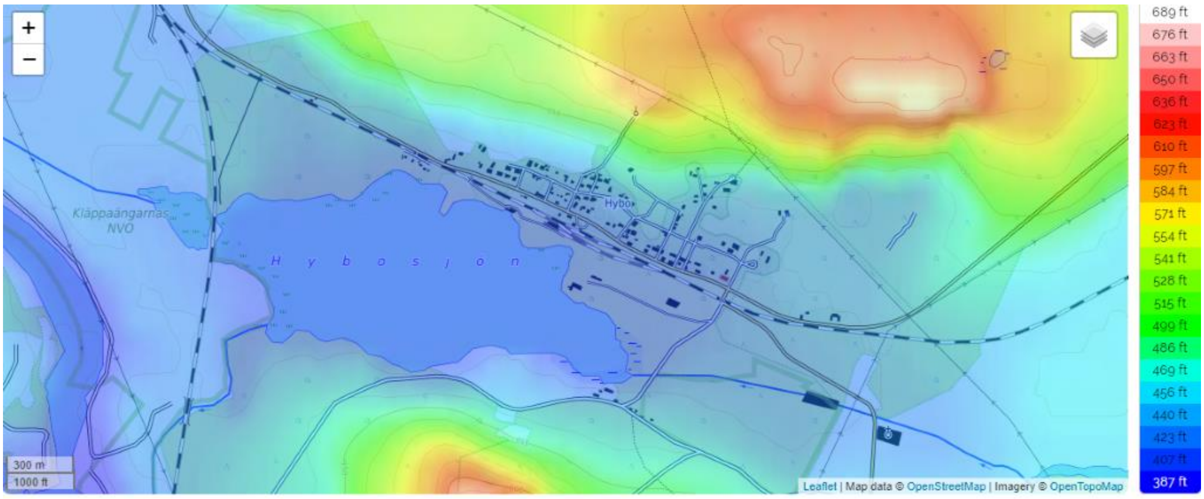

Figure 18. Topographic map of Hybo, retrieved from (OpenStreetMap, 2020)

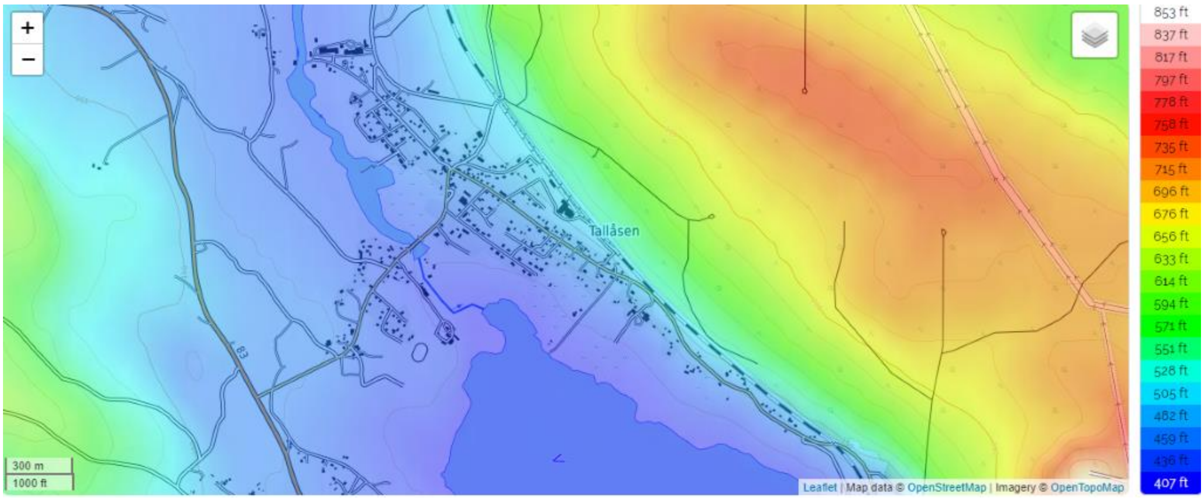

Figure 19. Topographic map of Tallåsen, retrieved from (OpenStreetMap, 2020)

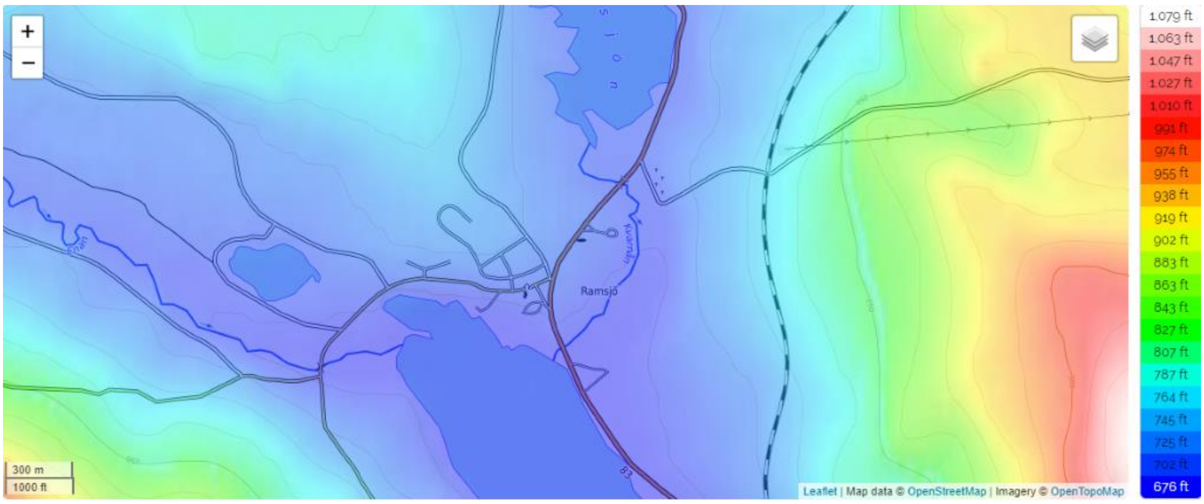

Figure 20. Topographic map of Ramsjö, retrieved from (OpenStreetMap, 2020)

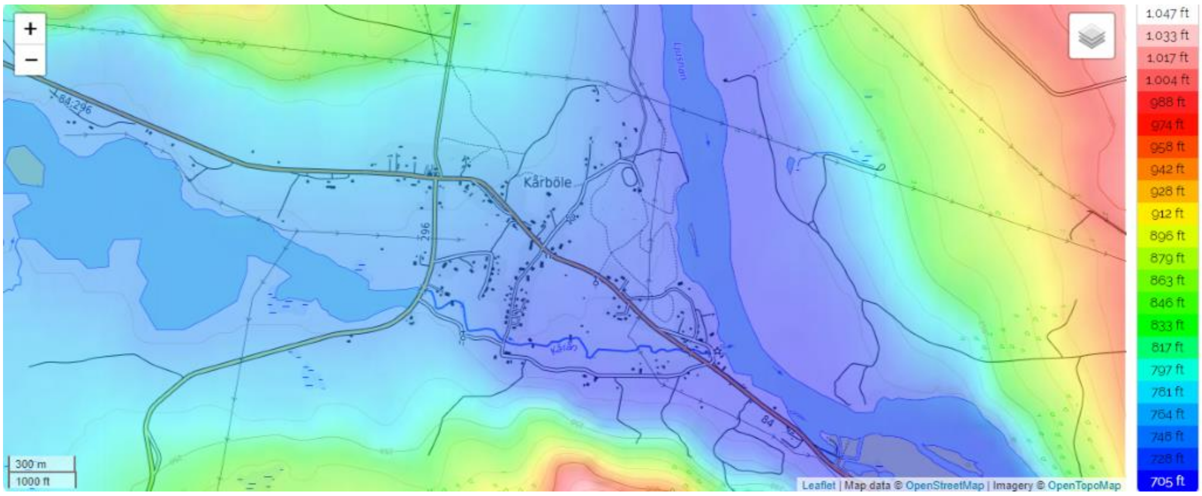

Figure 21. Topographic map of Kårböle, retrieved from (OpenStreetMap, 2020)

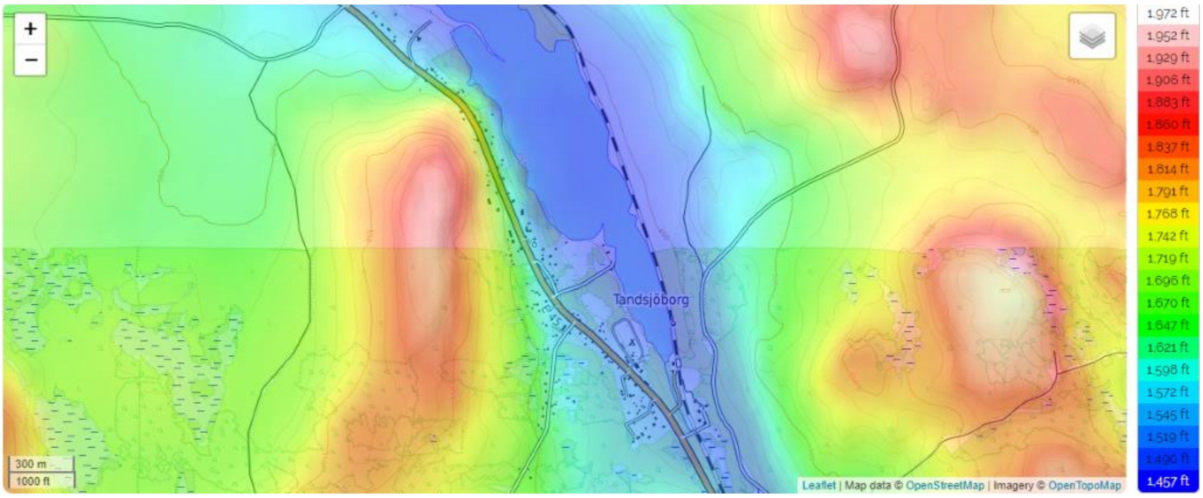

Figure 22. Topographic map of Tandsjöborg, retrieved from (OpenStreetMap, 2020)

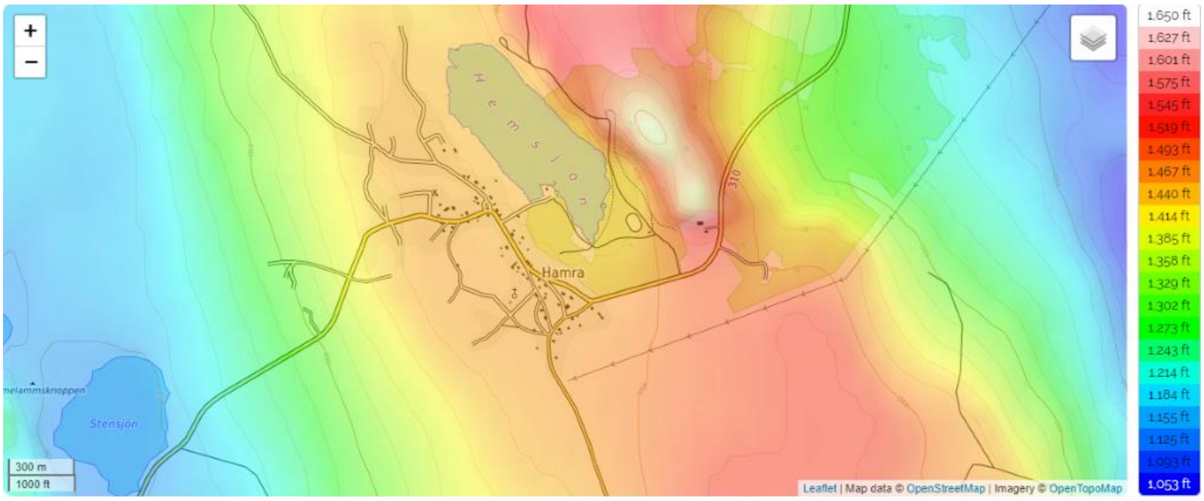

Figure 23. Topographic map of Hamra, retrieved from (OpenStreetMap, 2020)

Appendix 2. Comparison of systems

This appendix includes the comparison between each system´s input factors and the complete list of identified factors, presented in Table 59.

Table 59. Comparison of factors included in systems

Factor	**WUI in BC**	**No HARM**	**CWFIS**	**NFDRS**	**FFDI**
Relative humidity		X	X	X	X
Dry days					
Precipitation		X	X	X	X
Wind speed		X	X	X	X
Wind direction		X	X	X	X
Temperature		X	X	X	X
Bio geoclimatic zone	X				
Fuel moisture content	X	X	X	X	
Fuel characteristics					
Fuel load					
Fuel type		X	X	X	
Continuity	X				
Aspect	X	X	X		
Slope	X	X	X	X	X
Elevation		X	X	X	
Special land formations					
Fire barriers	X				
Fire size			X		
Fire type			X		
Fireline intensity			X		
Mode of fire development			X		
Wildfire occurrence	X		X		
Fire Duration		X	X		
Rate of spread		X	X		
Ignition source			X		
Materials involved in fire		X	X		
Fire fronts					
Wind produced by fire			X		
Smoke distribution					
Smoke toxicity					
Smoke visibility					
Building material					
Height of structure					
Size of structure					
Building type					
Building functionality					
Specific components					
Landscape maintenance					
Placement on slope	X				
Development density					

Wildland Urban Interface		X			
Wildland Urban Intermix		X			
Wildland Urban Occluded		X			
Distance to fire					
High hazard objects					
Road capacity					
Status of road					
Traffic management					
Occupancy rate community					
HVRA		X			
Population					
Number of households					
Population density		X			
Elderly					
Children					
People with temporary or permanent disabilities					
Occupancy rate structures					
Protective actions					
Means of communication					
Rescue service response time					
Responders					
Special competencies					
Fire stations		X			
Proximity to water					
Water sources					
Water capacity					
Training					
MSB forest fire depots					

Appendix 3. Procedures for retrieving data to case study

This appendix includes detailed information about the procedures for retrieving the data needed to perform the VAM in the case study.

Weather factors

All values for wind speed, temperature, precipitation and number of dry days for Preventive 1 were retrieved from the same source and for Delsbo´s measuring station. This was made for the months of June, July and August between 2010-2018 to create an average.

1. Go to website https://rl.se/
2. Press the tab that is called "Väder"
1. Press the tab that is called "Arkivet"
3. Press the tab that is called "Historiska data, övriga stationer"
4. Choose the year and month to see data from, e.g. "2010, may"
5. Press on the map, close to the location, in this case Ljusdal.
6. Choose Delsbo´s measuring station
7. Retrieve the values

Data for wind speed, temperature, precipitation, number of dry days for the Operational mode was retrieved according to the same process as for the Preventive 1 mode but looking specifically on the 18th of July 2018. Values for wind direction and relative humidity for Operational was retrieved according to the following process;

1. Go to website https://rl.se/
2. Press the tab that is called "Väder"
3. Press the tab that is called "Arkivet"
4. Press the tab that is called "Historiska data, flygstationer"
5. Choose the time and date to see data from, in this case 2018-07-18 13:20 to 2018-07-18 15:40
6. Retrieve the values on wind direction and relative humidity for Sveg

Fuel load

Data regarding fuel load was the same for Preventive 1 and Operational and was retrieved according to the following process;

1. Go to website https://www.scb.se/
2. Press on tab labelled "Kommuner i siffror"
3. Choose Ljusdal in the column labelled "Välj en kommun"
4. Choose Sverige in the column labelled "Jämför med kommun eller Sverige"
5. Press the tab labelled "Markanvändning"
6. Press "Visa diagram"
7. Retrieve the values for "skogsmark, produktiv" and "skogsmark, improduktiv"

Placement on slope/Slope/Aspect

Data regarding placement on slope/slope/aspect was the same for Preventive 1 and Operational and was retrieved according to the following process;

1. Go to website https://en-gb.topographic-map.com/maps/d9x/Sweden/
2. Choose which urban area you want to retrieve data from, e.g. Ljusdal

3. On the map approximate the proportion of the community placed on a slope (placement on slope). The average incline on the slope which the community is placed on is retrieved using the Pythagorean theorem and trigonometry(slope). The cardinal or intercardinal point that the slope is facing is retrieved directly from the map (aspect).

Distance to fire
This factor applies only for the Operational mode and the data was retrieved for the 18th of July 2018 according to the following process;

1. Go to website https://www.ljusdal.se/samhallegator/krisochsakerhet/informationombranderna2018/faktaombranderna.4.12be7f0e165140d0d1895a64.html
2. Look at the video and stop 34 seconds in which displays the extent of the fire on the 18th of July 2018
3. Do an approximation of the location of the Enskogen fire and look at a map to retrieve the distance between the urban area and the fire

Fire barriers/High Hazard objects
This factor is the same for both the Preventive 1 and Operational mode and the data was retrieved according to the following process;

1. Go to website https://www.google.com/maps
2. Search for the community you want to observe, e.g. Färila
3. Count all the Fire Barriers and High Hazard Objects which are present within the community borders.

HVRA
Data regarding HVRA´s was the same for Preventive 1 and Operational and was received according to the following process;

1. Go to website https://www.ljusdal.se/
2. In the searchbox, type "Riksintressen"
3. Press the result labelled "Översiktsplan Ljusdals kommun"
4. Press the file labelled "Karta Riksintressen"
5. Count the number of HVRA's present within each community

Road capacity
This factor is the same for both the Preventive 1 and Operational mode and the data was retrieved according to the following process;

1. Go to website https://www.google.com/maps
2. Search for the community you want to observe, e.g. Färila
3. Count all the roads (outgoing lanes) leading out of the community

Status of road
This factor applies only for the Operational mode and the data was retrieved for the 18th of July 2018 according to the following process;

1. Go to website https://sverigesradio.se/sida/artikel.aspx?programid=99&artikel=7000514

2. Look at the information regarding the 17th of July, 2018 that states which roads are closing down since the same roads are closed on the 18th of July, 2018

Population/ Population density

This factor is the same for both the Preventive 1 and Operational mode and the data for the small urban areas was retrieved according to the following process;

1. Go to website https://www.scb.se/
2. Press the tab which is called “Statistikdatabasen”
3. Press the tab which is called “Miljö”
4. Press the tab which is called “Småorter; arealer, befolkning”
5. Press the tab which is called “Landareal per småort (orter med 50-199 invånare), folkmängd och invånare per kvadratkilometer. (Uppdateras ej) vart femte år 1995-2010”
6. In the tab “Tabellinnehåll” choose “Folkmängd” to retrieve the population and “Landareal, ha” to retrieve the community size
   In the tab “Region” choose “Småorter” and choose Hamra, Kårböle, Ramsjö and Tandsjöborg
   In the tab “År” choose “2010”
7. Retrieve the numbers for the population and community size

The population and community size for the urban areas is retrieved according to the following process;

1. Go to website https://www.scb.se/
2. Press the tab which is called “Statistikdatabasen”
3. Press the tab which is called “Miljö”
4. Press the tab which is called “Tätorter”
5. Press the tab which is called “Befolkning”
6. Press the tab which is called “Folkmängd och landareal i tätorter, per tätort. Vart femte år 1960-2018”
7. In the tab “Tabellinnehåll”, choose “Folkmängd” to retrieve the population and “Landareal, ha” to retrieve the community size
   In the tab “Region” choose “Tätorter” and choose Ljusdal, Färila, Järvsö, Hybo, Lillhaga, Los and Tallåsen
   In the tab “År”, choose 2018
8. Retrieve the values for population and community size

To calculate the population density, divide the population with the community size for each community

People with limited ability to self-evacuate

This factor is the same for both the Preventive 1 and Operational mode and the data was retrieved according to the following process;

1. Go to website https://www.scb.se/
2. Press the tab which is called “Statistikdatabasen”
3. Press the tab which is called “Befolkning”
4. Press the tab which is called “Befolkningsstatistik”

5. Press the tab which is called "Folkmängd"
6. Press the tab which is called "Folkmängden efter region, civilstånd, ålder och kön. År 1968-2018"
7. In the tab "Tabellinnehåll", choose "Folkmängd"
   In the tab "Region", choose "Kommuner" and choose Ljusdal
   In the tab "Ålder", choose "Ålder, 1-årsklasser" and mark all ages
   In the tab "År", choose 2018
8. Retrieve the numbers for the total amount of children (0-17years) and elderly (85-101 years)

Fire size

Since there is no value for the fire size on the 18th of July 2018 for the fires in Ljusdals municipality, the final fire size is retrieved. This factor applies only for the Operational mode and the data was retrieved as a value for the 18th of July 2018 according to the following process;

1. Go to file https://www.skogsstyrelsen.se/globalassets/om-oss/publikationer/2018/rapport-2018-15-forslag-till-stod-efter-skogsbranderna-sommaren-2018.pdf
2. Go to section "2.1 Särskilt omfattande bränder"
3. Retrieve the fire size for the fires labelled "Enskogen" "Nötberget" and "Ängra"

Wildfire occurrence

Data regarding wildfire occurrence was the same for both Preventive 1 and Operational and was retrieved according to the following process:

1. Go to website https://ida.msb.se/ida2#page=3d635cdf-e7eb-4f49-b579-9612fb44c941
2. Press the tab which is called "Detaljerad statistik"
3. Press the tab which is called "Räddningstjänstens insatser: Basstatistik 1998-2018"
4. Press the tab which is called "Bränder I skog eller mark"
5. In the tab "Län", choose "Gävleborg"
   In the tab "Kommun", choose Ljusdal
6. Retrieve the numbers for the total amount of fires for each year

Rescue service response time

The data is the same for both Preventive 1 and Operational and was retrieved according to the following process;

1. Go to website https://www.google.se/maps
2. Search for the urban area "Ljusdal", "Färila" or "Järvsö"
3. Press the button which is called "Vägbeskrivningar"
4. In the field "Välj destination eller klicka på kartan…" write the name of the community
5. From Ljusdal, Färila and Järvsö retrieved the arrival time to the different communities

Proximity to water

Data for proximity to water applies for each community and was retrieved according to the following process;

1. Go to website https://www.ljusdal.se/
2. In the field "Ange sökord" write "Räddningstjänsten"

3. Choose the result labelled “Om oss- Räddningstjänsten”
4. Press the tab labelled “Handlingsprogram” and go to the file with the same name
5. Read section “6.8 Brandvattenförsörjning” regarding water supply

Water sources
The same data applies for the entire municipality and was retrieved according to the following process;

1. Go to website https://www.scb.se/
2. Press the tab which is called “Kommuner I siffror”
3. Choose Ljusdal in the column labelled “Välj en kommun”
4. Choose Sverige in the column labelled “Jämför med kommun eller Sverige”
5. Press the tab labelled “Markanvändning”
6. Retrieve the value for Ljusdal from the row labelled “Vatten(exklusive havsvatten)”

Appendix 4. List of chosen factors for VAM

Table 60 displays the complete list of the chosen factors for the VAM, divided by category.

Table 60. All factors chosen for the VAM

Category	**Factor**
Climate	Relative humidity Wind speed Wind direction Precipitation Dry days Temperature
Fuel	Fuel moisture content Fuel characteristics Fuel load Fuel type Continuity
Topography	Aspect Slope Elevation Special land formations Fire barriers
Fire characteristics	Fire size Fire type Fire intensity Wildfire occurrence Rate of spread Materials involved in fire Smoke distribution Smoke toxicity Smoke visibility
Structure	Building type Building functionality
Community	Placement on slope Wildland urban interface

	Wildland urban intermix Occluded wildland urban interface Distance to fire High hazard objects Road capacity Status of road HVRA
Population	Population Population density People with limited ability to self-evacuate
Mitigation	Rescue service response time Fire station Responders Proximity to water Water sources Water capacity