TECHNISCHE UNIVERSITÄT DRESDEN

Faculty for Environmental Sciences Institute for Cartography / Department of Geography

MASTER THESIS

LARGE-SCALE INDUSTRIAL SITE SELECTION USING A MINIMUM NATURAL RISK APPROACH – CONCEPT AND PROTOTYPIC IMPLEMENTATION

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Task of Master Thesis

Course of Studies: International Master Course in Cartography

Name of the Graduand: Anne Lange

Topic: Large-Scale Industrial Site Selection Using a Minimum Natural Risk Approach – Concept and Prototypic Implementation.

Framework of the Study:

Within a decision finding process for a major industrial plant location, a potential investor has to reflect on probability and severity of natural risks endangering the envisaged target area. This process involves similar reasoning as in the case of insuring staff and material goods. The study aims at a mostly universal approach to the problem, and will therefore disregard specific demands emerging from a particular sector of production (a highly critical example would be a nuclear power plant). As a case study the territory of the United States of America will be chosen. Site selection is reflected in a generalised way, which means that geographic zones of higher order are envisaged as the outcome of risk assessment, what will deliberately leave detail search for suitable and available parcels within potentially appropriate zones as a follow-on task beyond the scope of the present thesis.

Natural risks may be grouped according to hazardous events of geological, geophysical, meteorological/hydrological origin. Risk analysis can nowadays make use of a multitude of complementary digital information technologies. This refers to data capture, which is – if a large area is considered – strongly supported by comprehensive, open-access, digital geo-data archives encompassing query, selection and download facilities for off-line processing. Moreover, information technologies allow task-specific restructuring and context-specific evaluation of data within geo-databases. The subsequent attempt of a comprehensive risk calculation will typically deploy selected software functionality provided through GIS software or related library functions with an emphasis on the widely-used concept of map algebra. Last not least, results will favourably be visualised and distributed to an interested public on-line using Web-technology.

Goals of this Study:

After a critical review of relevant literature, a concept might be compiled, which reflects basics of natural risk assessment, its data needs and established data processing techniques resulting in a natural risk zoning. Since risk is technically a product of the probabilistic occurrence of a detrimental event and its severity (often measured as costs), a specific remark should be given to the probabilistic handling of time.
A screening of accessible geo-data along with a compact usability overview will form the basis of subsequent conceptual and implementation tasks. This will include:

- a mostly generic database model to take up all input information in a structured and easily manageable way,
- an efficient and transparent translation of primary geo-information into risk-specific secondary information,
- a definition and provision of methods for combining risk information, to finally arrive in
- a delineation and presentation of risk zones.

The geo-related results will only become meaningful, if a simple but indicative map product will be compiled through an integration of risk information and basic topo-graphic elements for the sake of spatial imbedding of the focus topic. A Web-mapping solution might be chosen as ideal means to convey these results. If such a solution will be designed, the front end should at least provide basic interaction controls.

Some further remarks: In order to avoid excessive data volumes, to secure comparability of datasets in terms of scale and consistent availability, it can be legitimate to decide for lower resolution data (a higher generalisation level), even if there exists more accurate large-scale data in a specific information segment. Moreover, it might be favourable to transform data into a uniform data structure (e.g. grids only) instead of using a complicated hybrid vector-raster geo-database. Thirdly, it might eventually help to download and to integrate selected subsets of input data only, since only risk-relevant subsets will require a detailed further consideration.
It should also be considered, that a complex risk measure (resulting from a combination of unrelated partial risks) will probably only be meaningful if specific costs can be calculated from a statistical risk event. Since no specification on the type of industry will be given here, the system might eventually output a ranked list (plus a maximum) of individual risk values instead of a somewhat "vague" integrate risk measure.

Deliverables:
The written document has to be delivered in three copies. The complete thesis and relevant digital data have to be added to the written document through an attached portable data storage media (CD, DVD, etc.). The contents of the digital media should be structured in a way, which facilitates a friction-free continuation of work on the topic. The results should furthermore be presented on an A0 poster using a poster template which is available through the institute's homepage.

Supervisison:	Prof. Dr. Arno Kleber, Dr. Nikolas Prechtel
Delivered:	April, 26, 2014
To be filed by:	October, 1, 2014.

Prof. Dr. Manfred Buchroithner	Prof. Dr. Arno Kleber	Dr. Nikolas Prechtel
Board of Examiners	Tutor	Tutor

STATEMENT OF AUTHORSHIP

Herewith I declare that I am the sole author of the thesis named

"LARGE-SCALE INDUSTRIAL SITE SELECTION USING A MINIMUM NATURAL RISK APPROACH – CONCEPT AND PROTOTYPIC IMPLEMENTATION"

which has been submitted to the study commission of geosciences today.

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Dresden, 30.10.2014 Signature

ABSTRACT

In this thesis, a prototypic implementation of an industrial site selection will be developed by using free geographical data. As an area of study, the USA including Alaska and Hawaii will be used. The geographical data will be selected on the basis of natural hazards, which are known to occur in this area. For each natural hazard type, a hazard map will be developed by using frequency-intensity-matrices, which are all based on the same frequency scale and the established intensity scales of each hazard type. The data will be processed with the help of ArcGIS, where the outcome will be individual hazard map raster files for each natural hazard type. Afterwards, the data will be implemented in a GeoTrellis application with a weighted overlay of a multi-hazard map, which will allow user interaction in terms of deciding which hazard type is more important for the user and changing the map to his needs. This application will help the user to decide where in the study area a new industrial site would be safe to establish. It also gives information about which kinds of hazards could still occur in the area in order to built resistant structures and select appropriate insurances.

KURZFASSUNG

In dieser Masterarbeit wird eine prototypische Implementierung einer industriellen Standortplanung erstellt, welche nur kostenlose geographische Daten nutzt. Als Anwendungsgebiet werden die USA inklusive Alaska und Hawaii benutzt. Dabei werden die geographischen Daten auf der Basis von Naturgefahren ausgewählt, die in dieser Region auftreten. Für jeden Gefahrentyp wird eine entsprechende Gefahrenkarte erstellt indem Frequenz-Intensitäts-Matrizen genutzt werden, die alle auf derselben Frequenzskala und den etablierten Intensitätsskalen für jeden Gefahrentyp basieren. Die Daten werden mit Hilfe von ArcGIS prozessiert, wobei das Ergebnis einzelne Gefahrenkarten-Rasterbilder für jeden Typ von Naturgefahren sein werden. Danach werden die Daten in eine GeoTrellis-Anwendung implementiert mit einem gewichteten Overlay einer Multi-Gefahrenkarte, welche Nutzerinteraktionen erlaubt. Der Nutzer kann so entscheiden welcher Typ von Naturrisiken ihm wichtiger ist und er kann die Karte dementsprechend anpassen. Diese Anwendung wird dem Nutzer helfen zu entscheiden wo im Anwendungsgebiet ein neuer industrieller Standort am sichersten zu gründen ist. Sie gibt außerdem Informationen darüber welche Arten von Naturrisiken in diesem Gebiet auftreten, wodurch die Planung von resistenten Gebäuden und die Auswahl von entsprechenden Versicherungen erleichtert werden.

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1 INTRODUCTION

During the last years, people are becoming more and more aware of natural hazards that cause a lot of financial and human loss. Alone in 2013, the reinsurance company Munich Re announced a financial loss of 125 billion US$ due to natural events (Munich Re, 2014). To lower the amount of damage caused by natural hazards it is not only important to develop better warning systems and safer constructions, but also to select industrial sites and sites for housing and services more carefully. Thereby, areas with a high risk caused by dangerous natural events like earthquakes, volcanic eruptions, landslides, tsunamis, storms, and floods can be avoided. The topic of an industrial site-selection should for that purpose include the search for locations with a minimum risk of occurring natural events. If this is done, a lot of money for the insurance of the new facility can be saved and non-productive times due to hazard damages can be avoided.

In the following chapters, a prototypic implementation of an industrial site-selection with a minimum natural risk approach will be presented. The developed basic approach will be done on the basis of Greiving's method of creating a multi-hazard map by using free geographic data from the US government. The resulting map can be used and adapted for any kind of industry, because it will allow the end user to select his own focus concerning the natural hazards. The result will be represented in an interactive web application where the data is implemented and processed on-time according to the user's preference.

Before the work is started, the terms of hazard, risk and vulnerability have to be defined as they can have different definitions depending on the background of the usage of the terms. Within a natural event setting, hazards are the outcome of a natural event, like an earthquake or hurricane striking the human and his goods. Based on how strong the natural event was the damage can be high or low including financial as well as human losses. At that point it is always important to remember that natural events can occur at many places of the world with a specific chance and men can decide if they want to expose themselves to the risk. Here, the term risk does not only stand for the likelihood of an occurring natural hazard, but also includes the damage that can be caused by the natural event. In the context of an industrial site-selection this risk should be as low as possible for any kind of natural event. The vulnerability of men to natural hazards is also discussed in this part of the thesis as it deals with the probability of men being exposed to a natural event as well as their coping capacities to deal with the consequences.

As next point, the chosen area of the USA including Alaska and Hawaii will be examined in terms of natural events that might occur there and should later be respected in the data selection. The presented natural events are the more common earthquakes, floods, wildfires, hurricanes and tornadoes as well as the often forgotten volcanic eruptions, tsunamis and landslides. Recent and famous historic examples will be introduced to show how much harm can be done by each of the natural events. Some examples are from a time where the construction of houses was much cheaper which lead to lower damage sums than the sums which would occur today with a similar event. In addition to that, the scales for the determination of the strength of the natural events are presented as they will be used during the data processing.

The next part will deal with natural hazard risk assessment strategies, which can be used for creating a risk map. Most of the literature includes the vulnerability of the area to the calculation of the risk in addition to the probability of an occurring natural hazard. For the case of an industrial site-selection the vulnerability can be excluded in the process and the focus should be laid on the probability of a hazardous event which is what will be mapped in the hazard map in the end. This probability can be estimated with the help of a matrix of frequency and intensity of already occurred events for every place of interest.

An approach for the creation of a multi-hazard map by Greiving, which he presented in 2006, will be used as basis for the process of developing a multi-hazard risk assessment. Greiving starts with the creation of an individual hazard map for each hazard and classifies the risk in five classes in order to make them comparable. Then the individual maps are assembled to an integrated hazard map where every hazard gets a certain weight and is added to the sum. Greiving’s next step is to add the vulnerability of the area to the integrated hazard map, but this step will not be part of this thesis, because for this case it is more important where hazards occur than how vulnerable the area is. In fine, the integrated hazard map will already be the multi-hazard assessment map.

After checking what kind of hazards can occur in the area of interest, it is time to search for suitable data that matches the requirements to create the hazard maps mentioned by Greiving. Records of past events will be used for the purpose of this thesis assuming that the risk of a hazard appearing in the same area is higher than in a different area. The time span of the data records should be as high as possible and – if possible – identical for all types of hazards. They should further include precise location information in geographic coordinates so they can be mapped. Only free datasets can be used for this thesis, which is a fact that might be changed in a real case of industrial site-selection, but the US government offers a large amount of free datasets and eases the task of finding suitable datasets.

Following Greiving's method, the data will be processed in ArcGIS to prepare raster data for the later web application that will present the data to the user. The result will be one raster file for each type of hazard with five risk classes based on a frequency-intensity matrix. These raster files will be combined to a multi-hazard assessment map in the web application. This will be done with the high performance geoprocessing engine GeoTrellis that allows the user to define custom weighting factors for the hazard layers and calculates a weighted overlay on time. Every company might have its own opinion on how important a specific type of hazard is for them and the interactive part of the multi-hazard assessment map makes it possible to leave this part in the user's hands. The user will also be allowed to exclude hazard types from the final result for the case that he is not interested in these types of hazards.

2 HAZARD, RISK AND VULNERABILITY

2.1 OVERVIEW

For a site-selection with a minimum natural risk approach the definition of a natural risk has to be depicted first. It all starts with nature appearing to be capricious, superior and destructive (Felgentreff, et al., 2008) in the case of a natural event like an earthquake, volcanic eruption, flood or hurricane. These natural events can occur on certain places on earth with a certain probability and what makes them dangerous for people is the occurrence in areas where they live. When there is a chance of men, and all kinds of land and structures used by them, being exposed to a natural event, it is called a risk. People then have a certain vulnerability regarding the natural event and it depends on their preparedness and financial status if the case of an occuring natural hazard involves human and financial loss. Should this event be above-average in its amount of destruction, it can be called a disaster. This can only happen when the vulnerability of a society is so high that the natural event can cause a large amount of damage while on some other place with lower vulnerability there would have been less destruction with the same event.

Due to the fact that these short definitions of the terms used in this thesis does not quite cover the whole matter of natural hazards, they will be further explained in the following chapters. Some of the terms also have many different definition approaches depending on the view of the scientist dealing with the term. These ambivalent definitions will also be discussed below.

2.2 HAZARD

A short definition for a hazard can be found on the website of United Nations Office for Disaster Risk Reduction specifying a hazard as "a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage"(UNISDR, 2007). It is further said that hazards can be caused by different sources such as geological, meteorological, hydrological, oceanic, biological, and technological reasons (UNISDR, 2007).

As far as this thesis is concerned, the focus will lie on hazards caused by geological, meteorological, hydrological and oceanic sources or shortly natural hazards. Those can be characterized by their magnitude or intensity, speed of onset, duration, and area of extent (UNISDR, 2007). The area of extent can vary with the type of the natural hazard. While an earthquake or landslide might affect only a small region, a flood or tsunami might cause damage to a much larger area. Also their speed is very different as earthquakes appear suddenly and have a short duration whereas floods build slowly and can linger in the affected area for days. Some hazards can also be coupled like a volcanic eruption that causes a landslide or a hurricane causing a flood. This already shows how difficult it can be to distinguish the amount of destruction that can be caused by one type of natural hazard, because they can also lead to each other.

However, these reasons of natural hazards are only natural events and only if human goods are involved they can be called a natural hazard. If a landslide occurs in an area without any human settlement, it does not cause any damage and is therefore a natural event. In addition, some hazards might appear to be natural, but in the end they have a man-made cause, for example if settlements are situated at the hillside of a volcano or in a floodplain. Constructions in danger of collapsing are man-made certainties as well as they are more vulnerable to be destroyed by a hazard (Felgentreff, et al., 2008). For many hazards the human influence might not be so obvious, but it can often be found after further investigation. This is why O'Keefe stands that the "vulnerability of the population [is] the real cause of [a] disaster" (O'Keefe, et al., 1976).

2.3 RISK

The term risk can be defined differently depending on the background of its usage. In a financial setting it might stand for a chance that a certain event will occur. An engineer would rather see it as a reduction of safety or a chance of loss. But in the background of natural hazards, a risk is the probability of loss occurring due to a potentially damaging event in a certain area with a certain time and magnitude (Felgentreff, et al., 2008). While the financial part focuses on the probability and the technical part has its emphasis on the consequences, both are important for the matter of natural hazards. So the United Nations Office for Disaster Risk Reduction (UNISDR) simply describes a risk as "the combination of the probability of an event and its negative consequences."(UNISDR, 2007).

The "Weltrisikobericht 2013" (world risk report) mentions that the risk of being a victim of a natural hazard is composed of the exposition to the natural event and the stage of development of the society. A country with higher funds and functioning national and civil structures can develop an adaptive strategy to suffer less from natural hazards (Bündnis Entwicklung Hilft, 2013). This would add the part of vulnerability of the society (see next chapter) to the definition of risk.

Susan L. Cutter also agreed on the definition of risk being the likelihood of occurrence of a hazard, but she also mentioned that risk has two domains. "It includes the potential sources of risk and the contextual nature of the risk itself. The second domain is a simple probalistic estimate based on the frequency of occurrence. Risks combine with mitigation to create an overall hazard potential." (Cutter, 1996)

Due to the fact that this thesis focuses on site-selection with a minimum natural risk approach, the used definition for risk is quite important for the further process. So, as this thesis is concerned, the definition for risk is simply the likelihood of occurrence of a hazard as defined by S. Cutter. The higher the chance of any hazard threatening an area, the higher the natural risk and the more it should be avoided in the site-selection process.

2.4 VULNERABILITY

The definition of vulnerability is a bit more difficult. A simple approach is that vulnerability is the relative loss susceptibility of human and property value (Felgentreff, et al., 2008). Another description can be found on the website of the UNISDR where vulnerability is described as "the characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard" (UNISDR, 2007). They further mention that vulnerability can have many aspects arising from various physical, social, economic, and environmental factors. "Examples may include poor design and construction of buildings, inadequate protection of assets, lack of public information and awareness, limited official recognition of risks and preparedness measures, and disregard for wise environmental management." (UNISDR, 2007).

A similar definition can be found in the "Weltrisikobericht 2013" (world risk report) where vulnerability is the matter of social, physical and economic factors which make humans and their systems vulnerable against effects of natural dangers and the negative effects of climate change. These factors cover the abilities and capacities of humans and their systems to manage and adapt to negative effects of natural risks. In short, vulnerability is the liability together with coping and adaptation factors (Bündnis Entwicklung Hilft, 2013).

Susan L. Cutter spent a bit more time on the matter of vulnerability and splits the short definition "potential for loss" (Cutter, 1996) into individual and social vulnerability as every person has to cope with hazards as well as social groups or the society. They all have to adapt to the changing conditions due to natural hazards. According to Cutter, the discrepancies in the definitions of vulnerability arise from different epistemological orientations and the subsequent methodological practices as well as the choice of hazard and the regions of examination. This leads to different statements where vulnerability can be the likelihood of exposure, of adverse consequences, or a combination of both. It can also be seen as risk/hazard exposure, as social response or the vulnerability of places (Cutter, 1996).

Vulnerability is an important matter in the process of risk assessment in most cases, but for the case of an industrial site-selection, the vulnerability will not be a part of the calculation process. For this purpose it is only crucial to know the probability of a hazardous event occurring in the focused area which is the definition of risk in this thesis. The vulnerability of the new industrial site would be ranked among the individual vulnerability mentioned by Cutter. It should be kept as low as possible and since the financial aids of a company stay the same, the risk of an occurring natural event is the changing variable and important for the decision making process.

2.5 DISASTER

In the case that a certain area has a high risk to be stricken by a natural event and the human vulnerability in this area is quite high, the chance that they suffer a certain amount of damage is also very high and it can be called a natural hazard. But should the occurring event be of above-average strength it can be called a natural disaster as the destruction caused by it is also above-average. Areas with a high vulnerability factor are more likely to suffer from natural disasters while areas with low vulnerability need a very high magnitude event to endure such a natural disaster.

Disasters are different to hazards concerning the amount of destruction, magnitude and area of impact. They are normally "singular large scale, high impact events" (Cutter, 2003). The UNISDR describes them as "a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources." (UNISDR, 2007). It is quite difficult to spatially delineate disasters beforehand as they are a combination of hazards, risks and vulnerability (Cutter, 2003). Also Felgentreff & Glade define disasters as sudden, massive incidents with losses that are perceived higher than average. In this aspect, nature is the causer or at least the causal activator of the event (Felgentreff, et al., 2008).

After this definition, it can be said that a natural disaster would be the worst-case scenario for a newly developed site of a company. But the boundary between a natural hazard and a natural disaster is not always easy to define as it can be fuzzy. To get a better view on the matter, Munich Re classifies hazards in the aspect of the amount of destruction they caused as shown in Table 1. The classification also shows quite nice how the financial loss is increasing every century for the same category, because the prices for property are increasing as well.

Catastrophe category			Overall losses				and/or
		Loss profile	1980s*	1990s*	2000s*	2010*	fatalities
0	Natural event	No property damage	-	-	-	-	none
1	Small-scale loss event	Small-scale property damage	-	-	-	-	1-9
2	Moderate loss event	Moderate property and structural damage	-	-	-	-	>10
3	Severe catastrophe	Severe property infrastructure and structural damage	US$ >25m	US$ >40m	US$ >50m	US$ >60m	>20
4	Major catastrophe	Major property, infrastructure and structural damage	US$ >90m	US$ >160m	US$ >200m	US$ >250m	>100
5	Devastating catastrophe	Devastating losses within the affected region	US$ >275m	US$ >400m	US$ >500m	US$ >650m	>500
6	Great natural catastrophe „GREAT disaster“	Region’s ability to help itself clearly overtaxed, interregional/international assistance necessary, thousands of fatalities and/or hundreds of thousands homeless, substantial economic losses (UN definition). Insured losses reach exceptional orders of magnitude.					

* Losses adjusted to the decade average.

Table 1. Catastrophe categories after (Munich Re, 2011).

3 NATURAL HAZARDS IN THE USA

3.1 OVERVIEW

The study area of this thesis is the USA including Alaska, Hawaii and other small islands. These regions are quite hazard prone by multiple kinds of hazards, which makes them an interesting example for this site-selection prototype. Well-known hazards in the USA are earthquakes, which occur especially in the western part of the USA, Alaska and Hawaii, but also frequently in central regions and on the north-eastern border to Canada. Another common kind of hazards are extreme wind events like tornadoes, which occur mostly in the center ("Tornado Alley") and eastern part of the USA, and hurricanes, that wander up from the Caribbean to the southern USA and often cause floods. Other extreme wind events are storms, as a weaker version of tornadoes and hurricanes, and blizzards, which often occur in the north-eastern part of the USA. Further kinds of hazards are floods, which mostly occur at larger rivers, and tsunamis, which obviously can only occur at the coasts, especially in Alaska, Hawaii and the west coast of the USA. The country also has some volcanoes, which are particularly active in Hawaii, but also occur in Alaska and in the western part of the USA. A lot of damage is also caused by wildfires mostly in Alaska and the western part of the USA. Last but not least are landslides, which appear in the whole country, but more often in the east of the USA.

3.2 EARTHQUAKES

Earthquakes rank among the deadliest and costliest natural events worldwide and also cause huge losses in the USA. The deadliest earthquake took place in Haiti in 2010 and caused 222,570 deaths and a financial loss of 8 billion US$. The costliest earthquake occurred in Japan in 2010 causing 210 billion US$ of financial loss and leading to the death of 15,880 people. In the USA the costliest earthquake happened in 1994 with a financial loss of 44 billion US$, but only 61 deaths (Munich Re, 2014). This shows that the USA can suffer large earthquakes with a high financial loss, but has a low vulnerability regarding human losses.

A definition for earthquakes depicts them as temporary shocks of the brittle lithosphere due to suddenly decruited elastic energies (Hendl, et al., 1997). They mostly occur at plate boundaries where those elastic energies can build up over time and can be released in a short moment. The strength of earthquakes is measured as magnitude (logarithm of the maximum seismic wave amplitude) (Hendl, et al., 1997). Most commonly used is the *C.-F.-Richter* Scale for measuring the magnitude of earthquakes. "Each of the nine magnitude levels corresponds to a tenfold change in the vibrational amplitude and a 31.5-fold change in energy release." (Petak, et al., 1982). An overview for the meaning of the magnitudes in the *C.-F.-Richter* Scale is provided in Table 2. Generally, it could be said that the higher the magnitude of an earthquake the higher the damage potential (Petak, et al., 1982).

Magnitude M	Description
up to 0.4	Earthquakes are instrumentally certainly detectable
up to 2.5	Earthquakes are sensible
up to 4.5	Small damage can occur
up to 7.0	Earthquakes reach catastrophic character
9.2	Strongest earthquake in the USA Prince William Sund, Alaska, 1964 (Statista, 2014)
9.5	Strongest earthquake measured until now Chile, 1960 (Statista, 2014)

Table 2. C.-F.-Richter scale magnitudes after (Hendl, et al., 1997).

The problematic fact about earthquakes is their irregular and unpredictable occurrence, but they are likely to appear more often in the same regions, which are mostly plate boundaries. Earthquakes are, as well as other hazards, only dangerous if cities or buildings, and roads are affected. For the size of destruction the magnitude of the shock is not implicitly a crucial factor. It is more a question of how the houses and roads are built and the type of the shockwave also plays an important role. Primary effects of earthquakes are collapsing buildings whereas secondary effects can be ground liquefaction, landslides, flood waves and fires (Felgentreff, et al., 2008).

3.3 VOLCANOES

Volcanoes might not be seen as very dangerous natural hazards, because they have fixed positions and can be easily observed. Scientists can estimate their activity by measuring seismic activities, temperature changes, and gas output. With the help of these measurements the strength of the early eruption can also be appraised. In the USA, volcanoes are located mostly in the north-west and many of them are still active.

But as volcanic areas are quite obvious, they can be easily avoided by people, which makes them a less risky natural hazard type.

Like earthquakes, volcanoes are also expressions of sudden discharges of energy in the Earth's crust and mantle (Felgentreff, et al., 2008). Those can lead magma and gas to the Earth's surface and cause damage to the surrounding area. The quality of magma (alkaline or acid, highly- or semi-fluid) and the quantity of magma determine the shape and kind of activity of the volcanoes as shown in Table 3.

Quality of the magma	small	Quantity of the lava	large	Kind of Activity
1	2	3	4	5
highly-fluid, very hot, alkaline	single lava flow	shield volcanoes		effusive
		Iceland type	Hawaii type	
semi-fluid, relatively cool	cinder cone	strato-volcano with		composite, ejective
	with lava flow, plug domes	predominant tuffs	predominant lava flows	
acid, extremely semi-fluid	maars, gasmaars (diatremes)		explosion crater explosion caldera	explosive explosive (only gases)

Table 3. System of the central volcanoes (after (Hendl, et al., 1997)).

At the first sight, the magma composition and volume seems to be quite important to determine the danger of a volcano, but the side effects which can occur during a volcanic eruption can be more destructive than the eruption itself. These side effects can be pyroclastic flows, lahars, surges, volcanic tsunamis and tephra fallout. Also volcanoes with longer rest periods are especially dangerous, because people do not expect another eruption (Felgentreff, et al., 2008). These side effects cannot always be anticipated in advance, because every eruption is different. Still, the explosive eruptions are mostly more dangerous than other and their size is classified in the Volcanic Explosivity Index (VEI) based on the erupted mass or volume of deposit (Newhall, et al., 1982) as presented in Table 4.

The table also shows famous examples to give a better impression of how strong the volcanic eruptions are. An example for the strongest volcanic eruption in the USA, which was also experienced by men, was the eruption of Mt. St. Helens in 1981. It is also interesting to see that the larger the eruptions of the volcanoes are, the longer they need to recharge for the next eruption. This is the reason why many volcanoes seem to be inactive, but actually they are only gathering their strength for the next event. Based on the time span since the last eruption, a volcano can still be considered as active after resting for 10,000 years.

VEI	General Description	Cloud Column Height (km)	Volume (m^3)	Quali-titative Description	Classification	How often	Example
0	non-explosive	<0.1	$1x10^4$	Gentle	Hawaiian	daily	Kilauea
1	Small	0.1-1	$1x10^6$	Effusive	Hawaiian/ Strombolian	daily	Stromboli
2	Moderate	1-5	$1x10^7$	Explosive	Strombolian/ Vulcanian	weekly	Galeras, 1992
3	Moderate-Large	3-15	$1x10^8$	Explosive	Vulcanian	yearly	Ruiz, 1985
4	Large	10-25	$1x10^9$	Explosive	Vulcanian/ Plinian	10's of years	Galunggung, 1982
5	Very Large	>25	$1x10^{10}$	Cataclysmic	Plinian	100's of years	St. Helens, 1981
6		>25 km	$1x10^{11}$	paroxysmal	Plinian/ Ultra-Plinian	100's of years	Krakatau, 1883
7		>25 km	$1x10^{12}$	colossal	Ultra-Plinian	1000's of years	Tambora, 1815
8		>25 km	$>1x10^{12}$	colossal	Ultra-Plinian	10,000's of years	Yellowstone, 2 Ma

Table 4. Volcanic Explosivity Index (VEI) (Newhall, et al., 1982).

3.4 EXTREME WIND EVENTS

Wind is the exchange of air between high and low air pressure areas. It can occur with different speeds and will be called a storm at a Beafourt Wind Force of 10, which is at an average of 96 km/h. The Beaufort Wind Force Scale is used to classify wind speeds and assign the probable destruction to those (see Table 2). In the statistics of Munich Re extreme wind events rank amongst the costliest and deadliest events worldwide and especially hurricanes caused large damage in the USA. The latest and costliest example is hurricane Katrina in 2005 which caused 125 billion US$ of financial loss and took the lives of 1,322 people (Munich Re, 2014). This is probably due to the fact that hurricanes cause not only storm damage but also floods, which makes them a combination of two different natural hazards. Next to the hurricanes, tornadoes cause a lot of damage every year in the central USA, e.g. in 2011 with 19 billion US$. Another extreme wind event is the blizzard, which often occurs in the northeast of the USA. In 1993 nearly the whole county had to suffer the largest blizzard with 5 billion US$ damage.

Beaufort Wind Force	Wind Speed	Descriptive term		Criterion (Land)
		American	British	
0	< 1 km/h	Light	Calm	Smoke rises vertically.
1	1-5 km/h	Light	Light air	Direction shown by smoke but not by wind vanes.
2	6-11 km/h	Light	Light breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind.
3	12-19 km/h	Gentle	Gentle breeze	Leaves and small twigs in constant motion; wind extends light flag.
4	20-28 km/h	Moderate	Moderate breeze	Raises dust and loose paper; small branches are moved.
5	29-38 km/h	Fresh	Fresh breeze	Small trees in leaf begin to sway.
6	39-49 km/h	Strong	Strong breeze	Large branches in motion; umbrellas used with difficulty.
7	50-61 km/h	Strong	Near gale	Whole trees in motion; inconvenience felt when walking against the wind.
8	62-74 km/h	Gale	Gale	Breaks twigs off trees; generally impedes progress
9	75-88 km/h	Gale	Strong Gale	Slight structural damage; chimney-pots and slates removed.
10	89-102 km/h	Whole Gale	Storm	Trees uprooted; considerable structural damage.
11	103-117 km/h	Whole Gale	Violent Storm	Widespread damage; very rarely experienced.
12	118-132 km/h	Hurricane	n/a	Countryside is devastated.
13	133-148 km/h			
14	149-165 km/h			
15	166-183 km/h			
16	184-200 km/h			
17	>200 km/h			

Table 5. Beaufort Wind Force Scale after (National Weather Service, 2010).

Hurricanes, which are tropical storms, are counter-clockwise rotating low-pressure swirls with a diameter several 100 km, over 119 km/h wind force and an eye with lower wind speeds in the centre. Hurricanes develop over tropic oceans when warm water bodies and an insecure and moist atmosphere come together in a certain distance to the equator. Those tropic storms lead to extreme sea disturbance which can, together with the always changing wind direction, destroy ships and offshore oil platforms. When a hurricane encounters the coast, storm tides, heavy precipitation, wind force and tornados can lead to a huge amount of damage. The expected damage is shown in Table 6**Fehler! Verweisquelle konnte nicht gefunden werden.** according to the Saffir-Simpson-Scale that is used to classify tropical storms (Felgentreff, et al., 2008).

Intensity	Wind force [km/h]	Cases	Average damage [US$]	Damage potential	Occurring damage
Tropical storm	<119	118	< 1,000,000	0	Hardly damage
SS1	119-153	45	33,000,000	1	Minimal damage at trees etc.
SS2	154-177	29	336,000,000	10	Trees uprooted, buildings damaged, coastal highways flooded
SS3	178-209	40	1,412,000,000	50	Mobile houses destroyed, wind crushes windows, houses unroofed
SS4	210-249	10	8,224,000,000	250	Mobile houses completely blown away, low lying areas flooded
SS5	>249	2	15,973,000,000	500	Disastrous damage, heavy floods, buildings destroyed

Table 6. Damage potential of tropical storms (1925-1995). The damage potential is an indicator and refers to occurred damage of a hurricane of the category 1 on the Saffir-Simpson-Scale (SS1) (after (Felgentreff, et al., 2008)).

A second example for an extreme wind event is a tornado, which is a rotating compact air column with wind speeds of up to 500 mph (Petak, et al., 1982) and a diameter of maximally few hundred meters. It stays in contact with the cloud bottom side as well as the Earth's surface. When the atmosphere is unstably layered, the Earth's surface is sufficiently heated, and a strong vertical wind shear appears a tornado is likely to occur (Felgentreff, et al., 2008).

Especially the Midwest and the Southeast of the USA are the areas where tornados occur most. They may appear at every time of the year, but specifically between April and June larger numbers of tornados are experienced due to favorable weather conditions (Petak, et al., 1982). The hazard potential of this extreme wind event lies in the wind force and the pull of sudden pressure deviation. The force of a tornado is declared by the Fujita-Scale as shown in Table 7. It is not based on current wind measurements, but on the severity of harm (Felgentreff, et al., 2008).

Fujita	F0		F1		F2		F3		F4		F5	
v(m/s)	17-25	25-33	33-42	42-51	51-61	61-71	71-82	82-93	93-105	105-117	117-130	130-143
S_{light} (%)	0.05	0.10	0.25	0.80	3.00	10.0	30.0	90.0	100	100	100	100
S_{solid} (%)	0.01	0.05	0.10	0.25	0.80	3.0	10.0	30.0	60.0	80.0	90.0	95.0

Table 7. Fujita-Scale for wind speed classes where building damage is expected. Building damage is declared as S = damage sum/replacement value x 100 for (European) lightweight (S_{light}) and solid (S_{solid}) construction (after (Felgentreff, et al., 2008)).

Another kind of storms is the westerly cyclone, which occurs due to the difference in temperature of warm subtropical and cold polar air. This temperature difference is higher in autumn and winter which is why the strongest storms occur especially at this time. The wind force is mostly not as high as for hurricanes, but can also reach up to 200 km/h. At most times, these storms occur in Europe, but a special form, the blizzard, appears regularly in the northeast of the USA (Felgentreff, et al., 2008). A winter storm will be called blizzard when it reaches wind speeds of 35mph (56.3 km/h) and falling or blowing snow reduces the visibility to less than ¼ mile for at least three hours (National Weather Service, 2009).

3.5 LANDSLIDES

Landslides are a less common natural hazard, which mostly occur in small areas and therefore cause less damage. They mostly appear in areas with inclined surfaces, e.g. mountainous or coastal terrains. Together with the type and wetness of the material the inclination of the slopes is crucial for the kind of landslide. In the USA, mass wasting occurs often in the east, the west coast, and the western center, but the largest landslides were observed in Alaska, e.g. 1958 Lituya Bay with a volume of $30 Mm^3$ causing a 524m high megatsunami.

Shifts of rock, rubble and fine bedrock moving downhill directed and following gravity are called landslides or mass wasting. The shifting processes include tilting, falling, sliding, flowing and combined, complex movements. They can be caused by different natural events like earthquakes and volcanic eruptions, extreme precipitation, long lasting humid periods or snow melts. Landslides can occur discretely at one hillside or by 1,000’s in an area. Important factors for the occurring damage are the moved volume ranging from some cubic meters to several cubic kilometers and especially the speed, which can vary between millimeters or centimeters per year up to several meters per second. The volume depends of the available material and is not a determining fact for the speed (Felgentreff, et al., 2008).

There are three main types of mass wasting. The first type is fall, where soil or rock masses fall down from cliffs or massive broken, faulted, or jointed bedrock. Sometimes these cliffs can also be man-made when steep ledges are undercut. Mostly, the areas where rock/soil fall happens, e.g. high mountain areas, are known and should be avoided by humans (Petak, et al., 1982).

Flows are the second type and probably the most dangerous as they cannot always be foreseen. Surface material breaks up and moves down a slope as viscous fluid. This can occur as earth-flow, mudflow, debris flow, flow-slide, and spontaneous liquefaction. The areas where these flows happen should also be known and avoided, because landslides can happen without further notice or warning. They can lead to total destruction of buildings and they are very unpredictable (Petak, et al., 1982).

The last type belongs to creeps where earth mass is moving slowly down-slope. They might not be as dangerous, because they do not occur fast, but they can be a signal for a potentially dangerous slope condition (Petak, et al., 1982).

3.6 FLOODS

The floods mentioned in this part are inland floods due to a large amount of precipitation, melting of snow packs or glaciers, or the break of water reservoirs (Felgentreff, et al., 2008). Floods in coastal areas are either described in the chapter of extreme wind events or the tsunami chapter. The costliest flood in the USA happened in 1993 and caused damage of 21 billion US$. Another one in 2008 lead to damage of 10 billion US$.

There are three cases that can lead to floods. The first one is a temporary rise of the water level over a set threshold and leads to high water. A second case is a larger amount of convective precipitation in Mediterranean, semiarid or arid climate which provokes an abrupt increase of discharge in small catchment areas, which is then called flash flood. The last case of a so called outbreak wave is the burst of an artificial or natural water reservoir that leads to temporary extremely high amounts of water (Felgentreff, et al., 2008).

Floods lead to high damage in urban areas due to the mechanical force of water. Also the moisture can harm the building fabric for a longer period. Another factor is the rising underground water level which can damage building floors (Felgentreff, et al., 2008). The amount of damage is also a question of the type of the structure, the depth of the floodwaters, impacts of floating debris (Petak, et al., 1982).

3.7 TSUNAMIS

Tsunami is Japanese term made up of “tsu” (=harbor) and “name” (=wave) which then means “wave, which is dangerous at the coast”. The triggers of tsunamis can be seaquakes, large submarine landslides, eruptions of gas hydrate, rock and ice falls at cliff lines, eruptions of submarine volcanoes, collapsing volcanoes, caldera formation in the ocean, meteorite and comet impacts (Felgentreff, et al., 2008). Since the USA has long coastlines and also seismic active areas, tsunamis are also likely to occur there. Especially the west coast, Hawaii and Alaska are affected by Tsunamis and the highest tsunami ever recorded happened in Lituya Bay, Alaska in 1958 with a height of 524m.

Starting from the source, waves are building in the ocean for the whole water depth with a speed of up to 1000 km/h. The large water volume travels to the coast and slows down in the shallow water. But because there is still water pressing from behind, waves are rising up to 50 – 100 m height over sea level. At flat coasts, the water can enter far into the country and lead to a lot of damage. Several waves are following within intervals from minutes to more than two hours. Due to the fact that waves spread in all directions, all coasts surrounding the center of the tsunami are affected (Felgentreff, et al., 2008).

The amount of damage is on the one hand determined by inundation and the force of the impacting wave (Petak, et al., 1982), and on the other hand also by coastal landforms, wave-breakers like corals or mangroves, and sediments which can be carried by the waves (Felgentreff, et al., 2008). In most cases, tsunamis cause great damage to buildings and also human lives. In addition, boats can break their moorings and pound against other boats or buildings, or are carried ashore (Petak, et al., 1982). A new Tsunami Intensity Scale for the categorization of tsunamis in connection with the occurring wave height was announced by Gerassimos A. Papadopoulos and Fumihiko Imamura at the ITS in 2001. Table 8 shows an insight to the 12 point Tsunami Intensity Scale.

Rank	Description	Wave height	Intensity
I. Not felt	(a) Not felt even under the most favorable circumstances. (b) No effect. (c) No damage.	< 1 m	0
II. Scarcely felt	(a) Felt by few people onboard small vessels. Not observed on the coast. (b) No effect. (c) No damage.	< 1m	0
III. Weak	(a) Felt by most people onboard small vessels. Observed by a few people on the coast. (b) No effect. (c) No damage.	< 1 m	0
IV. Largely observed	(a) Felt by all onboard small vessels and by few people onboard large vessels. Observed by most people on the coast. (b) Few small vessels move slightly onshore. (c) No damage.	< 1 m	0
V. Strong	(a) Felt by all onboard large vessels and observed by all on the coast. Few people are frightened and run to higher ground. (b) Many small vessels move strongly onshore, few of them crash into each other or overturn. Traces of sand layer are left behind on ground with favorable circumstances. Limited flooding of cultivated land. (c) Limited flooding of outdoor facilities (such as gardens) of near-shore structures.	< 1 m	0
VI. Slightly damaging	(a) Many people are frightened and run to higher ground. (b) Most small vessels move violently onshore, crash strongly into each other, or overturn. (c) Damage and flooding in a few wooden structures. Most masonry buildings withstand.	2 m	1
VII. Damaging	(a) Many people are frightened and try to run to higher ground. (b) Many small vessels damaged. Few large vessels oscillate violently. Objects of variable size and stability overturn and drift. Sand layer and accumulations of pebbles are left behind. Few aquaculture rafts washed away. (c) Many wooden structures damaged, few are demolished or washed away. Damage of grade 1 and flooding in a few masonry buildings.	4 m	2
VIII. Heavily damaging	(a) All people escape to higher ground, a few are washed away. (b) Most of the small vessels are damaged, many are washed away. Few large vessels are moved ashore or crash into each other. Big objects are	4 m	2

	drifted away. Erosion and littering of the beach. Extensive flooding. Slight damage in tsunami-control forests and stop drifts. Many aquaculture rafts washed away, few partially damaged. (c) Most wooden structures are washed away or demolished. Damage of grade 2 in a few masonry buildings. Most reinforced-concrete buildings sustain damage, in a few damage of grade 1 and flooding is observed.		
IX. Destructive	(a) Many people are washed away. (b) Most small vessels are destroyed or washed away. Many large vessels are moved violently ashore, few are destroyed. Extensive erosion and littering of the beach. Local ground subsidence. Partial destruction in tsunami-control forests and stop drifts. Most aquaculture rafts washed away, many partially damaged. (c) Damage of grade 3 in many masonry buildings, few reinforced-concrete buildings suffer from damage grade 2.	8 m	3
X. Very destructive	(a) General panic. Most people are washed away. (b) Most large vessels are moved violently ashore, many are destroyed or collide with buildings. Small boulders from the sea bottom are moved inland. Cars overturned and drifted. Oil spills, fires start. Extensive ground subsidence. (c) Damage of grade 4 in many masonry buildings, few reinforced-concrete buildings suffer from damage grade 3. Artificial embankments collapse, port breakwaters damaged.	8 m	3
XI. Devastating	(b) Lifelines interrupted. Extensive fires. Water backwash drifts cars and other objects into the sea. Big boulders from sea bottom are moved inland. (c) Damage of grade 5 in many masonry buildings. Few reinforced-concrete buildings suffer from damage grade 4, many suffer from damage grade 3.	16 m	4
XII. Completely devastating	(c) Practically all masonry buildings demolished. Most reinforced-concrete buildings suffer from at least damage grade 3.	32 m	5

Table 8. Tsunami Intensity Scale (Papadopoulos, et al., 2001).

3.8 WILDFIRES

Wildfire is an uncontrolled fire in a natural environment (Rougier, et al., 2013). It is a frequent kind of natural hazards in the USA (see Figure 1) that is a bit different to the others mentioned above as it can have natural and human sources. The fire itself needs oxygen, fuel and heat to live (Abbott, 2012), but the triggers to start it can be quite different ones. As soon as enough dry fuel, e.g. grass, shrubs, trees or slash (organic debris left on the ground after logging or windstorms) is provided (Abbott, 2012), which is often the case in summer or in drought prone areas, the fire can be started by natural causes (e.g. lightning), accidental or malicious ignition, or managed burns getting out of control. The US National Interagency Fire Center presents statistics of the last 13 years where annually 10,000 fires were started by lightning and 62,631 fires by humans in the USA (National Interagency Fire Center, 2014). Due to the reason that so many fires are started by human actions and human activities around the world are increasing, the frequency of wildfires is also increasing (Rougier, et al., 2013).

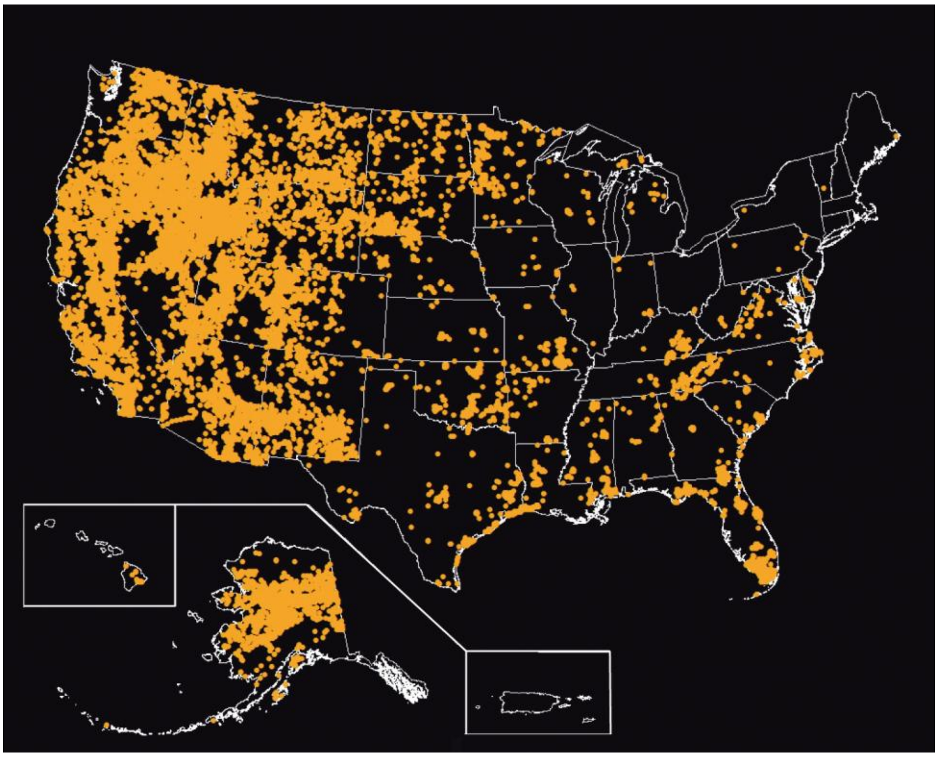

Figure 1. This map shows locations that experienced wildlfires greater than 250 acres, from 1980 to 2003. Map not to scale. (U.S. Department of the Interior; U.S. Geological Survey, 2006)

Wildfires have quite complex dynamics and together with atmospheric feedbacks (wind, more oxygen, and warm air) the behavior of the fire can be hard to predict. These combined with the high temperatures and movement speeds of up to 10 – 20 km/h of the fire make escape or survival nearly impossible. Embers can blow over longer distances and vulnerable structures can catch fire. This leads to the destruction of crops, buildings, damage to the ecosystem, economic losses and societal disruption. The smoke is also dangerous, because it contains carbon and greenhouse gas and is also detrimental to visibility and human health. The areas affected by wildfires can range from 10's to 1,000's of km² (Rougier, et al., 2013).

4 METHODOLOGY OF HAZARD MAPPING

4.1 RISK ASSESSMENT

As mentioned in chapter 2.3, risk can be defined as a combination of probability and loss and those are also the two parts of every risk assessment strategy. At first the probability of an occurring hazardous event has to be determined for every place in the area of interest. The next step is to evaluate the vulnerability of this area to each natural hazard and then assign the probability to the hazard outcomes. However, for industrial site-selection only the first part of estimating a probability is important and will be in focus of this chapter.

The bases of defining a probability of a certain hazard in a certain area are often historical records of hazardous events. They give information about place and time of occurrence of events with a given magnitude. Felgentreff and Glade present different methods for hazard analysis and estimations of event risk, which are sometimes depending on the scale. Qualitative methods, which can be used for all scales, imply the creation of inventories or heuristic analyses and provide information about the spatial distribution of the processes. For these qualitative methods field mappings, aerial images, digital height models, and satellite images are used. The heuristic methods are based on expert's assessments, which can be often hard to retrace. Quantitative methods can only be used for large scales and include statistic analysis and models based on detailed terrain specific assessments (Felgentreff, et al., 2008).

Rougier presents strategies for quantifying hazard losses and gives important information about the probability estimation and how to combine probability with loss. At first he states three points to define the term probability which say that "(1) All probabilities are non-negative. (2) The probability of the certain event is 1. (3) If events A and B cannot be true, then Pr(A or B) = Pr(A) + Pr(B)."(Rougier, et al., 2013). He then states that risk is always the combination of probability and loss. So, after calculating a probability for the event, the loss has to be linked to it. This is quite important, because two events (e.g. supervolcano eruption and asteroid impact) can have the same loss effect, but the supervolcano has a higher probability and this leads to a higher risk. Two events can also have the same risk if they have the same probability, but actually one always induces medium-sized losses and the other leads normally to small losses, but occasionally to very large loss. Now, to estimate the risk of a hazard, some data is needed. At first, the hazard domain has to be specified with spatial region and the time interval where hazards should be "predicted". Then, every hazard event that already occurred in the area should be collected together with its time of appearance, location, and magnitude. Afterwards, these events will be linked with their own probability to get an exact overview on what kind of events occurred where (Rougier, et al., 2013).

Since the descriptions of Rougier do not include instructions on how to estimate the probability for a hazard, a semi-quantitative approach by Neri et al. of multi hazard mapping in volcanic areas was used to understand the matter. They created a threat matrix with the help of historical data to create a hazard map of the area. The vulnerability of the area was left out as it should also be done in this thesis. For the creation of the threat matrix intensity and frequency classes were defined. According to the amount of damage of historical events, the intensity classes were created and ranged from I_1 = "very low" to I_5 = "very high" and they got numerical equivalents from 0.5 to 100. The frequency classes ranged from 5'000 - 10'000 years (F_0 = "very low") to 1 - 10 years (F_6 = "quasi permanent") in logarithmic steps. These two scales were then combined in threat matrix to get factors to define how threatening a hazard was (Neri, et al., 2013).

The concept of the threat matrix will also be used for the industrial site-selection by finding historical data of the types of hazards that happened in the USA and adapting the frequency scale to the time-span that is covered by this data. Intensity classes will be defined according to already existing magnitude scales of the different hazards. If such scales do not exist (e.g. floods) literature with similar projects and information from historical events can be used to depict an intensity scale.

4.2 MULTI-HAZARD MAP CREATION BY S. GREIVING

In 2006 Stefan Greiving published a method for integrated risk assessment of multi-hazards. The goal of his studies was to determine the total risk potential of a sub-national region by aggregating all relevant risks for the area to receive an integrated risk potential (Greiving, 2006). His approach should combine all relevant hazards which threaten a certain area as well as the vulnerability of the region to these hazards. However, for the problem that will be solved in this thesis only the risk of the natural hazards is important as regions with low hazard potential should be detected.

Greiving's method starts with the creation of hazard maps for each spatially relevant hazard to determine where and how intense the individual hazards occur. For calculating the intensity the magnitude and frequency of occurrence are taken into account. It is then classified in 5 classes to get equal representation for all hazards (Greiving, 2006). This step will also be the first part of this thesis and will be described in detail in chapter 6.

The next step of Greiving's method is to create an integrated hazard map, which includes the information of all single hazard maps. The single hazard intensities are added at every location depending if they are overlapping. A weighting of the single hazard intensities takes place according to a Delphi method which uses the opinions of several experts (Greiving, 2006). This step will also be used in this thesis, but, as the weighting should be in the hand of the user, this will be part of the user modifications in the web-mapping application. The integrated hazard map is then produced on-time according to the user's wishes.

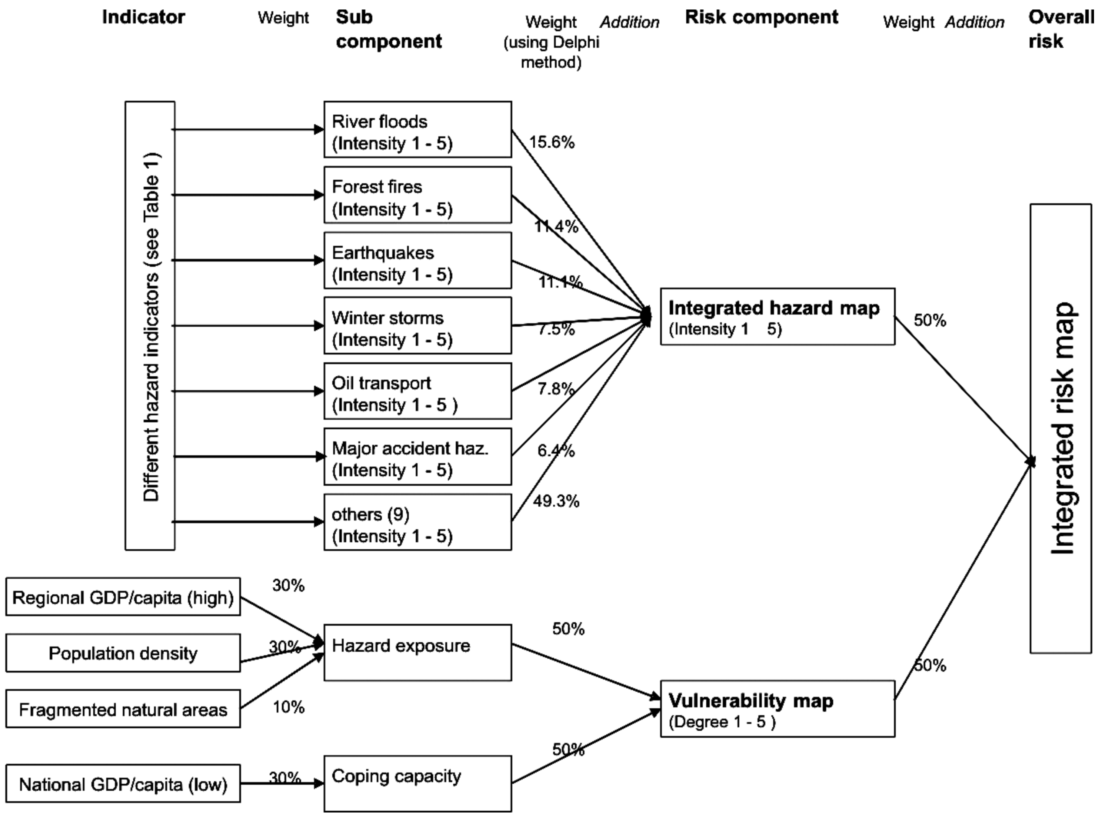

Figure 2. Calculation of the Integrated Risk Index (Greiving, 2006).

As shown in Figure 2 Greiving's next step would be to create a vulnerability map with information about the region and its hazard coping capacities. This map would then be used for the final integrated risk map (Greiving, 2006). However, these steps are not needed for solving the problem of this thesis, because the task is only to search for areas with a low hazard probability.

5 DATA ACQUISITION

5.1 IDEAL DATASET

For calculating whether an area has a certain risk that a certain natural event can occur a particular dataset is required. The basis of probability calculation is historical data in combination with a frequency-intensity-matrix. It is then clear that the ideal dataset contains the exact time of occurrence of every natural event that happened in the area of interest in order to get a frequency. It is also important to know the magnitude of the events so that they can be assigned to the intensity classes of the matrix.

It follows from the above that a complete and consistent dataset for each individual natural event is needed for the area of the USA. This dataset should contain the time of occurrence and magnitude of the particular events and their location. The location can be given by coordinates as a point, but it would be more sufficient to know a discreet area where the event occurred. In order to calculate a more reliable frequency the time span of the events should be as large as possible and preferably the same for each event dataset.

5.2 ACTUAL FOUND AND USED DATA

The U.S. government offers a large selection of different datasets as open data, which can be found in the data catalog of Data.gov (US government). By using keywords like "natural hazards", "earthquake", "volcano", etc. the catalog offers links to different federal, state, or university data that is free to use. During the search the link to the National Geophysical Data Center appeared and it offered quite useful datasets for this thesis. The used datasets are about significant volcanic eruptions, significant earthquakes and tsunami runups. The databases offered worldwide data, but as the USA is the required field of study, only the events that happened in the USA were selected. The found datasets will be described in detail during the next subsections.

5.2.1 Significant Earthquakes

The content of this dataset is described on the website of the National Geophysical Data Center like this: “The Significant Earthquake Database contains information on destructive earthquakes from 2150 B.C. to the present that meet at least one of the following criteria: Moderate damage (approximately $1 million or more), 10 or more deaths, Magnitude 7.5 or greater, Modified Mercalli Intensity X or greater, or the earthquake generated a tsunami.” (National Geophysical Data Center / World Data Service (NGDC/WDS)).

A closer look on the actual data (only USA selected) shows that the recorded events in the USA start 1500 A.D. and not 2150 B.C., probably because America was not discovered by the western world until Christopher Columbus “accidentally” sailed there in 1492. All recorded earthquakes have at least a year when they occurred and sometimes even the exact second. The coordinates of the point location of the earthquakes are also given, but unfortunately not the area of impact which would have been important for a more exact calculation. The intensity of the earthquakes is given either as magnitude of the *C.F.-Richter* Scale or as Modified Mercalli Intensity. Some events lack the information of intensity, but the handling of problems like this is further described in the data processing chapter.

Additional information for the earthquake effects like amount of damage, number of deaths, and the number of destroyed houses is also given for some of the events, but it is not important for the process of this thesis and can be ignored.

5.2.2 Significant Volcanic Eruptions

Similar to the significant earthquake database, this dataset contains all significant volcanic eruptions and is described by the website of the National Geophysical Data Center as follows: “The Significant Volcanic Eruption Database is a global listing of over 500 significant eruptions which includes information on the latitude, longitude, elevation, type of volcano, and last known eruption. A significant eruption is classified as one that meets at least one of the following criteria: caused fatalities, caused moderate damage (approximately $1 million or more), with a Volcanic Explosivity Index (VEI) of 6 or larger, caused a tsunami, or was associated with a major earthquake.” (National Geophysical Data Center / World Data Service (NGDC/WDS)).

The first record in this dataset is the eruption of the Black Peak in Alaska 1900 B.C. which is quite early compared to the earthquake dataset. However, volcanic eruptions occur not as often as earthquakes and so it is quite useful to have records going back to this early time. This will later be solved with the frequency-intensity-matrix. Again, all records have at least the year and some also the month and day when they occurred. The exact second of the eruption is not so important for volcanoes thus the day (and for older records the year) is sufficient. Exact locations of the volcanoes are given by point coordinates. Unfortunately, again there is no area of impact recorded, but a point dataset will also be sufficient. The strength of the volcanic eruptions is indicated in the Volcanic Explosivity Index (VEI).

Further information like associated tsunamis and earthquakes, number of deaths, destroyed houses, etc. is also given, but it is not important for the calculations presented in this thesis. However, it could be an important weighting factor in a more complex process.

5.2.3 Tsunamis Runups Database

The website of the National Geophysical Data Center also offered datasets for tsunami source events and runups. The tsunami runup database was used for this thesis and its content is described on the website like this: "The NOAA/WDC Tsunami Runup database (…) contains information on locations where tsunami effects occurred. It is related to the Tsunami Source Event database which contains information on the source of the tsunami."(National Geophysical Data Center / World Data Service (NGDC/WDS)).

This database contains all tsunami runups that were recorded worldwide. By searching only for runups in the USA, records starting from 1500 A.D. are shown and used for this thesis. Like the other two databases, the events are recorded as points in geographic coordinates and with no information about the area of impact. Besides the basic information of time and location of occurrence, additional data like cause of the event, distance to source event, travel time, period of first cycle, maximal water height, and maximum horizontal inundation is given. Other important factors are the numbers of death, damaged houses, and the amount of financial damage which occurred due to the tsunami.

There is also a column for event validity for every tsunami event in the database, which is used to show the validity of the tsunami based on the number of reports of that event. It is a scale from -1 to 4 at which -1 stands for an erroneous entry, 0 for an event that only caused a seiche or disturbance in an inland river, 1 for a very doubtful tsunami, 2 for a questionable tsunami, 3 for a probable and 4 for a definite tsunami. This scale will be important for further data processing as only tsunami runups that are definite or probable tsunamis will be used for site selection.

5.3 COMMENT TO USED DATA

Even with the large amount of different datasets offered by the US government, it was quite difficult to find data that matches the scheme of the ideal dataset as described above. Firstly, the data was often only available for a small part of the USA like a state or county. Then the data types were not always useful for this kind of project and many datasets did not include discreet coordinates, but rather descriptions of the area. With more time and a program to read the structure of these datasets, they might have been useful.

Also the actually used data is not perfect for the project, but sufficient. The first unfortunate part of all datasets is the fact that all events are only recorded as points and not with their area of impact. This can cause the later data processing to lead to inaccurate outcomes. Another drawback is the absence of some data entries. Some events lack information about the location, magnitude/wave height, which in the first case will not be used for later data processing and in the second case also lead to inaccurate results.

The last point is about the different time spans where the data was recorded. The earthquakes and tsunami runups were both recorded since 1500, which is fortunate. But the volcano database reaches far more back in time. Anyway, this might not be such a poor drawback as volcanoes can have a very long time without eruptions, but they are still active. This issue will be solved during data processing with the help of the frequency-intensity-matrices. However, the database does not include the Yellowstone volcano, which is unfortunate.

Despite the drawbacks of the existing data, it can still be used to show the principle of industrial site selection. If a real industrial site selection should be made, the company can probably invest more time and money in the data so that a perfect dataset can be found. The data processing and later calculation will basically be the same with some smaller changes in the first steps of data processing which will be mentioned in the following chapters.

6 DATA PROCESSING

6.1 SHORT DESCRIPTION OF DATA PROCESSING PROCEDURE

According to Greiving's method, individual hazard maps should be created. This will be done with the help of frequency-intensity-matrices adapted to the data of the natural events that were described in chapter 5.2. For doing that, the databases have to be prepared by cleaning out unnecessary information, creating point datasets and, as follow-on step, raster datasets out of the provided data. The individual matrices will be applied to the raster files to determine the hazard probability for every individual raster cell. This process is an important preparation for the web application that will be creating hazard maps according to the user's interest and focal point.

First of all, the datasets for volcanoes, earthquakes and tsunami runups will be cleaned from unnecessary information like the number of deaths or destroyed houses. The only important data for this project is the location and the magnitude of each individual event. Also erroneous entries where location or intensity information is missing will be deleted. After all databases are cleaned, they can be displayed as points in ArcGIS and saved as shapefiles.

As next step, the shapefiles will be split into individual files where all entries have the same intensity class. Prepared like that, these shapefiles can now be converted to raster files, where each raster cell contains the count of records that occurred in this cell with certain intensity. For this step, a constant raster is used in order to get the same structure for all raster files. This results in one raster file for every intensity class of volcanoes, earthquakes and tsunami runups. The count of events in every cell will be used to determine a frequency and the cells will be reassigned with the threat-factors of the frequency-intensity-matrix. The so created raster files will then be combined to a simple hazard map by adding them together. Prepared like this, the hazard maps are ready for a GeoTrellis web application where multi-hazard assessment maps will be created in time by user request.

6.2 THE FREQUENCY-INTENSITY-MATRICES

Before the data is processed, the frequency-intensity-matrices have to be created. The frequency scale will be the same for all hazard types, but every type of hazard needs its own intensity scale for these matrices. Crucial factors for the scales are the time intervals of the historical datasets and intensity scales for the correspondent hazard type. The values of each scale are then multiplied with each other to form the threat factors, which will be used later to reassign cell values in the hazard raster files. The paper by Neri et al. of multi hazard mapping in volcanic areas, which was mentioned in chapter 4.1, will be used as basis for the creation of the matrices.

Frequency class	Qualification of the event frequency	Return period for the type of activity or phenomenon (order of magnitude)	Quantification of the phenomenon frequency $\boldsymbol{Q_f}$	Index used for matrix ($\boldsymbol{Q_F = 100 \times Q_f}$)
$\boldsymbol{F_1}$	very low	1000 – 5000 yr	2×10^{-4}	0.02
$\boldsymbol{F_2}$	low	500 – 1000 yr	10^{-3}	0.1
$\boldsymbol{F_3}$	moderate	100 – 500 yr	2×10^{-3}	0.2
$\boldsymbol{F_4}$	high	50 – 100 yr	10^{-2}	1
$\boldsymbol{F_5}$	very high	10 – 50 yr	2×10^{-2}	2
$\boldsymbol{F_6}$	quasi-permanent	1 -10 yr	10^{-1}	10

Table 9. Frequency scale for frequency-intensity-matrices (after (Neri, et al., 2013)).

The first step of the matrix creation is the development of a frequency scale, which will be determined by the period covered by the dataset. Since some of the datasets cover a larger time span than others, the largest one will be used for the scale and not occurring frequencies in other datasets will be left out. Usually, the covered period should be the same for all datasets, but the significant volcanic eruptions database covers a much larger space of time than the other two datasets. Since volcanoes can have a very long resting period, it is quite important not to ignore the older records, only because the other two datasets do not date back to the same time. This is why there is an exception for the volcanic eruption dataset. The oldest record in this dataset is from 1900 B.C., which is why the lowest frequency was chosen as 1000 –

5000 years. Based on that, a logarithmic frequency scale was chosen as presented in Table 9.

While the same frequency scale can be used for all frequency-intensity-matrices, the intensity scales are another matter. They are based on the amount of destruction that can be expected of an event. In the databases, some records include information about the damage dealt by the events, but this always depends on the area where the event happened and the financial damage that could be expected by a similar event might change drastically within time. For this reason, independent scales, like the Richter scale, Volcanic Explosivity Index and the Tsunami Intensity Scale, will be used as intensity scales for the matrices. This is quite useful, because all records include information of the intensity of the events based on these scales (or values that can be related to these scales, e.g. Tsunami Intensity Scale). Neri et al. used numerical equivalents for the intensity scale that range from 0.5 to 100 and have increasing gaps between the numbers without any obvious mathematical scheme. But since they only included five different intensity levels, the numerical values had to be changed to a sequence of numbers with up to ten levels (e.g. for earthquakes) and best also with the same mathematical scheme behind them. By searching for such a numerical order, the sequence of $y = x^2$ came up with a solution for ten numbers ranging exactly from 1 to 100, which is perfect for the earthquake matrix. In order to adapt this sequence to different intensity scales, a different scheme for the series was found:

$$y = 1 + (x-1) \cdot [3 + a \cdot (x-1)] \qquad \text{with} \qquad a = \frac{99 - 3 \cdot (n-1)}{(n-1)^2}$$

The variable a is 2 for ten intensity levels and can be adapted for different scales with n being the number of levels. The so defined numerical orders all range exactly from 1 to 100 and have increasing intervals between the numbers. The calculated results of y should be rounded to integers.

In the final matrices, the values of the frequency scale are multiplied with the rounded values of the intensity scale. This multiplication results in partly decimal numbers, which are a problem in the later process of reassigning the values of the raster files (only integers are allowed). For this reason, all values are later multiplied with 100, but they are shown without this step in the following chapters.

6.2.1 Matrix for Earthquakes

The strength of an earthquake is generally measured with the C.-F.-Richter scale as presented in chapter 3.2. It ranges from 1 to 10 and the same range will be used for the intensity scale of earthquakes. Since there can be values between two whole numbers, the magnitude values will be rounded to the nearest whole number (e.g. 6.3 will be rounded to 6; 6.8 will be rounded to 7). For the numerical equivalents, the series of square numbers was used, because it includes ten values with growing space between them and ranges from 1 to 100. Due to the fact that the records of the significant earthquake database date back to 1500 A.D. the frequency scale can be shortened to the range of F_3 to F_6 (1 to 500 years). The intensity scale for earthquakes and the resulting frequency-intensity-matrix are presented in Table 10 and Table 11.

Intensity class	Magnitude range on C.-F.-Richter scale	Numerical equivalent
$\boldsymbol{I_1}$	0.5 – 1.4	1
$\boldsymbol{I_2}$	1.5 – 2.4	4
$\boldsymbol{I_3}$	2.5 – 3.4	9
$\boldsymbol{I_4}$	3.5 – 4.4	16
$\boldsymbol{I_5}$	4.5 – 5.4	25
$\boldsymbol{I_6}$	5.5 – 6.4	36
$\boldsymbol{I_7}$	6.5 – 7.4	49
$\boldsymbol{I_8}$	7.5 – 8.4	64
$\boldsymbol{I_9}$	8.5 – 9.4	81
$\boldsymbol{I_{10}}$	9.5 – 10	100

Table 10. Intensity scale for earthquakes based on the C.-F.-Richter scale.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}
F_3	0,2	0,8	1,8	3,2	5	7,2	9,8	12,8	16,2	20
F_4	1	4	9	16	25	36	49	64	81	100
F_5	2	8	18	32	50	72	98	128	162	200
F_6	10	40	90	160	250	360	490	640	810	1000

Table 11. Frequency-intensity-matrix for earthquakes.

6.2.2 Matrix for Volcanic Eruptions

As described in chapter 3.3, the intensity of volcanic eruptions is measured with the Volcanic Explosivity Index (VEI) ranging from 1 to 8. This leads to an intensity scale with eight levels and the value of a for the formula mentioned above is 1.5918. The calculated results were rounded to whole numbers in order to make calculations in the matrix simpler. Most records in the significant volcanic eruptions database include information about the VEI of the eruptions and can so be used with this matrix. The first records in the database are from 1900 B.C., which is why the whole frequency scale can be used for the matrix. The intensity classes with their VEI and numerical equivalents are presented in Table 12 and the final frequency-intensity-matrix is shown in Table 13.

Intensity class	Magnitude on Volcanic Explosivity Index	Numerical equivalent
$\boldsymbol{I_1}$	1	1
$\boldsymbol{I_2}$	2	6
$\boldsymbol{I_3}$	3	13
$\boldsymbol{I_4}$	4	24
$\boldsymbol{I_5}$	5	38
$\boldsymbol{I_6}$	6	56
$\boldsymbol{I_7}$	7	76
$\boldsymbol{I_8}$	8	100

Table 12. Intensity scale for volcanic eruptions based on the Volcanic Explosivity Index.

	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
F_1	0,02	0,12	0,26	0,48	0,76	1,12	1,52	2
F_2	0,1	0,6	1,3	2,4	3,8	5,6	7,6	10
F_3	0,2	1,2	2,6	4,8	7,6	11,2	15,2	20
F_4	1	6	13	24	38	56	76	100
F_5	2	12	26	48	76	112	152	200
F_6	10	60	130	240	380	560	760	1000

Table 13. Frequency-intensity-matrix for volcanic eruptions.

6.2.3 Matrix for Tsunamis

The dataset of tsunami runups includes a lot of information about the events, but only the water height can be connected with the Tsunami Intensity Scale to measure the strength of the tsunamis. It already includes five intensity levels and links them to certain water heights of the wave. For calculating the numerical equivalents, the variable a gets the value 5.4374 and the results are rounded to whole numbers to make later calculation easier. Table 14 shows the intensity classes for tsunamis with their according water height and numerical equivalents. The records in the tsunami runup database date back to 1500 A.D., which is why the first two frequency levels can be ignored. The final frequency-intensity-matrix is presented in Table 15.

Intensity class	Water height on Tsunami Intensity Scale	Numerical equivalent
I_1	1m – 2m	1
I_2	> 2m – 4m	9
I_3	> 4m – 8m	29
I_4	> 8m – 16m	59
I_5	> 16m	100

Table 14. Intensity scale for tsunamis based on the Tsunami Intensity Scale.

	I_1	I_2	I_3	I_4	I_5
F_3	0,2	1,8	5,8	11,8	20
F_4	1	9	29	59	100
F_5	2	18	58	118	200
F_6	10	90	290	590	1000

Table 15. Frequency-intensity-matrix for tsunamis.

6.3 CLEANING OF THE TABLES

The data, as it was requested from the National Geophysical Data Centre website, was displayed as simple tables looking like shown in Figure 3. These were copied into three individual Excel-Files (one for each database request) for easier handling and editing. As first step, the unnecessary columns of every table were deleted. For the significant earthquake database this included the associated events, because it is not important to know which earthquake also caused a tsunami or was part of a volcanic eruption as the natural events should be considered individually for the principle of

Greiving. The additional information about the effects of the earthquake (number of deaths, injuries, financial damage, destroyed and damaged houses) as well as photos of the event were also not important for this basic approach to creating hazard maps. The earthquake parameters focal depth and Mercalli scale were also ignored, because the records of the magnitude of the earthquake had fewer gaps in the data and were therefore chosen for the calculation. These gaps had to be ignored, because no strength could be assumed for those events. Some records were also lacking information of the location in exact coordinates. Those were also deleted so they will not cause errors in the further processing.

Date						Assoc		Addl EQ Info	Earthquake Location			Earthquake Parameters			Earthquake Effects										Photos
															Deaths		Injuries		Damage		Houses Destroyed		Houses Damaged		
Year	Mo	Dy	Hr	Mn	Sec	Tsu	Vol		Name	Latitude	Longitude	Focal Depth	Mag	MMI Int	Num	De	Num	De	$Mill	De	Num	De	Num	De	
1500						Tsu		*	HAWAII																
1668	4	13				Tsu		*	BOSTON AND SALEM, MASSACHUSETTS	42.350	-71.050			4											
1700	1	27	5	0		Tsu		*	CASCADIA SUBDUCTION ZONE	45.000	-125.000		9.0												
1755	11	18	9	11	35.0	Tsu		*	MASSACHUSETTS: EAST OF CAPE ANN	42.700	-70.300		7.0	8						2					
1788	7	21				Tsu		*	ALASKA PENINSULA: UNGA ISLAND	57.000	-153.000		8.0	7											
1788	8	6				Tsu		*	ALASKA PENINSULA	55.000	-161.000		8.0												
1792						Tsu		*	ALASKA: KODIAK ISLAND	57.000	-152.000			7						1					
1806	3	25	8			Tsu		*	CALIFORNIA: SANTA BARBARA	34.400	-119.700			6						1					
1811	12	16	8	15		Tsu		*	ARKANSAS: NORTHEAST (NEW MADRID EARTHQUAKES)	35.600	-90.400		8.5	11		1				3					
1811	12	16	14	15		Tsu		*	ARKANSAS: NORTHEAST (NEW MADRID EARTHQUAKES)	35.600	-90.400		8.0	10											
1812	1	23	15			Tsu		*	MISSOURI: NEW MADRID	36.300	-89.600		8.4	10						3					
1812	2	7	9	45		Tsu		*	MISSOURI: NEW MADRID	36.500	-89.600		8.8							3					
1812	12	8	15					*	CALIFORNIA: SAN JUAN CAPISTRANO	34.370	-117.650		6.9	8	40	1				2				1	
1812	12	21	19			Tsu		*	CALIFORNIA: PURISIMA	34.200	-119.900		7.5	8	1	1		1		2			100	1	

Figure 3. Significant Earthquake Database. First results for Country = USA.

The process was similar for the significant volcanic eruptions database. Here, the deleted columns included the associated effects like earthquakes, tsunamis and mass wasting, the elevation of the volcanoes and the type as well as the side effects (number of deaths, injuries, financial damage, destroyed and damaged houses) and photos of the events. Somehow, the requested database included records of other countries like Japan, so these records were also deleted. The magnitude of the eruptions is depicted as Volcanic Explosivity Index (VEI) and shows no gaps in the records so it could be left as it was.

Analog to the other two datasets, the tsunami runup database was cleaned as well. A lot of information about the events, like the source event and its magnitude, distance to the event source, travel time, maximum inundation, was deleted. Also the additional information about the number of deaths, injuries, etc. was deleted similar to the cleaning of the other datasets. All records with an event validity of less than 3 were deleted as only probable and definite tsunamis were wanted as basis for the hazard map. The column for the maximum water height during the event was important for the later processing as it will be used for the connection to the frequency-intensity-matrices as described in chapter 6.2.3. Some of the records were missing exact coordinates and were deleted to prevent later errors.

In summary, all databases were cleaned of unnecessary additional information remaining only with the date of occurrence, the coordinates, and an expression for the strength of the event like magnitude, VEI or maximum water height. Records without exact coordinates were also deleted, because they would cause errors in the subsequent processing. Now, the datasets were ready to create shapefiles and classify them for raster creation.

6.4 CREATING CLASSIFIED POINT DATA

After cleaning the tables of all unnecessary information, they can be loaded into ArcMap and displayed as XY data. The so created point layers were then saved as shapefiles for further processing. Figure 4 shows the result of this step with an administrative layer of the USA (Natural Earth Data) in the background for better orientation.

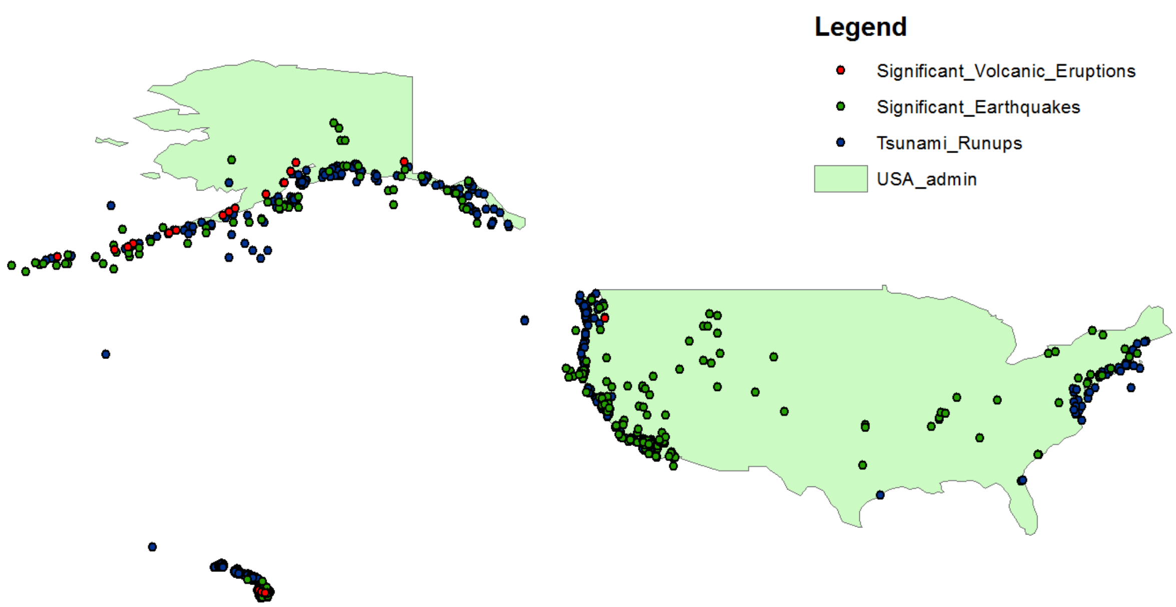

Figure 4. Point display of Significant Volcanic Eruptions database, Significant Earthquakes database and Tsunami Runup database in ArcMap with USA administative layer for orientation.

Now, each shapefile of the natural events had to be split into multiple individual layers each containing records in the specific range of each intensity level, which is connected to magnitude, VEI, or max. water height. For the significant earthquake database this meant a splitting into ten separate shapefiles. Every shapefile included a span of 1.0 magnitude points in a way that the files could be later connected with the frequency-intensity-matrices (more details in chapter 6.6).

Similar to the previous process, the significant volcanic eruptions database was split by the Volcanic Explosivity Index. This index does not allow decimal values between two natural numbers, so for this case every individual shapefile contained only one value of the Volcanic Explosivity Index which can later be connected with the intensity scale. The results after the classification were six individual classes with a VEI of 0 to 6. There were no records with VEI = 1 so the class with VEI = 0 will be used for intensity level 1 as these volcanoes are still important and can cause damage to the surrounding area.

Classifying the tsunami runup database was a different matter since the only indication to the strength of the tsunamis was the maximum occurring water height. The Tsunami Intensity Scale was used to solve this matter by splitting the shapefile according to the wave height in this scale. Since the first five groups of tsunamis refer to tsunamis with a wave height less than one meter and some groups share the same wave height, the levels of the intensity scale were chosen according to the intensity of the tsunami. The exact arrangement after Papadopoulos is shown in Table 16. The tsunami runup database was split into five classes ignoring all tsunamis with a maximum water height of less than one meter as they have the intensity of 0.

Tsunami Intensity	Wave height
0	< 1m
1	1m – 2m
2	> 2m – 4m
3	> 4m – 8m
4	> 8m – 16m
5	> 16m

Table 16. Connection of tsunami wave height and its intensity (after(Papadopoulos, et al., 2001)).

The so created individual shapefiles could now be used to create raster files where every cell contains the count of events that occurred in it. This will be used to determine the frequency in each cell of every intensity level in order to connect the information to the frequency-intensity-matrices.

6.5 CREATING RASTERS

As a next step, the classified shapefiles should now be converted into raster files in a way that they can be compared to each other and can be used in the next step of the hazard map creation, which will be described in chapter 6.6. To assure the individual raster files to be matching and comparable, a basic raster has to be used as snap grid for the raster conversion. It can be easily created with the "Create Constant Raster"-tool of ArcMap. The extent of the constant raster is determined by simply merging all the point shapefiles, which were created out of the three databases for the natural events. Some of the points were located west of the 180° meridian and would cause the later raster to spread from 180° W to 180° E. To prevent that, these points, which lay at the western part of the Aleutians and the Midway Islands, were deleted. They could be processed with an extra raster, but this thesis is only a prototypic implementation so it is not important to cover the complete area of the USA. The points were deleted in all shapefiles to prevent later errors. Now that the extent is determined the constant raster can be created with a raster cell size of 0.5° and a constant value of 0.

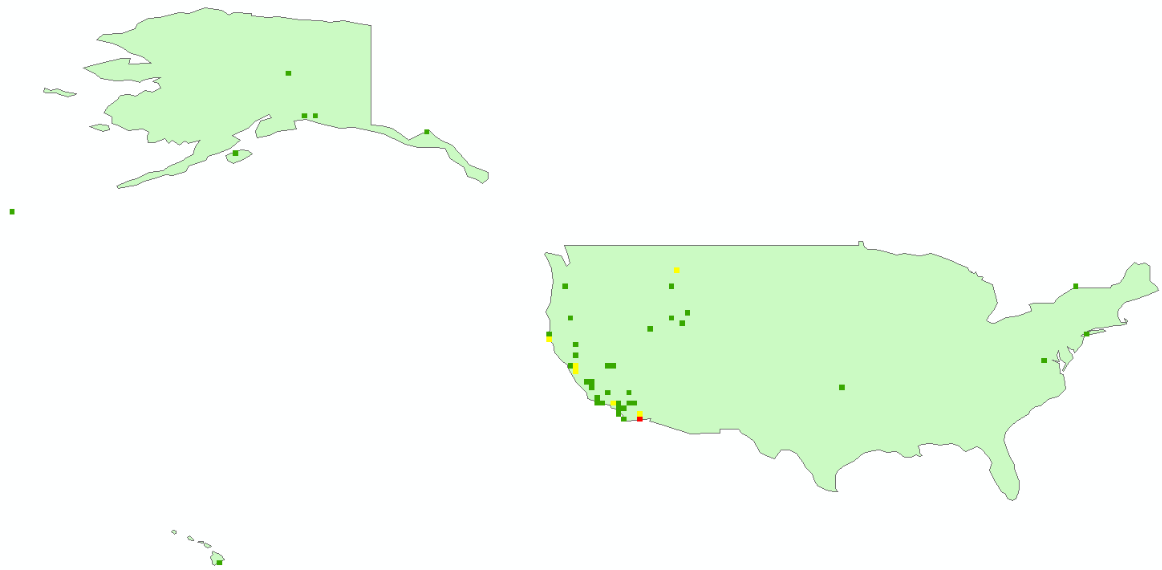

Figure 5. Raster created with the count of earthquake records of intensity level 6 with USA administative layer for orientation (green = count 1, yellow = count 2, red = count 3).

This constant raster can now be used as snap grid for converting the classified shapefiles to raster files. For this task the “Point to Raster”-tool of ArcMap is used. Each class of the natural events’ shapefiles will be used individually as input for the tool. Important is the cell assignment type, which should be count, so that the number of points in the raster cell will be counted and assigned to the cell. Again, the cell size should be 0.5° as the tool is not getting it from the snap grid, which is the previously created constant raster and is set in the “Environments” of the tool.

By using this method, raster files are created from all classified shapefiles of the natural events looking as shown in Figure 5. The count of points in each cell can now be used to determine the frequency of each cell. This is different for the volcano dataset than for the earthquake and tsunami datasets, because they have different time spans. The exact correlation of frequency classes and point count is calculated by dividing the total time span with the min and max of every frequency class. The results are presented in Table 17. The new values according to the frequency-intensity matrices can be assigned with the help of the “Reclassify”-tool. All raster cells, where the count of points was 0, were assigned “NULL”, which would be a problem for the later calculation of combining the raster files. For that reason, cells with a former “NULL”-value were now assigned with “0” as their new value and will not cause problems at the next calculation steps. All other cells were assigned with the values of the according frequency-intensity-matrices.

Frequency class	Number of points in cell	
	for volcanoes	for earthquakes and tsunamis
$\boldsymbol{F_1}$	1 – 4	
$\boldsymbol{F_2}$	5 – 8	
$\boldsymbol{F_3}$	9 – 39	1 – 5
$\boldsymbol{F_4}$	40 – 78	6 – 10
$\boldsymbol{F_5}$	79 – 391	11 – 51
$\boldsymbol{F_6}$	392 – 3914	52 – 500

Table 17. Assignment of frequency classes to the number of points in one raster cell.

The result of this whole step are ten raster files for significant earthquakes, six raster files for the significant volcanic eruptions, and five raster files for the tsunami runups.

The values of the raster cells correspond to the values in the frequency-intensity-matrices and cells with a "NULL"-value were set to "0". The outcome is shown in Figure 6.

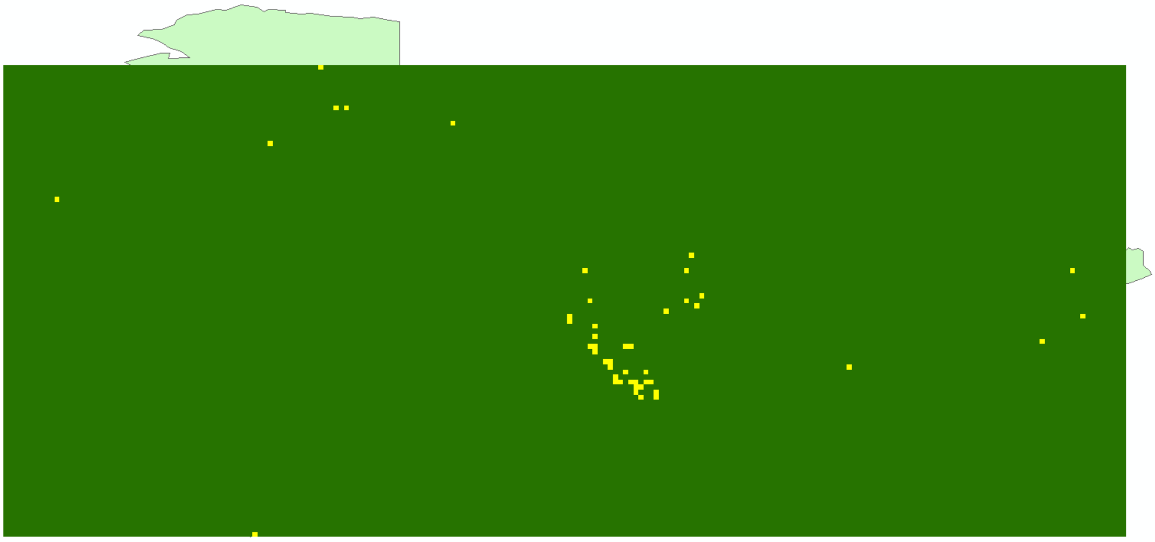

Figure 6. Raster created with the count of earthquake records with intensity level 6. Count was reclassified according to frequency-intensity-matrices and "NULL"-values were set to "0"(dark green).

6.6 COMBINING RASTERS TO A HAZARD MAP

After creating the raster files out of the classified shapefiles of the natural events, they can be combined to three individual hazard maps (one for each natural event). This will be done by calculating a sum of the raster files. The "Weighted Sum"-tool in ArcMap is perfect for creating a raster file from individual other raster files. The weighting factors were all set to 1, because the values from the matrices already gave a certain "weighting" to the raster cells. Greiving suggested to classify the individual hazard maps in five classes before adding them to the multi-hazard map so the maps can be better compared. This step is not necessary here, because the frequency-intensity-matrices already make the raster data comparable to each other. The resulting raster files were saved as GeoTIFF files and are ready to be used in the web-application that combines them to a multi-hazard assessment map (see next chapter).

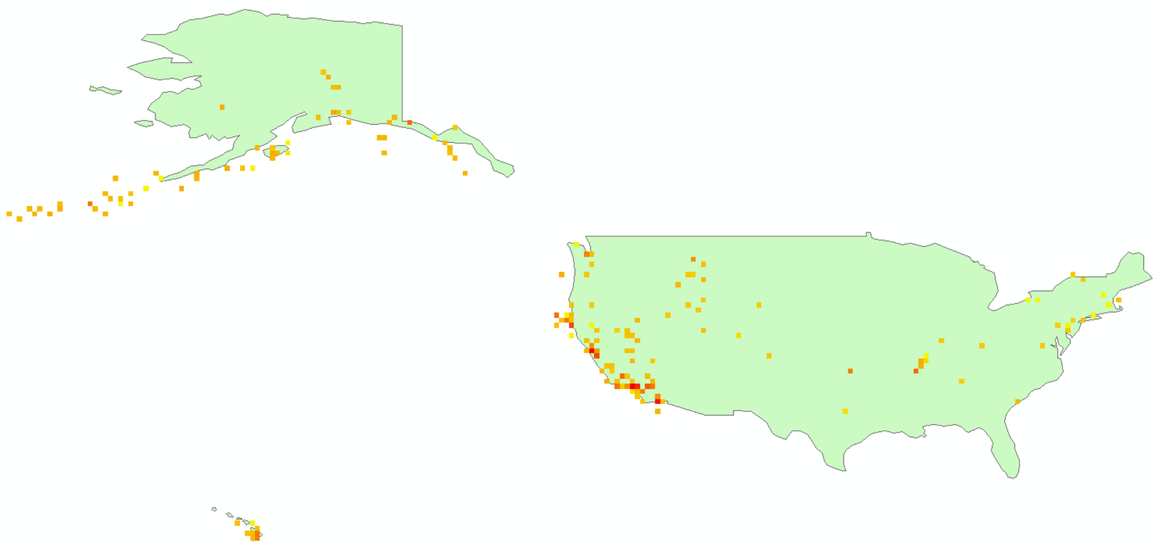

Figure 7. Sum of the significant earthquake database calculated in ArcGIS.

7 EMBEDDING DATA IN GEOTRELLIS WEB-MAPPING SERVICE

7.1 EXAMPLES OF ALREADY EXISTING APPLICATIONS

There are already a lot of risk maps existing online and most of them can be accessed for free. A first example would be the Natural Hazard Viewer by the National Geophysical Data Center (National Geophysical Data Center, 2014), which uses the same data as this thesis, but it displays all events as points with different symbols, colors and sizes. It gives an overview about where the events happened, but because they are all overlaying, some events might be hidden. For a user, who wants to get a good overview about where hazards occur, what kind, and with what strength, this is a bit too complicated.

Another example is the Nathan world map of natural hazards (Munich Re, 2011), which shows very detailed where on the Earth the different types of natural hazards occur. But this map is not interactive and does not even allow the user to inspect areas in detail. This makes it quite difficult to determine the risk for small areas, but it gives a good overview in small scale. A bit larger scales are presented in the world map of natural hazards from 1998 (Schweizerische Eidgenossenschaft, 1998) where the continents are inspected in detail and a lot of historical events are listed. But it is still a print product, which does not allow the user to interact and inspect smaller regions, and it is also a bit outdated.

The United States (e.g. FEMA) themselves also published a large selection of maps, which should help people to get a better overview on historical events of specific hazard types and dangerous zones in their county, but it is often difficult to find consistent maps for all states. In most cases, the maps also focus only on one kind of hazard and it takes a lot of time to find sufficient information for a specific area. Therefore, a prototypic multi-hazard map was developed in this thesis and the already processed data should now be presented in an interactive web-application, which gives the user a good overview of hazards in the USA and allows detailed inspections.

7.2 FAVOURED RESULT

For an industrial site selection the user should have a map, which shows the risk of every individual natural hazard that might occur in the area where he wants to settle. In the case of this thesis the area is equal to the area of the USA including Alaska and Hawaii. The later web map should show the whole region and enable the user to zoom into his special area of interest. For better orientation the map should have a scalable basemap that shows important cities, state boundaries, and coastlines depending on the zoom level. On top of this basemap, the natural hazard layer should be placed with a certain colouring to determine differences in the likelihood of hazard occurrence. The layer should also be a bit transparent in a way that the base layer is still visible.

The natural hazard layer should include all individual hazards added together in a weighted sum. This time, the weighted sum should be determined by the user's interests, which means that the user should be able to choose the weighting factors. That part is quite important, because the user might find certain hazards (e.g. earthquakes) important, but is not interested in the occurrence of other hazards (e.g. volcanoes) for some reason. To decide which hazard gets which weighting, there should be sliders next to the map.

To calculate a weighted sum on-time according to the user's request is not as simple as to only display some geodata layers. The solution is a geodata processing engine named GeoTrellis, which was created by Azavea. It is perfect for the project of a multi-hazard assessment map with the user interaction as mentioned above.

7.3 GEOTRELLIS

As described on their website, "GeoTrellis is a geographic data processing engine for high performance applications" (GeoTrellis, 2014). It works with the Scala programming language and the Simple Built Tool (sbt) as basis. The GeoTrellis project of Azavea has the goal to let the user interact with geospatial data with a realtime geospatial analysis in interactive web applications (GeoTrellis, 2014). It uses raster datasets for applications like a weighted overlay on a map where the user can select the weighting factors for each data layer. Such a project is also used as basis for the multi-hazard assessment map application of this thesis. Other features of GeoTrellis are also about the manipulation of raster data including cropping/warping, Map Algebra operations, and rendering operations, as well as vector to raster operations such as Kernel Density and vectorization of raster data. Besides that, GeoTrellis can also be used to do fast batch processing of large raster data (GeoTrellis, 2014).

In order to use GeoTrellis, the Simple Built Tool (sbt) has to be installed on the computer. GeoTrellis also works without installed sbt, but then an executable sbt-folder would have to be in the source folder of the project. However, this would take storage space away if more than one project is created. All files needed to run the application are downloaded when it is started, so no further installation is required. After the first start, the files are only downloaded again when imports are changed or the period since the last start is too long (e.g. one day). The sbt will check for updates of the used files in these cases. If it does not do this, the project can be cleaned and started again in order to download the newest updates.

When the project is ready to use, it can be installed on a sever using one exclusive port to show the web-application for the user. An extra folder containing the style of the web application has to be created and loaded to the server for that purpose. The user can then use the application in his browser of choice as long as he has the corresponding link. This makes the application available at every place with an internet connection, but to get a port from a server is not as simple as using some individual web space.

7.4 PREPARATION

Before the created raster files from chapter 6.6 can be used for a GeoTrellis application, they have to be converted to Azavea Raster Grid Format (ARG), which is a very simple encoded raster format. It consists of two files, the JSON metadata file that contains all information about extent, geo-location, cell-size, and coordinate system (see the example Figure 8). The second file contains the values of every cell in binary format starting from the upper-left to the lower-right corner of the raster file.

```
{
      "layer":"Earthquake",
      "type":"arg",
      "datatype":"int8",
      "xmin":-179.971000,
      "ymin":18.910000,
      "xmax":-69.471000,
      "ymax":65.410000,
      "cellwidth":0.500000,
      "cellheight":0.500000,
      "rows":93,
      "cols":221,
      "epsg":4326
}
```

Figure 8. Example for JSON file of the Azavea Raster Grid Format (ARG).

The raster files can be easily converted from GeoTIFF to ARG by using python GDAL with the `gdal_translate` command. GDAL is part of OSGeo4W, which makes an installation quite simple. After converting the raster files, the datatype in the JSON-files had to be changed from “uint8” to “int8” otherwise the files were not readable for GeoTrellis. The raster files in ARG format were now ready to be used with the GeoTrellis application.

7.5 THE MULTI-HAZARD ASSESSMENT MAP

With the help of GeoTrellis, a multi-hazard assessment map was created with the processed and prepared hazard data. The application is available at http://141.30.137.195:8888/. Most parts of the project were adopted from the GeoTrellis Chattanooga demo (GeoTrellis, 2014), which is also working with a weighted overlay, but it has more features that are not necessary for the multi-hazard map.

The website opens with the map showing a large section of the data in most of the USA with a part of Alaska. Each data layer has the same weighting factor (3) in order to show a simple sum of the three natural hazard raster files. The raster cells appear not quadratic due to the web Mercator projection, but they still have the size of 0.5°x0.5°. The color ramp goes from yellow to red where yellow cells have a lower risk and red cells have a larger risk of an occurring natural hazard of any kind. If only a single kind of hazard should be presented, the weighting factors of the others have to be set to zero. By panning and zooming the whole dataset can be shown and further explored. The raster overlay is always only calculated for the map extent, which can lead to changes in the colors of the cells and also their placement, because the coordinates of the map corners have to be converted to WGS84 and with larger scale the conversion gets more accurate. An example of how the GeoTrellis map looks is presented in Figure 9.

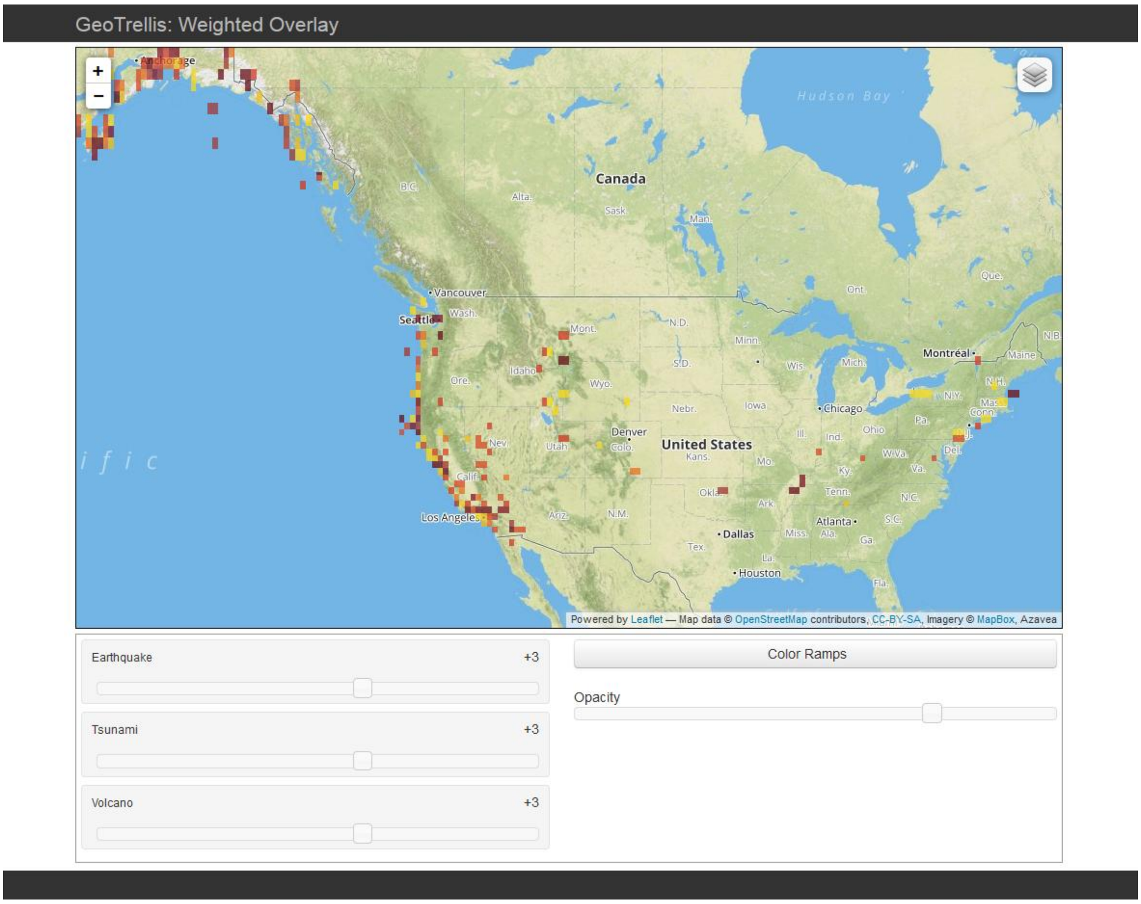

Figure 9. GeoTrellis map with the natural hazard layers as weighted overlay.

The color ramp of the raster overlay ranges from yellow, for areas where hazards occur, but with low intensity and/or frequency, to a dark brownish red, which indicates that hazards have higher intensities and frequencies in these cells. Areas with no raster overlay have either no data of historical events or are free of the three hazard types: earthquake, volcano and tsunami. However, the cells should not be seen as strictly defined areas where hazards might occur, but rather as indicators that in the area of the cell and maybe also in the surrounding area hazards are likely to occur.

7.6 USER MODIFICATIONS

Since the multi-hazard assessment map is interactive, the user can make specific modifications to the map in order to apply it to his wishes. Most important are the sliders for the weighting factors of the hazard layers, which are placed on the beneath the map. Those weighting factors range from 0 to 5 and are used to define the importance of a specific layer. Every layer will be multiplied with its weighting factor and a weighted sum of the layers will be displayed in the weighted overlay of the map. If one natural hazard (e.g. earthquakes) is of high importance for the user, the weighting factor should be set to 5. Another layer, which might be less important for the user, but should still be included in the map, will be set to a lower weighting factor like 1 or 2. For the case that one hazard (e.g. tsunamis) should be excluded from the map, the weighting factor can be set to 0.

In addition to setting the weighting factors, other more basic changes can be made to the map. The user is allowed to pan and zoom in and out of the map for closer exploration of areas of special interest. The basic layer can be changed from “Default” to a less distracting “World Light” map, which shows only administrative boundaries and important names without any coloring. The colors of the weighted overlay can also be changed with the help of the “Color Ramps” menu. Additionally, the opacity of the weighted overlay can be changed with the “Opacity” slider in order to make the basemap visible and increase the orientation.

7.7 CODE INSIGHTS

The GeoTrellis application for the presentation of the data as weighted overlay and also user interaction with the data has the typical structure of a GeoTrellis project (as presented in Figure 10). Within this chapter, the heart of the whole application is presented and explained with some small code insight. It is the “GeoService.scala”-file, which can be found in the “scala”-folder. The file is actually larger, but the presented part contains the code, which creates the weighted overlay. Most of the code taken from the Chattanooga demo of GeoTrellis and modified.

```
weightedOverlayServer/
   geotrellis/
      data/
         < arg-files >
      project/
         < folder created by GeoTrellis >
      src/
         main/
            resources/
               < files to include in main jar >
            scala/
               < main scala sources >
   web/
      < html, css, and javascript files for appearance of website >
```

Figure 10. Folder structure of GeoTrellis project.

The “GeoService.scala”-file includes the most important part of the code of the whole application. When the website is opened or the extent shown by the map is changed by zooming or panning, the first part of the code (see Figure 11) will be running. At first, the bounding box of the map is requested to get the exact part of the raster that should be displayed above the map content. These values of the bounding box are delivered by the “application.js”-file in the “web” folder. The requested bounding box coordinates from the map are delivered in web Mercator projection, but they have to be transformed to WGS84 in order to be used with the raster layers. This is done with the “toGeographic()”-function.

The next step deals with the weights of the individual hazard raster files. They are also delivered by the “application.js”-file as strings and are now split into arrays and converted to integer format in order to use them for the calculation. Now, the overlay data layer is prepared with the weights of the hazard raster files, their addition, and the transparency is defined. “.zip” connects the layer array with the weights to a two-dimensional array and “.map” multiplies every raster with its weighting. With the help of “.localAdd” the weighted raster files are added to one layer and “.localMap” sets “0”-values to “NODATA” so they will be displayed as transparent cells. The last part defines the color ramp of the weighted overlay to range from yellow to a dark red.

```
val geoBbox = toGeographic(bbox)
val extent =
        Extent(geoBbox.getMinY(),geoBbox.getMinX(),geoBbox.getMaxY(),geoBbox.getMaxX())
val re = RasterExtent(extent, height, width)

val layers:Iterable[String] = layersString.split(",")
val weights = weightsString.split(",").map(_.toInt)

val overlay = layers
        .zip(weights)
        .map { case (layer, weight) => RasterSource(layer, re) * weight }
        .localAdd
        .localMap{ x => if (x > 0) x else NODATA }

val ramp = ColorRamps.HeatmapYellowToRed
val png:ValueSource[Png] = overlay.renderPng(ramp)
```

Figure 11. Part of the code that creates the weighted overlay.

8 COMMENT TO POSSIBLE IMPROVEMENTS

Since the application is a prototypic implementation, there are several points, which could be improved in future work. The first point deals with the quantity of the data, which was used for the application. Instead of only using data for three types of natural hazards, all hazard types should be covered, but all data should include similar time spans and should also have similar resolution. However, with the inclusion of all hazard types comes also the difficulty to find intensity scales for all kinds of hazards. Especially wildfires and floods are difficult to measure and it is also hard to say if they will occur with the same strength again in the same area.

The quality of the data could also be improved, but this always depends on the study area. If the area is smaller, the data can be more detailed and especially the USA often offers special datasets for a state or county. It would be quite useful to know the exact spatial extent of every hazardous event instead of only points, or at least a radius of the area around the point that was affected by the event. Also datasets with more records, even the smaller ones, would increase the accuracy of the hazard maps.

With better quality and quantity of the base data, the raster for the hazard maps could also be improved regarding the size of the raster cells. This could be done in a way that raster cells would not be visible anymore and particularly hazard prone areas would have fuzzy borders, which would match the actual nature of hazards much better. This would also mean that the multi-hazard map could be much more useful for larger scales.

The GeoTrellis application itself could also be improved, which would require a better documentation of GeoTrellis, because most functions are not yet described by the developers and that makes programming quite difficult. An important point for improvement is the placement of the raster overlay. At the moment the coordinates are taken from the map extent, transformed to the raster coordinate system, and then the raster extent is placed in the map. The transformation leads to mistakes in accuracy and this can be seen at the edges of two tiles or by zooming in or out.

The user interface could also be improved by means of making it look more appealing. Some descriptions about how the map works, what it shows, and how the user interactions can change the content of the overlay would also be useful.

9 SUMMARY

Within this thesis, a prototypic implementation of an industrial site-selection with a minimum natural risk approach was presented. It was made to help a company to get an overview of all kinds of natural hazards, which could happen in an area in order to pick a safe place to built a new site and be prepared for the natural hazards that might still occur there. As investigation area, the USA including Alaska and Hawaii were chosen, but with the right data, the application could be used for any part of the world. The processed data is presented in an interactive GeoTrellis web application, which allows the user to change the map to his needs.

As fundamentals for the further work, the terms of hazard, risk and vulnerability were defined for the background of natural events. Those natural events can be volcanic eruptions, storms, or floods, etc. and they can appear at some places with a certain probability. At the point where human life and goods are harmed by such events and financial or human losses occur, the term of natural hazard is used. This obviously only occurs when people expose themselves to the risk of a natural hazard, which should be avoided with the help of the developed site-selection application. In this setting, risk refers to the probability that a certain hazard occurs in a certain area with certain strength. The term vulnerability is a bit more complicated as it not only refers to a human or property being exposed to the risk, but also to the capabilities to cope with that risk in terms of financial means and structure stability. In an area, where a certain natural event is known to occur quite often, people are usually prepared for it, but their funds might not allow them to pay for repair, insurances, etc., which means that their vulnerability is high. However, the here presented application deals with lowering the vulnerability by avoiding risky areas and increasing the knowledge about which natural events occur where.

Now that the important terms were clear, it was time to investigate the chosen area and research what kinds of natural hazards are occurring in the USA. The list included earthquakes, volcanic eruptions, extreme wind events (hurricanes, tornadoes, etc.), landslides, floods and wildfires. Next to describing how those natural events work, it was important to show scales that can be used to measure the strength of those events in order use them later for data processing. To give a better impression on how dangerous those hazards are, examples of historical events were presented.

As next step, natural hazard risk assessment strategies, that could help to develop the hazard map, were researched. In many cases, the vulnerability of the area was combined with the probability of an occurring natural hazard. Since the vulnerability should be lowered by avoiding hazard prone areas, it should not be included in the process of site-selection. So the probability came more into focus and it was to be estimated with the help of frequency-intensity-matrices on the basis of historical events.

Due to the fact that in the later application all natural hazards should be combined in one map, the approach by Greiving in 2006 was used as guideline for the process of creating a multi-hazard map. He started with the creation of an individual hazard map for each kind of hazard and later assembled them to an integrated hazard map. Each hazard map got a certain weight depending on expert opinions on their importance. In the case of this thesis, an expert opinion was not available and the idea occurred of letting the user decide which kind of natural hazard he thinks is more important to him and let him therefore set the weighting factors.

Now that the basic guidelines were set, it was time to search for suitable data. As this thesis is only a prototypic implementation, it was not necessary to use data for all kinds of hazards. The ideal quality of the data would have been a dataset with all historical records of the area including information about the exact time, strength, and place as area information. The actually used data were three free datasets from the US government for significant earthquakes, significant volcanic eruptions and tsunami runups. They all include a large list of historical events with their strength and time of occurrence, but the spatial information only consists of point coordinates and no information about the affected area. However, these datasets were sufficient to show the prototypic implementation.

In order to start with the processing of the data, the frequency-intensity-matrices had to be created for the three hazard types. The frequency scale was the same for all matrices and used a logarithmic scheme in the basis of the time span covered by the datasets. The intensity scales were based on the well-established scales, which are normally used to measure the strength of each hazard type. Both scales were combined together in three frequency-intensity-matrices. After the datasets were converted to point layers in ArcGIS, they were split up into the intensity levels. Those were then converted to raster files, where every cell contained a count of points of events that happened in that cell. On the basis of this count, a frequency was assigned and the cells could be reassigned with the values of the frequency-intensity-matrices. The individual raster files were now added together in order to create three hazard maps for the three hazard types.

The last step was to combine those hazard maps into a multi-hazard map as it was suggested by Greiving. This was done in a GeoTrellis application that includes on-time data processing, which allows the user to interact with the map in a way that he can set the weighting factors for each kind of hazard. The application consists of a basemap for orientation and the weighted overlay, which is a weighted sum of the three hazard maps. The map then shows areas with a certain probability of occurring hazards with the help of colored raster cells and the user can decide which hazard type is more or less important for him and adapt the map to his needs.

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