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Preface

This thesis marks the end of a five-year journey to obtain a Master of Science in Risk Management at the University of Stavanger. The has been done research and been written from January to June 2019.

The choice of topic has been influenced by an interest in the Arctic and more specifically Svalbard, which I got from a summer spent in Longyearbyen taking a course integrated in my master. The thesis has required me to immerse myself into a whole new and interesting topic, and in doing so there has been no shortage of challenges. To overcome these challenges, special thanks are owed to my academic supervisor, Associate Professor Roger Flage (University of Stavanger) and external supervisor, Professor Seth Guikema (University of Michigan).

A special thanks is owed to my fellow students and co-workers for making these last five years as remarkable as they have been. An additional thanks to Marie, who was so kind as to help me with maps of Longyearbyen, and Vikrant whom I consulted on constructional engineering.

Finally, I will quickly thank my family and friends back home. A special thanks to my mother, father, and uncle for proofreading and coming with constructive advice regarding my thesis.

Emmerentia Egidius Austvik, Stavanger 15/6-2019

Summary

During the last decades, climate change has been a heavily debated theme in both the news media and in the academic world. A warmer climate will have huge implications for large areas around the world, and the Arctic has received special concerns related to climate change lately. Because of polar amplification, temperatures will rise much faster in the Arctic and Antarctic regions than in the rest of the world. One of the consequences of climate change is thawing of permafrost, which potentially can damage buildings and infrastructures that are constructed on top of it. Because heat is transferred from building to ground, it results in the ground to move which consequently makes the buildings move as well. This phenomenon will be further impaired by climate change.

The main objective of this master thesis is to investigate the damage to buildings as a result of different levels of permafrost thawing for the community in Longyearbyen, Svalbard. The levels of different permafrost thawing are based on climate change scenarios from the IPCC (Intergovernmental Panel on Climate Change).

The methods chosen in this thesis was developed and first used to estimate damage and costs due to climate change in the Russian Arctic. The method has then been adapted to fit specific issues in Longyearbyen, where a higher level of salinity could be a problem. The method is a semi-quantitative assessment, which is modified to highlight assumptions. It needs little data to produce values, but this results in rather crude numbers. The method used in this thesis contributes to existing methods because it has introduced a semi-quantitative assessment which is adapted to fit local challenges and it measures the effects of climate change on buildings in Longyearbyen. As far as the author know, this has not been done to this extent earlier.

The results from different climate scenarios uncover that there might be need for different focuses with shifting scenarios. For the least severe scenario there is a bigger need for research on failure limits of bearing capacity and thaw subsidence. In the case of the other two more severe scenarios, bigger efforts may be put into research regarding construction methods for a warmer climate, along with recommendations for how to secure important existing buildings. Some specific areas should receive special attention, where the most critical areas are Lia and Nordre Lia.

There is a need for more research as a mitigating measure, especially regarding how the soils reacts to climate change and hence also the limits of failure of bearing capacity and thaw subsidence. This will help increase the accuracy of the vulnerability assessments of at least the mildest scenario. These is also a need for finding more information about critical areas, and information about areas that lacks information. Testing the validity of the equation for thaw subsidence is also important.

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List of Abbreviations

ALT	Active layer thickness
ESD	Empirical statistical downscale
ESM	Earth system model
COSO	Committee of sponsoring organisations
GCM	Global climate models
ISO	International organisation for standardisation
IPCC	Intergovernmental panel on climate change
QRA	Quantitative risk assessment
RCM	Regional climate model
RCP	Representative concentration pathway

1. Introduction

1.1 Background

During the last decades, climate change has been a heavily debated theme in both the news media and in the academic world. According to the Intergovernmental Panel on Climate Change (IPCC), the worlds mean temperature has already increased by 1°C since pre-industrial times (IPCC, 2017). Climate change is defined by NASA (2014) as a change in the usual weather found in a place. This could be a change in how much precipitation one finds in a place throughout a year, or it can be the change in temperature for a month or a season. Unlike climate, weather can change in a matter of hours. Climate takes hundreds, or even millions of years to change (Shepherd, 2005).

Warmer climate will have huge implications for large areas around the world. To mention a few; dessert areas will expand, oceans will become more acidic (which in turn will result in coral bleaching), sea level will increase due to glacial melt, increased frequency of storms, floods and other extreme weather events that will make it more difficult for people in certain areas to live (IPCC, 2013).

The Arctic has received special concerns related to climate change lately. Because of polar amplification, temperatures will rise much faster in the Arctic and the Antarctic regions than in the rest of the world. Polar amplification is the phenomenon that warming and cooling tend to be stronger over high latitudes, particularly over the Arctic where the heating will be roughly twice as strong as on lower latitudes (Lee, 2014; Wickström, 2018).

Furthermore, the Poles work as the “air conditioner” of the world because of heat loss from these areas. This is due to heat transportation with large weather systems from Equator, where the suns radiation is at its strongest, up to the Poles where this heat can escape back out through the atmosphere. The poles also reflect more of the energy from the sun due to the albedo effect (Norwegian Polar Institute, 2014).

The Arctic region is an area of growing strategic importance, which is partly why states such as Russia keeps the coal mining going on Svalbard even though it has not been commercially viable for many years (Åtland, 2004). There is also a growing interest for the Arctic as a tourist destination, which will have repercussions on the Arctic’s fragile environment if not managed with care.

Another consequence of warmer climate that can have world-wide consequences is permafrost thawing. Permafrost is defined as ground which remains at temperatures below 0°C for at least two consecutive years. Permafrost significantly affects geomorphic, ecologic, and hydrologic processes in the high latitudes (Streletskiy, Suter, Shiklomanov, Porfiriev, & Eliseev, 2019). Within the permafrost, large amounts of methane and carbon dioxide gas are trapped, and since methane gas is a strong greenhouse gas it is feared that release of this gas will further increase the greenhouse effect. Currently, permafrost occupies 20-25% of the Northern Hemisphere (Humlum, Instanes, & Sollid, 2003), and hence there is a potential for enormous releases of methane. Because of this it is important to continuously monitor and assess the Arctic region; the environment, its people and the linkages to global feedback systems.

Permafrost thawing has consequences at a more local level as well. For example, it has a large impact on the stability of hills, coastal erosion, and the infrastructure that is built on top of permafrost soil. Ecological change such as new vegetation is also a result from climatic change, and can already be seen in Alaska (Osterkamp, 2009). Furthermore, it affects human activities such as the costly and unique engineering designs and practices that had to be developed to maintain the thermal stability of permafrost during the construction and lifespan of infrastructure. An increase in temperatures in permafrost areas can significantly reduce the ability of frozen ground to carry loads imposed by structures. It can also result in ground subsidence and uneven surface deformation, which can further reduce the stability of engineering structures (Streletskiy et al., 2019). As a matter of fact, the Global Sea Vault at Svalbard now need to be deconstructed due to the permafrost inability to restabilise after construction. This is due to the unexpected change in temperature and weather conditions (Henriksen, 2017).

This thesis will focus on a local level. As mentioned in the previous section, thawing of permafrost can potentially damage buildings and infrastructures. Conventional construction method should not be used in permafrost areas, as this will cause heat to transfer from building to ground. Because when the ground begins to heat up and starts to move, it consequently makes the house move as well and contributes to making the construction unstable. Therefore, special building techniques have been developed in order to keep buildings on top of permafrost soil stable. In Longyearbyen, which is the focus on this thesis, the most common way to build houses are on piles that are drilled down into stable permafrost. However, some are built on a direct foundation, and many of them have exceeded their estimated lifetime even though it was anticipated that it would fail long ago (Instanes & Rongved, 2017).

Due to the thawing of permafrost, precautions that once were enough to build safe infrastructure in the Arctic, will not necessarily be adequate in the future. Other measures must be taken into consideration. Therefore, the focus of this thesis is going to be conducting a vulnerability assessment of the potential complications that thawing of permafrost might lead to for the community of Longyearbyen.

1.2 Objectives

The main objective of this master thesis is to investigate the potential damage to buildings as a result of different levels of permafrost thawing for the community in Longyearbyen, Svalbard. The different levels of permafrost thawing are based on scenarios from IPCC. This main objective will be achieved through fulfilment of the following partial objectives;

- Identify likely temperature and thawing scenarios
- Investigate how much damage that will be inflicted for each scenario
- Present a vulnerability description

1.3 Scope and Limitations

The thesis will cover selected public constructions and private buildings. Roads, pipes, the piers (Nykaia and Kullkaia) and other infrastructure in the city will not be included because of lack of reliable data and that it is too time consuming. Other structures, such as cottages located around Longyearbyen, the airport and the Kjell Henriksen Observatory will also not be included. The buildings that are included will be described in more detail in Chapter 2.

Permafrost thawing leads to other risks, that will not be included in this thesis. Examples of these are destabilisation of hills which will lead to increased frequency of rock and debris flows that in turn can damage infrastructure. However, the risks of slope processes will be mentioned in section 3.4.1. Costal erosion that potentially will erode areas where there currently are buildings, will not be included either.

1.4 Definitions

Risk	The two-dimensional combination of consequences (of the activity considered) and the associated uncertainties (what will be the consequences of the activity?) (Aven, 2015)
Vulnerability	The two-dimensional combination of the consequences (of the activity considered) and the associated uncertainties (what will be the consequences of the activities?) given an initial event (or a risk source) (Aven, 2015).
Climate change	A change in the usual weather found in a place. This could be a change in how much precipitation one finds in a place throughout a year, or it can be the change in temperature for a month or a season NASA (2014).
Permafrost	Ground which remains at temperatures below 0°C for at least two consecutive years (Streletskiy et al., 2019).
Active layer	The top layer of soil within a permafrost area that thaws during the summer, and freezes during winter (Hanssen-Bauer et al., 2019; Humlum et al., 2003; Isaksen et al., 2017).

2. Structures Included in the Thesis

The areas shown in Figure 1, are Sjøområdet, Skjæringa, Melkeveien, Elvesletta Sør, Midtre Elvesletta, Nordre Elvesletta, Sjøskrenten, Forskningsparken, Gruvedalen, Sentrum, Lia, Nedre Lia, Nordre Lia, Haugen and Svalbardhallen. The geographical divisions of the “city parts” are based on the type of buildings found in the areas, along with fairly homogenous geology for each area. Some of the areas have already been defined by previous efforts to retrieve information about ground conditions, and some are made for this study.

- The areas designed earlier are; Sjøområdet, Sjøskrenten, Skjæringa, Midtre Elvesletta, Elvesletta Sør, Sentrum, Lia, Haugen, Svalbardhallen, Forskningsparken and Gruvedalen
- The areas made by author are; Elvesletta Nord, Nedre Lia and Nordre Lia.

Figure 1: Overview of selected areas of Longyearbyen. Figure: Marie Olsen

The buildings shown with a yellow colour are residential buildings, whilst the grey/beige ones are public buildings or other buildings such as hotels and restaurants/cafés. In both Melkeveien and Elvesletta Nord one can see that there are no buildings yet. Melkeveien is an area that is planned for residential buildings. There are still no plans for Elvesletta Nord, and therefore this area will not be included in this thesis even though there are some records of examinations of the ground conditions. These records have on the other hand been used to estimate certain ground conditions of nearby areas, which will be reviewed more in-depth in Chapter 4.

There are several specific buildings which Statsbygg has already made an analysis of. For these buildings extensive knowledge has been gained about not only the ground conditions, but also the foundation and how it is estimated to be affected by climate change. These buildings are; Forskningsparken, Radisson SAS, Svalbard Kirke, Sysselmannsbygget, Sysselmannsgården, Statsbygg Kontor, Statsbygg Lager, Post- og Bankbygget, Næringsbygget, Kulturhuset, Svalbardbutikken, and Kjell Henriksen Observatoriet. The locations of these buildings are marked in Figure 2.

Figure 2: An overview of the buildings that ground conditions and the buildings stability is already evaluated. (Rognved, Eraker, & Instanes, 2017).

In this thesis the areas that will be included are shown in the map above. Due to the large risk of snow avalanches, Nybyen is soon to be abandoned and will therefore not be included in this thesis. The areas are identified based on assumed geological similarities, even though there might be local variations. Furthermore, ground conditions in some areas of the city are not as well documented as others, and because of this, assumptions have been made that nearby areas are similar.

The piers, Nykaia and Kullkaia has not been included in the thesis either, due to the very specific prerequisites that piers need to fulfil in order to be operational. Gammelkaia/Sjøomådet will however be included because it is not mainly used as a pier anymore, because of poor ground conditions.

3. Climate Change on Svalbard

Svalbard is located in the midst of the most important area for atmospheric heat transportation to the Arctic, where variations in weather together with ocean currents from the Atlantic and sea ice prevalence during winter time leads to large natural fluctuations from year to year, and from decade to decade (Isaksen et al., 2017). As a result of this, the Barents Sea, along with the Svalbard Archipelago, are experiencing one of the fastest temperature increases in the world, together with the highest rate of sea ice loss in the Arctic (Descamps et al., 2016).

This chapter reviews how the climate has been and how it will be affected in the future at Svalbard. This is done through a historic description of what has happened over the past 100 years, together with prognosis of the future climate up to 2100 and to some degree for 2200. An evaluation and prediction of changes in temperature, precipitation, and wind will be included in both the past and the future climate review. In the first section, however, an inspection of how the climate will change in the rest of the Arctic will be reviewed. At the end of the chapter, an examination is made of how these changes in weather will affect the permafrost.

Much of the following information is retrieved from Isaksen et al. (2017), which is the first part of three in a report that seeks to determine how to best manage constructions in a long-term perspective in Longyearbyen. It presents a thorough review of the historical development of the climate, which includes temperature, snow and rain, and wind. There are also estimations of how the future climate is going to develop, until 2200, based on three emission scenarios made by IPCC. These three are called; “RCP8.5”, “RCP4.5”, and “RCP2,5”, which each represent certain scenarios based on what might happen in the future. RCP8.5 is considered as a “worst case scenario”, where emissions of greenhouse gases continues to increase throughout the century, RCP4.5 is where emissions are the same until 2050, and then decreases toward 2100. RCP2.6 is viewed as the “best case scenario”, which included drastic emission cuts already from 2020.

3.1 Climatic Change in the Rest of the Arctic

The circumpolar Arctic region consist of the partly ice-covered Arctic Ocean along with land areas of the eight Arctic States; Canada, Denmark (including Greenland and the Faroe Islands), Iceland, Norway, Sweden, Finland, Russia, and the United States (European Environment Agency, 2017). Exactly where the limits of the Arctic go, is not specifically defined. However, IPCC chooses to define the Arctic as the area within the arctic circle (66°N) and incorporating a degree of flexibility when describing the polar regions in areas in relation to particular subjects (Larsen et al., 2014). The following sections will describe what will happen in various areas of the Arctic, along with global challenges as a result of a warmer Arctic.

As mentioned earlier, the Arctic will warm more rapidly than the rest of the world due to polar amplification. This refers to the phenomenon that warming and cooling trends are strongest over high latitudes, particularly over the Arctic. This can be found in historical events, such as during the last glacial maximum when the gradient was higher than of the present day climate. Polar amplification is also evident today, as the fluctuations of the surface temperatures near Equator are smaller, but increase with latitude, and are largest in the polar regions (Lee, 2014). It is not known exactly how much the fluctuation is affected in the Arctic, however, it is estimated that the heating is approximately twice as high as on lower latitudes (Wickström, 2018). Polar amplification is a result of heat that has been transported from lower latitudes get "trapped" at the poles, because it cannot escape as efficiently through the atmosphere as before (see Chapter 1 about "air-conditioner of the world").

Exactly how much the Arctic is going to warm is not easy to predict. According to IPCC (Larsen et al., 2014), there is evidence that Arctic land surface temperatures have risen substantially since mid-20th century, and the future rate is expected to exceed the global rate of today. How much is however difficult to estimate. Sea ice extent has decreased considerably over the last decades, and it is expected that the Arctic Ocean will be nearly ice free during summer time within this century. Since the late 1970s, the permafrost temperatures have increased between 0.5°C and 2°C.

A lack of sea ice will also affect the ability to reflect the energy from the sun back out from Earths atmosphere, also called the albedo effect. Ice has a higher ability to do reflect the radiation waves compared to other surfaces, such as a body of water. The albedo effect means that surfaces such as ice or thick clouds reflect more radiation from the sun than for example the ocean. If the ice melts, the albedo effect will decrease and more radiation will be trapped in the Earths atmosphere (Norwegian Polar Institute, 2014). This means that if the ice melts, the amount of trapped radiation from the sun will increase, and in turn it will lead to an acceleration of heating on a global scale.

As a result of an ever warmer Arctic, it is observed numerous concerns and challenges that will affect not only the Arctic, but the whole world as well (European Environment Agency, 2017). One of them is melting of land based ice masses, such as over Greenland, Iceland, and Svalbard, as it contributes to a global sea level rise (European Environment Agency, 2017). For low lying countries such as Bangladesh or The Netherlands, this may result in large parts of these countries being uninhabitable.

Finally, an introduction of freshwater into the Arctic basin from the Greenland ice sheet and other melting glaciers in the Arctic and northern Europe, can affect the thermohaline circulation, which drives the North Atlantic current and has a strong influence on European weather and climate. The thermohaline circulation is the system of oceanic currents which is controlled by temperature and salinity, and with an influx of fresh water, the salinity will drop and might affect the currents.

On a more local level, altered ecosystems change the breeding conditions for several migrating species, including a large number of bird populations. There is also a potential problem with invasive species that enter Arctic biodiversity. Furthermore, the rising of atmospheric greenhouse gas concentration has led oceans to absorb more carbon dioxide and become more acidic. Oceanic acidification affects the lower levels of the Arctic food chain, in particular plankton, which is essential to maintain the Arctic fish stocks, and in turn - their predators and migrating whales (European Environment Agency, 2017).

Due to properties of the global wind system, long-range pollutants are transported to the Arctic and stored in the ice and snow there. When this melts, it enters the Arctic food chain and can be a hazard for living creatures. These pollutants include herbicides, persistent organic pollutants (POPs), mercury, radioactivity, and black carbon. At this time, pollutants are still at safe levels within fish and shellfish, but higher levels of POPs and mercury have been found in marine mammals (NPI, 2018).

As already mentioned, it is difficult to estimate how much the temperatures in the Arctic have increased and especially how much it is going to increase in the future. The differences in temperature varies widely according to latitude, topography, wind, and land cover. This problem goes for Svalbard as well. Later it will be described that there are not only large amounts of uncertainty related to air temperatures, but to permafrost temperatures also.

3.2 Historical Climatic Development in Svalbard and Todays Climate

At Svalbard Airport one of the oldest systematic measurements of temperature in the Arctic exists, which goes all the way back to 1898. This makes it easier to estimate the changes of temperatures near Longyearbyen. In 1975, the Meteorological Institute (MET) installed a year-round manned weather station that measures precipitation levels at the airport as well. Furthermore, when collecting measurements from Longyearbyen and around Isfjorden one can establish a series of historical precipitation back to 1912. There are, however, large challenges with measuring the correct amount of snowfall, partly due to snow drifting with the wind (snøfokk) and also because the instruments cannot capture all of the falling snow.

The following section will review the development of temperature, why the temperature has changed, development of snow and rain events, and change in wind.

3.2.1 Temperature

There have been large variations in temperatures since 1898, both from year to year, and from decade to decade. Examples are the cold periods in the 1900's and 1960's, and warmer periods in the 1930's and 1950's. Overall, the average temperature has increased by approximately 3°C since 1898, and the temperature rate has escalated since the 1970's, after 2000 there have been several years with new, high records, notably 2006, 2007, 2012, 2014, and 2015. Currently, 2016 holds the record year so far, with a middle temperature of -0.1°C. All months have been above average since 2010 (see Figure 3).

Before 1930 it is unclear as of why the temperature increased, but from 1960-1990 there is evidence of a change in the atmospheric circulations. During the last 15 years, there has been a change in air masses, where the wind from every direction is warmer than usual. This is a result of ever larger ice free oceans combined with warmer seas that heats up the air coming over Svalbard, both from the Barents Sea in the south and the Arctic Ocean in the north during winter time. This shows that the increase has actually not been coming from warm "southerly wind", but rather because of a retreat of the sea ice. It is not possible to determine whether the warming is natural or human made. However, it is clear that the increase of greenhouse gases in the atmosphere is the main reason for the warming during the last 50 years (Isaksen et al., 2017).

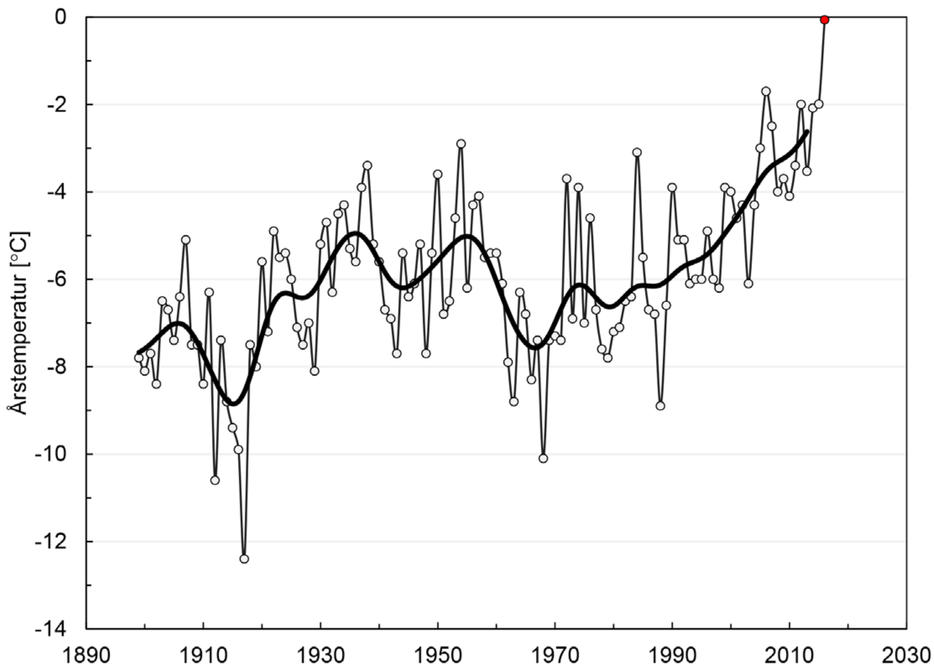


Figure 3: Development of yearly temperatures at Longyearbyen Airport from 1980 to 2016 (Isaksen et al., 2017). Note that the thick line represents an 10-year rolling mean (Isaksen et al., 2017).

3.2.2 Precipitation

When it comes to rain, it is not only important to know whether it rains at all during a day, but also how much it rains over a certain period. Studies show that when it rains more than 20 mm/day on Svalbard it severely increases the chances of avalanches such as landslides and active layer detachment (Hanssen-Bauer et al., 2019). Until now, the precipitation level has increased by 2% every decade since the beginning of measurements in 1912.

Several extreme rain events that have happened over the years, the most prominent are the events of 1972, 1981 and in 2016. As a result of these events, avalanches, mostly in the form of debris flows, followed in and around Longyearbyen. In January 2012, a slush avalanche dislodged from Vannledningsdalen which resulted in quite significant destructions of infrastructure around Haugen (Isaksen et al., 2017).

As stated in Isaksen et al. (2017), it is difficult to measure the exact amount of a snow fall. However, it is possible to measure how much snow cover there has been, and information from the airport shows that in the years between 1976-1997 there were 253 days of snow cover on average each year. Whilst in the period from 2006-2016, there were only 216 days of snow cover, which means that there was more than a month less with snow cover in the last decade than in the period from 1976-1997.

3.2.3 Wind

Over the last 40 years, there has been a slight decrease in the frequency of strong winds. However, there are large variations from year to year, and the topography of the area leads to large local variations as well (Isaksen et al., 2017).

3.3 Future Climatic Development in the Area Around Longyearbyen

Because of the location of the Svalbard Archipelago, it is expected that there will be large differences in temperature, precipitation, and wind in the future compared to today. The main reason for this is the retreat of the sea ice cover north of the island group, whilst the southern parts of the sea is now primarily ice free throughout the winter season. That more of the ocean surface becomes ice free, will affect the weather systems which will lead low pressure systems to move further into the Barents Sea area. This will in turn lead to more precipitation in the Svalbard area, where more is estimated to fall as rain and not snow.

In the following sections it will be reviewed what is predicted to happen at Svalbard in the next century in terms of climate change. To predict these changes, simulations called Global Climate Models (GCM) and Earth System Models (ESM) are applied to describe processes and interactions in the climate system with assistance from mathematical formulas. The climate system is then divided into grid routes where the horizontal size usually is 200 x 200 km^2. When assessing smaller areas, it is necessary to downscale the results from the global models. There are two different ways of doing so which are called; RCM (Regional Climate Model) and ESD (Empirical Statistical Downscaling), which are respectively based on physical-dynamical models which covers regional areas and empirical statistical downscaling.

The MET report (Hanssen-Bauer et al., 2019) apply four different simulations called; Arctic CORDEX, METS regional climate model for both 25 km and one for 2.5 km, and lastly empirical statistical downscale (ESD). The four approaches are further described in the points below:

- Arctic CORDEX regional climate model is based on approximately 50 km RCM simulations, where a total of 12 simulations are used combined with the 3 RCP scenarios, 4 GCM's and 3 RCM's. The data used covers the period from 1951 to 2100. There have been extracted time series with daily mean values and precipitation (Isaksen et al., 2017).
- METs regional climate model, where two different downscale models are used. One for approximately 25 km and one for 2,5 km. The simulations have used data for the three climate scenarios (the RCPs) and the time periods 1971-2000 and 2071-2100. The METs 2.5 climate model is extremely costly and time consuming. Because of this only two time periods are estimated, and only for climate scenario RCP8.5 (Isaksen et al., 2017).
- ESD (empirical statistical downscale) are different from the three other simulations in the sense that it does not use RCMs. Instead it used the other method, ESD, which allows for the use of less computer power, connecting observed data and model results, and it can use new information from independent sources (Isaksen et al., 2017).

The reason why so many models are used, is because the various models have different strengths and weaknesses, and by using several models, one can eliminate some uncertainties. The simulations are used to estimate future temperature, precipitation, and wind, which will be how the sections will be organised, respectively. Permafrost change and activity is heavily influenced by these factors, especially by temperature and precipitation. It is important to see the results from different climate models in order to estimate more accurate results.

3.3.1 Temperature

According to simulations from Arctic CORDEX, the results change from 1971-2010 to 2031-2060 and 2071-2100. For the earliest case there is a change in 4,6°C and 5°C for the RCP4.5 and RCP8.5 scenarios. For the latest case the temperature will change with 6.3°C and 8.7°C (see Table 1). It is important to use the simulations for RCP2.6 between 2071-2100 with care because there is only one simulation.

Table 1: RMC results for changes in temperatures from 1971-2000 to 2031-3060 (on top) and 1971-2000 to 2071-2100 (at bottom). Estimations from Arctic CORDEX. (Isaksen et al., 2017).

1971-2000 to 2031-2060
Change (°C) in temperature

	RCP4.5 (5 simulations)			RCP8.5 (simulations)		
	Median	Low	High	Median	Low	High
Year	4,6	4,1	6,6	5,0	4,6	8,3

1971-2000 to 2071-2100
Change (°C) in temperature

	RCP2.6(1 simulation)			RCP4.5(5 simulations)			RCP8.5 (simulations)		
	Median	Low	High	Median	Low	High	Median	Low	High
Year	6,0	6,0	6,0	6,3	4,8	8,5	8,7	7,5	14,2

The MET regional climate model (25 km), is run by the COSMO-CLM model on 25 kilometres, and estimates an increase of 2.5°C, 3.5°C, and 7°C for the RCP scenarios respectively. The ice cover will drastically change from RCP4.5 to RCP8.5 according to this model, and as already mentioned, lack of sea ice will result in large differences in temperature.

When it comes to the MET regional climate model (2.5 km), it generates more precise data for the area of Longyearbyen because weather for Longyearbyen is not well represented for the 25 km grid that it is located in. However, care must be shown when using this approach, because the simulations are run on such a short time period and therefore have large uncertainties.

According to ESD, the median estimates of the temperature change in 2031-2060 will be 3.6°C, 4.9°Cm and 5.6°C for the different scenarios. From 2071-2100 an increase of 3.8°C, 6.7°C, 10.1°C are expected.

As can be seen here, ESD predicts the highest change of temperature for all RCPs and across the time periods. The different methods do not measure all time periods and RCPs, mostly due to lack of simulations and funds (Hanssen-Bauer et al., 2019).

3.3.2 Precipitation

The Arctic CORDEX predicts that the annual precipitation will increase with 21% for RCP2.6, 28% for RCP4.5, and 38% for RCP8.5 and the frequency of heavy rain will increase and become more common towards the end of the century.

The MET regional climate model, both 25 km and 2.5 km, makes a distinction between precipitation of snow and rain. However, the results from both of them are similar, and it shows that rain will increase in all scenarios. For RCP8.5 an increase of more than 50% is expected for central parts of Svalbard, but it will be slightly less for the Longyearbyen area. Naturally, it also predicts a larger amount of snow inland and more rain on the coast. MET regional climate model (2.5 km) predicts a lower level of precipitation than Arctic CORDEX, but this is mainly due to the grid size and the fact that it is more precipitation inland than in Longyearbyen.

3.3.3 Wind

For all scenarios it is expected the same trends; an increase in winds from the northeast and a decrease in the southwest winds, especially during winter. The main wind direction will be steady. According to ESD, the storm activity will increase toward the end of the century, especially for RCP8.5.

3.3.4 Toward 2200

For all scenarios, it is expected that there will be a further increase in temperature. As expected, the RCP8.5 scenario has the worst outcome, with a temperature increase of 13°C. Even the best-case scenario, RCP2.6, shows that there will be an increase of 2.5°C. When it comes to the precipitation forecast, the answers are inconclusive, since there already are large uncertainties related to todays precipitation level.

3.4 Climate Change Effects on the Permafrost

Permafrost is defined as an area that consists of sediments or rock and includes ice and organic material, which remains at or below 0°C for at least two consecutive years (Hanssen-Bauer et al., 2019; Humlum et al., 2003; Isaksen et al., 2017). Indicators for change in permafrost is either through measuring the temperature in the permafrost itself or by measuring the active layer thickness. The active layer thickness is known as the top layer of soil within a permafrost area that thaws during the summer, and freezes during winter. The best indicator for a long-term change in permafrost, is to measure temperatures at the depth where the temperature is constant throughout the season. This depth is called the zero annual amplitude, and the depth is normally located between a couple of meters in warm, ice-rich permafrost and 20 meters or more in cold permafrost and in bedrock on Svalbard (see Figure 4).

Research on permafrost has mostly been limited to countries in the west, which include the Canadian and Alaskan Arctic, and Svalbard. The research shows that Svalbard has the warmest permafrost for its latitude. At Svalbard, the permafrost is continuous and normally 100 meters thick in the valleys and along the coasts, and 400-500 meters in the mountains (Isaksen, Sollid, Holmlund, & Harris, 2007).

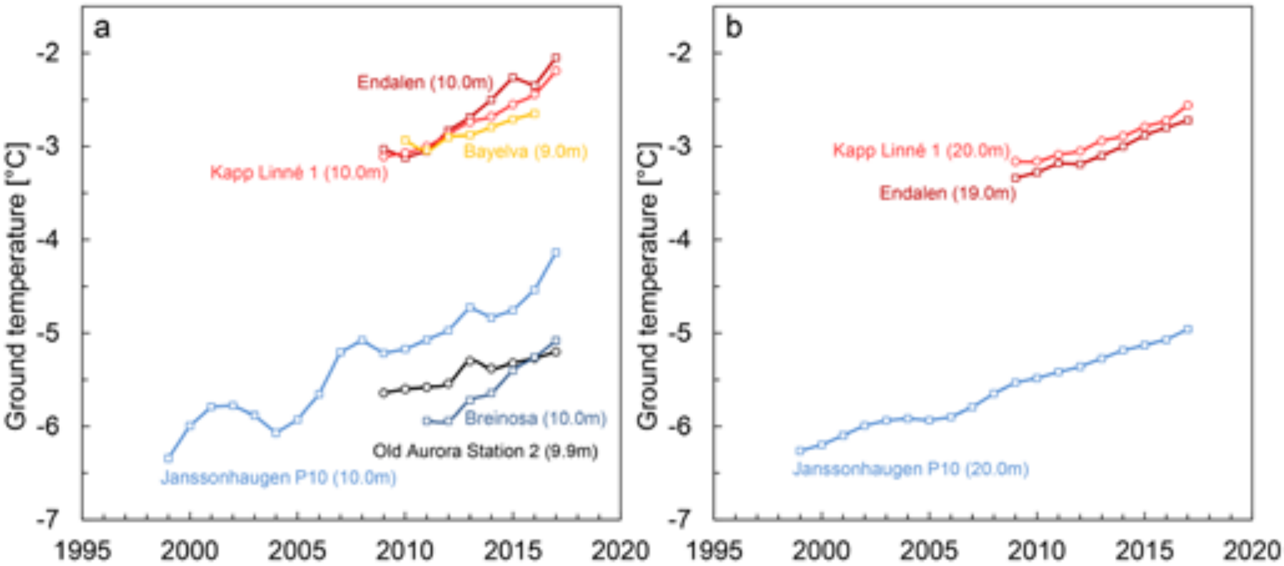


Figure 4: Annual mean ground temperatures (MGT) during hydrological years at selected permafrost monitoring sites on Svalbard. a) 10 m below the surface and b) at 20 m depth, near or at the depth of zero annual amplitude. Only showing available data. (Hanssen-Bauer et al., 2019)

In the years 2016-2017 the temperature in the zero annual amplitude was between -2.6°C and -5.2°C at six monitoring sites around Svalbard. The differences between the sites are due to snow cover, landforms, and ground-ice content. It is also an indication of low lying areas being especially sensitive to warming of permafrost, which incidentally is where the inhabited areas on Svalbard are located. Permafrost records from various areas show an increase between 0.06°C and 0.15°C in the upper 10-20 meters. There are naturally smaller differences at 20 meters than 10 meters. The active layer thickness is also changing around Svalbard. Records from Jansonhaugen indicate an increase of 1.6 cm/year between 1999 and 2018, whilst records from Adventdalen indicate an increase of 0.6 cm/year from 2000 to 2017 (Hanssen-Bauer et al., 2019).

Before 2100 the active layer thickness, according to Instanes and Rongved (2017), will increase from 1.5 meter to 2.5 meters using the RCP4.5 scenario. The zero annual amplitude will still be at -2°C and -3°C. If the scenario ends up at somewhere between RCP4.5 and RCP8.5, the near surface permafrost (5 meters) is expected to disappear by 2100 (Instanes & Rongved, 2017).

Even though there still exist areas with permafrost after 2100, the permafrost will get warmer and the active layer will become more massive and can therefore potentially lead to strength deterioration, deformation, potential accelerated subsidence, and possible foundation failure on buildings and structures. Therefore, mapping and monitoring of the changing permafrost is important for future planning, design, construction, and maintenance of buildings and structures (Hanssen-Bauer et al., 2019). It is especially important to review how the slope stability will be affected by this change, as the gravitational forces plays an active role in the stability of buildings and structures. Furthermore, the heating of permafrost might also affect bedrock with steep inclinations, but this has not been researched much on Svalbard.

3.4.1 Solifluction, Avalanches, and Landslides

Slow downwards movement of the active layer due to gravitational forces is called solifluction. It can be observed all over Svalbard, in Longyearbyen one can see wooden piles from former houses being tilted (see Figure 5) and old wood mining structures that are being crushed due to the forces from the moving layer. Research indicate that an increase in temperature itself will not affect the rate of solifluction. However, it is believed that an increase in precipitation and warm weather events during wintertime will influence solifluction rates. During warm weather events at winter time there has been detected a disturbance in the temperature up to 2 meters down on a solifluction sheet. An occurrence of multiple warm events can contribute to the observed heating of the permafrost in this type of landform (Strand, 2016).

Figure 5: Example of how the active layer affects structures on Svalbard. Here you can see remaining piles that have been tilted due to downward movement of the active layer. Photo: Viktor Gydemo, June 2018.

With its hilly and steep topography, slope processes are a dominant part of the landscape of Svalbard. Avalanches come in different forms dependent on the type of movement and type of sediment. Snow avalanches, are naturally an avalanche containing mostly snow. These avalanches can vary from being relatively dry – a dry snow avalanche, to being very wet – a slush flow. They can also be further sub categorised, but this will not be reviewed in more detail because it is outside of the scope of this thesis. Other landslides may be rock falls, debris slides, debris flows, earth slides, and mudflows. Active layer detachment is also a normal landslide in an arctic environment. An assessment of the risks of these will not be reviewed in this thesis either (Hanssen-Bauer et al., 2019).

Even though slope processes will not be included in this thesis, it is important to emphasise their significance as avalanches can cause massive economic losses and is known to have claimed lives in Longyearbyen on several occasions. In 1953 a slush avalanche from Vannledningsdalen killed three people and many were injured. In 1989 and 2012, slush flows caused massive damage to various infrastructure. In 2015, two people died and ten houses was destroyed when a snow avalanche was triggered from Sukkertoppen. The same thing happened again in 2017, but fortunately, this time no one were killed. After large rain events, debris flows and slides have caused damage to infrastructure in Longyeardalen (1972) and in Longyearbyen (2016).

With climate change, and an ever growing population along with increasing tourism, it is not unthinkable that the frequency of such accidents may increase. Higher frequency of slope process events combined with more people in the city and in the backcountry will potentially increase the likelihood of damage. That is why an analysis of these types of events should be performed at a later opportunity.

3.5 Uncertainty Categories and Uncertainties Related to Climatic Change in the Arctic

A general challenge when evaluating uncertainty is to conceptualise it and then try to measure it. The basic concept is that one does not know the true value of the uncertainty about a quantity or the future consequence of an event, which leads to the use of concepts such as probability, interval probability, and possibility. Aven (2014) distinguish between three different categories of uncertainty;

1) Uncertain quantities (including the occurrence or non-occurrence of events).
2) The future.
3) Phenomena.

Uncertainties about quantities are often described through the use of subjective probabilities, where subjective (knowledge-based) probabilities express the assessor's degree of belief about the occurrence of an event A. The probability is denoted as $P(A|K)$, where K is given as the conditional background knowledge. A popular interpretation is the uncertainty standard, where the probability is denoted by for example $P(A|K) = 0.1$, which means that the assessor compares his/her uncertainty about the occurrence of the event A with the standard drawing at random a specific ball from an urn that contains ten balls (Aven, 2014). Under the uncertainty about quantities, both model error and model output uncertainty are included. It is, however, not viewed as the same, but are closely linked. The model error is defined as the difference between the model prediction and the true future value, whilst the model output uncertainty is the uncertainty about the magnitude of the model error.

Uncertainty about the future means that one does not know what the consequences of an event or activity will be. The true future consequences of an activity or event might not be the same as what one pre-defines as the "consequences" today. For example – today one might set "more extreme weather" as a consequence of climate change, but in reality the consequences might differ and the real consequence is for example actually "less extreme weather". Furthermore, when it comes to uncertainty about the future, it does not only cover the described uncertainty component, but also the background knowledge. This means that the uncertainty is not only reflected by the estimated uncertainty, but a combination of the pair; uncertainty and background knowledge. To cover the uncertainty aspects when making a judgement about the background knowledge, one can use a scheme to decide whether the knowledge base is strong or poor (Aven, 2014);

- The degree to which the assumption made represent strong simplifications.
- The availability of relevant data.
- The degree of agreement/consensus among experts.
- The degree of understanding of the phenomena involved.
- The existence of accurate models.

If the background knowledge is judged as poor, it would affect the total score of the uncertainties in terms of whether they are high or low.

Uncertainty about a phenomenon is uncertainties related to how the relationship between cause and effect is connected, as for example the relation between salinity in the ocean and the deep ocean currents. A lack of knowledge about the phenomenon will result in a problem where some underlying correct value exists, but cannot be found.

In a climate change perspective, the uncertainties are mostly related to boundary conditions like past and future green house emissions, solar emissions etc. Traditionally the major uncertainties in climate projections can be categorised in three main categories: incomplete knowledge related to future anthropological emissions, incomplete knowledge related to natural variations, and model uncertainties (Isaksen et al., 2017).

In an arctic environment it is also important to emphasise the marginal ice zones as biases for initial sea ice extent, because this heavily influences the surrounding climate and is not properly accounted for in many simulations (Hanssen-Bauer et al., 2019). Therefore, an additional source of uncertainty called "the initial state of the sea ice" has been added as well. The four sources of uncertainty will be reviewed in further detail in the following sections, where Table 2 also shows the relation between the definition of uncertainty by Aven (2014) and the classification used by climate projectors (European Environment Agency, 2017; Hanssen-Bauer et al., 2019)

Table 2: Relationship between Aven's categories of uncertainty vs. a common way of categorising uncertainty within climate change research.

	Uncertain quantities	The future	Phenomena
Future anthropological emissions	x	x	
Natural variations	x		x
Model uncertainty	x		x
Extent of sea ice	x		

It can be seen from Table 2 that the climate change classifications to varying degrees cover the different categories from Aven (2012). They all cover uncertain quantities, and to a very limited extent cover the uncertainties about the future. Future anthropological emissions cover both uncertain quantities and the future; which means that it is unknown how much man-made emissions it is going to be, and it is uncertain how these emissions will affect the future climate. Natural variations cover uncertain quantities and phenomena, where the uncertain quantities might refer to not knowing how much the natural variations will vary, which again can be a result in lack of knowledge about the phenomena involved inn the natural variation. Model uncertainties reflect the same uncertainties as the natural variations, because the models try to simulate the real natural variations, which can lead to model errors and model output uncertainty. The uncertainties related to extent of the sea ice is related to uncertainties regarding the whereabouts of the sea ice, which is a quantity.

3.5.1 Incomplete Knowledge Related to Future Man-Made Emissions

When reviewing the uncertainties related to future anthropological emissions, it is important to look at potential population growth, technological development like more cost-effective ways of utilising sun and wind power, and political interventions such as for example restricting emission to a level that can affect the future climate. There are uncertainties related to the classic greenhouse gases (as carbon dioxide, methane, and chlorofluorocarbon gases) as well as short lived gases (as precursors to greenhouse gases such as carbon monoxide, volatile organic compounds) and aerosols (as soot, sulphur dioxide, nitrogen dioxide) (Hanssen-Bauer et al., 2019).

As Hanssen-Bauer et. al (2015), stated "Today, it is not possible to say what emission scenario is most realistic. Today, actual emissions reflect the RCP8.5 scenarios, but this can quickly change if one achieves binding, international climate agreements, or as a result of renewable energy source becoming compatible with fossil fuels. Because low, median, and high projections within each emission scenario only span part of the total uncertainty, it is difficult to give any quantitative measure of the probability and it cannot be ruled out that future climate change may be lying under "low" or above "high" projections" (p. 153).

Because of this, the scenarios RCP2.6, RCP4.5, and RCP8.5 have in that report been included in order to try to consider the uncertainties involved, where the Arctic is the place where the regional differences are the largest between the scenarios (IPCC, 2013).

RCP2.6 as the "best case scenario" is the only scenario that is optimistic enough for the goals from the Paris agreement in 2015 to be fulfilled. This is, however, not very realistic, as it involves reducing greenhouse gas emissions drastically by 2020 (IPCC, 2013). Furthermore, even if it could be managed to reduce the emissions by 2020, the temperature in Svalbard will continue to rise over the next decades (Isaksen et al., 2017).

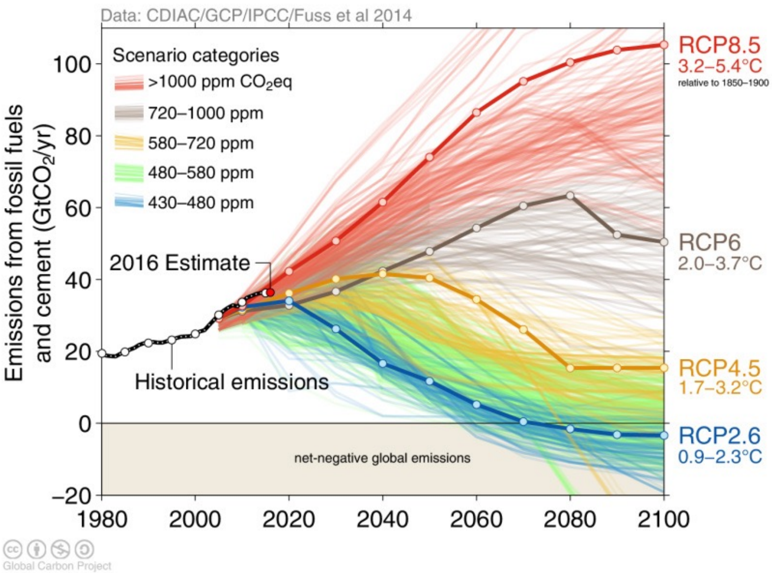


Figure 6: Global emissions of climate gases, observations from 1980-2015, and for four different emission scenarios until 2100. Compared with pre-industrial times an increase in temperature will be; RCP2.6: 0,9-2,3°C; RCP4.5: 1,7-3,2°C; RCP8.5: 2,0-3,7°C. (Isaksen et al., 2017)

Many choose to use RCP8.5 as a "worst case scenario" (Hanssen-Bauer et al., 2019; Isaksen et al., 2017). According to IPCC (2013), the Arctic Ocean is likely going to be near ice free by the middle of this century in this scenario. From Figure 14, one can observe that the emissions from 2015 was closest to the RCP8.5 scenario. Therefore, the Norwegian government has stated that the precautionary principle should be followed and that a "worst case scenario" should be evaluated when considering climate change issues (Meld.St.33, 2013). The precautionary principle means that when there are scientific uncertainties about something, caution should be the overriding principle (Aven, 2015). The RCP8.5 scenario shows a unrealistically high temperature increase for the most extreme cases, and has therefore been excluded from the evaluation (Isaksen et al., 2017). An annual temperature at 9°C, which is higher than any annual temperature on the main land of Norway today, and a 25°C increase during wintertime is viewed as very unrealistic. The reason for these numbers are mainly because Longyearbyen is today simulated to be located far within the sea ice limit on many of the models that are used. This results in unrealistically low winter temperatures for present time, and when the models simulate that the sea ice limit moves beyond Longyearbyen, the temperature increase drastically (Isaksen et al., 2017). Therefore, most extreme temperatures in the figures are not to be used (see Figure 15 and Figure 16).

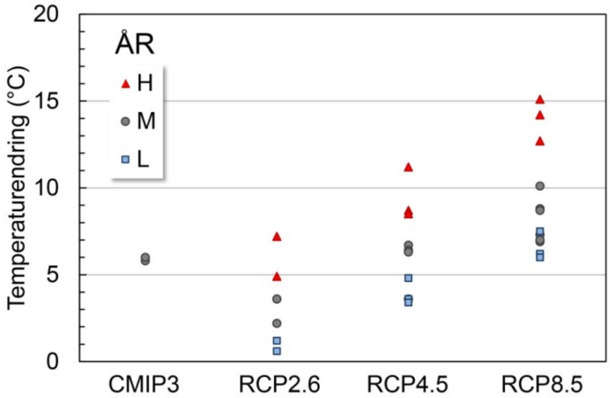


Figure 7: Projections of yearly change in temperature in Longyearbyen from 1971-2000 to 2071-2100 for the different climate scenarios. The values from median (M), low (L) and high (H) are retrieved from ESD, and Arctic CORDEX (Isaksen et al., 2017).

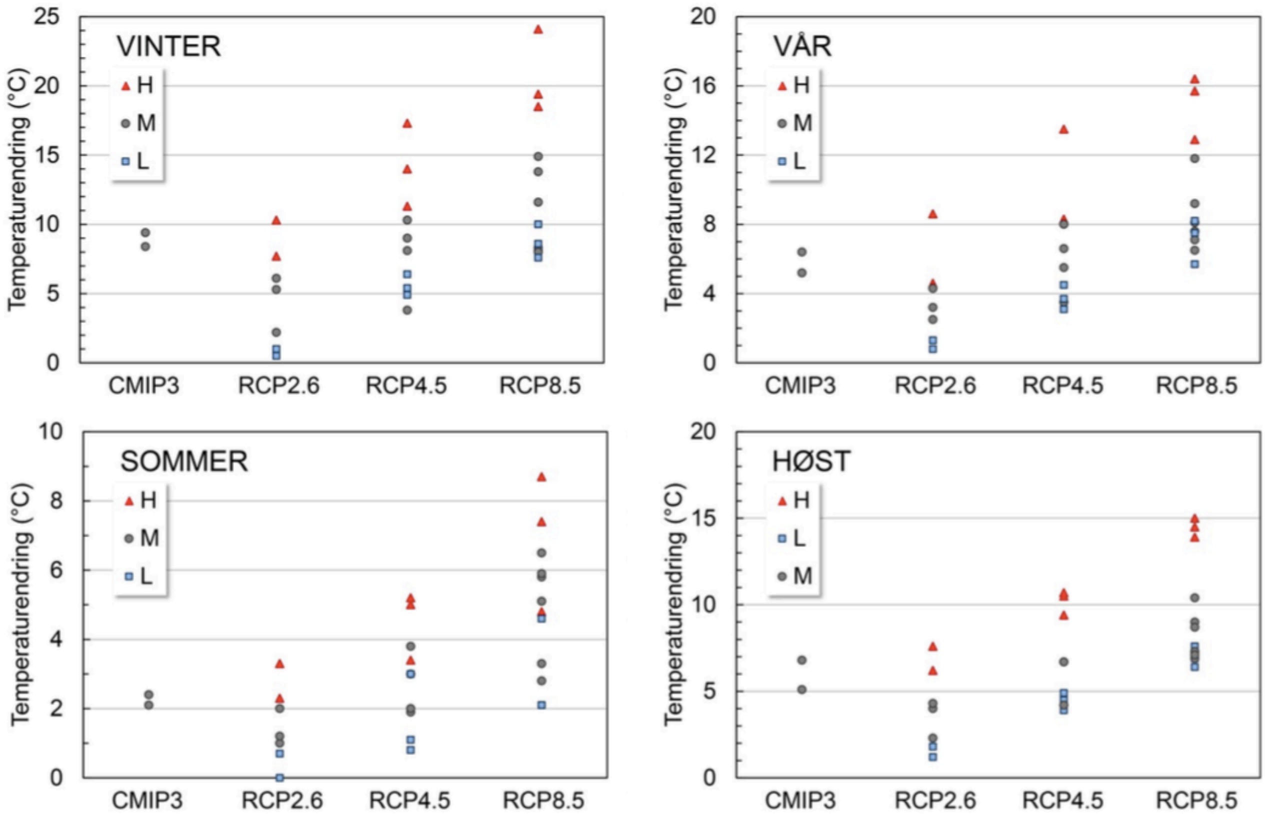


Figure 8: Projections of changes in temperature for "winter", "spring", "summer", and "fall" in Longyearbyen from 1971-2000 to 2071-2100. The values from median (M), low (L) and high (H) are retrieved from ESD, and Arctic CORDEX (Isaksen et al., 2017).

3.5.2 Incomplete Knowledge Related to Natural Variations

Uncertainties related to natural variations is partly due to the fact that the climate system is chaotic and non-linear, and partly because of lack of knowledge about certain phenomena such as for example solar radiation or tectonic activity as volcanic eruptions. Hanssen-Bauer et al. (2019) divide this part of uncertainty into two classes, uncertainties related to internal variations, and uncertainties connected to natural external forcing.

The first class refers to uncertainties related to the inability to quantify or measure certain phenomena concerning climatic variations. This is due to the chaotic and non-linear qualities of the climate system, which makes it difficult to simulate climate from year to year, or decade to decade. Examples of such phenomena are the heat transportation from shallow to deep water, natural climate variations such as El Niño and La Niña, or heat transport by atmosphere and ocean. Many of these are well-known interval variations that are included in the climate models, however, it is not known how consistent the frequencies of these cycles are, and therefore it is difficult to produce a model that is synchronised in time with the observed interval variability. Furthermore, since many of these systems redistribute energy from one place to another, it does not necessarily change the global energy contents, and will thus have a larger effect locally (Hanssen-Bauer et al., 2019). Such changes can give biases to how much heat comes from the variations versus how much that comes from actual global warming.

The latter classification; incomplete knowledge connected to natural external forcing, refers to external variations that is impossible to gain more knowledge about in order to predict its variations. Examples of this are the well-known 11-year cycle of solar radiation. Today this cycle is known and constant, but there is no possibility of gaining knowledge of whether the cycle of the sun will become unstable or change in the future or not. However, if the sun's variation stays the same as it has the past 100 years, the uncertainties will be smaller than many others listed in this chapter. The same principle basically goes for tectonic activities as well, but since a volcanic eruption has a large impact on the weather over a few years, the effect will be on climatic extremes (Hanssen-Bauer et al., 2019).

3.5.3 Model Uncertainty

The model uncertainties naturally involve uncertainties related to the statistical simulations used to model the future climate. The uncertainties can either be due to lack of knowledge about the climate system or due to climatic systems that are presently unknown to us. When there is lack of knowledge of a phenomenon, it is very difficult to make statistical models that predicts accurate estimations. It can also be a lack of ability to implement the phenomena into numerical terms along with limiting supercomputer abilities.

Model uncertainties can to some degree be reduced with the use of repeated simulations using different parameters. However, there will still be distortions due to faulty initial assumptions or variables, as a result of biased corrections.

3.5.4 Initial State of the Sea Ice

As mentioned earlier, the state of the sea ice is important when modelling the future climate of the Arctic. Many of the models used (such as Arctic CORDEX) assume that Longyearbyen is well within the limit of the sea ice today. This is, however, not the case, and this results in that todays climate of Longyearbyen looks much colder than it is (Hanssen-Bauer et al., 2019). Too limited sea ice extent would give the opposite result.

4. Permafrost Engineering

Structures placed on, or in, permafrost areas will alter the heat exchange between the ground and the atmosphere, which will in most cases result in the ground being heated compared to areas without structures. The physical and mechanical properties of permafrost are generally temperature dependent and are most prominent at temperatures within 1 or 2°C of thawing. An increase in permafrost temperature can potentially lead to deteriorating strength and deformation of structures, potential acceleration of the subsidence and possible foundational failure. Thus, it is important to evaluate the thermal effects of a structure during planning, design, construction, and maintenance in Svalbard, and in the Arctic in general. Most engineering concerns related to design on ice-rich permafrost, such as in Longyearbyen, can be classified into those related to increases in permafrost temperatures, active layer thickness, and degradation of permafrost (Humlum et al., 2003). In the following sections, it will be reviewed which settlements exist on Svalbard, how one usually builds on permafrost, what issues that might come up when building on permafrost, and why these issues of construction rise.

Svalbard currently have five main settlements. Ny-Ålesund, Sveagruva, Longyearbyen, Pyramiden, and Barentsburg. These settlements were initially established because of coal mining activity, but today, only Barentsburg and Sveagruva depends solely on mining activity. Ny-Ålesund (40-100 inhabitants) has developed into a large scale research facility, Longyearbyen (more than 2000 inhabitants) depends on tourism, research and education, in addition to mining. Ny-Ålesund, Sveagruva and Longyearbyen are Norwegian settlements, while the remaining two, Barentsburg and Pyramiden are Russian. There are characteristic differences between the building styles in the Russian and Norwegian settlements. For example, the Norwegian communities seldom have more than 2,5 storeys high buildings, to minimise the loads on the foundation piles. In Russian settlements, the buildings can often be more than 4 storeys high, and therefore require a large number of piles to spread the forces and increase the support (Humlum et al., 2003).

Much of the infrastructure in Longyearbyen was built during the 1970ties. Some of the challenges connected with foundation techniques as a result of thawing permafrost, has together with varying maintenance, increase of population, and generally an increase in level of activity, resulted in a lack of maintenance of important and critical infrastructure. Climate change can contribute to further loads on an already vulnerable infrastructure, and may demand more upgrading and maintenance than before (Meld.St.33, 2013).

Different building techniques are developed in order to cope with the various problems related to permafrost. Some are better suited for areas with specific issues, such as solifluction creep or high salinity. Therefore, a list of different building techniques will be listed in the chapter below, where all of them have been applied on Svalbard, though some are more frequently used than others.

4.1 Building Techniques

Depending on the soil condition and ground thermal regime, there are principally three main approaches to foundation design on permafrost, all at some point used on Svalbard; the conventional design, the passive method, and the active method. The passive method aims to preserve the permafrost located underneath the building by letting the natural cold climate keep the permafrost stable. The active method uses artificial cooling to keep the permafrost stable (Shur & Goering, 2009). The passive method is the most commonly used in Longyearbyen.

Rognved et al. (2017) has made a review of various methods of foundation works used in permafrost areas. In the report they make a point of the importance that if a passive approach is used, the height underneath the buildings should be at least 0.5-2 meters so that the air can circulate under it. A general problem in Longyearbyen is that snow accumulates under and around buildings, which contributes to isolating the area against the cold weather during wintertime. Surface water which accumulates under buildings can also lead to complications. Under some of the buildings in the city, the topography is made so that water can accumulate, which in turn can be unfortunate for the construction because it leads to relatively rapid warming of the ground compared to drained areas. Rognved et al. (2017) reviews six different foundation methods, which are presented in the following sections;

4.1.1 Isolated Shallow Foundation

This technique refers to when the constructions are set directly onto the permafrost, where the active layer is dug away. Examples of such buildings in Longyearbyen are Bergmesterboligen, Sysselmannsgården, Huset, and parts of Spitsbergen Hotel (Funken). All of the mentioned buildings have exceeded their assumed life time (older than 50 years), but they are all subjects to extensive damage due to subsidence.

Of the mentioned buildings, Sysselmannsgården has gone through renovation with the insertion of artificial cooling in order to stop or slow down the subsidence. This is a costly and time consuming activity, and for new buildings ground examinations should be made in order to ensure that buildings withstand the external loads within its expected lifetime.

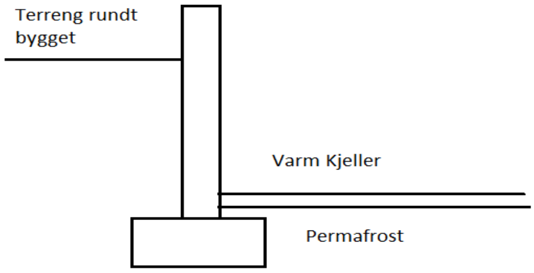


Figure 9: Depiction of a direct foundation (Rognved et al., 2017).

4.1.2 Pile Foundation

Pile foundation has been the most common method for constructions in Longyearbyen since the 1980-ties. This is an example of a passive approach where buildings are constructed on top of piles, so that air can circulate underneath the buildings and keep the permafrost at normal temperatures. Due to the soil being ice-rich and has partly high salinity, the soil has relatively low bearing capacity and a high development of subsidence – even with the use of long piles. Wooden piles have traditionally been the most common material, and they have also been relatively short (less than 6 meters). Lately, steel piles have been used more frequently, along with the use longer piles. Local entrepreneurs are often negative to the use of piles longer than 10 meters, mainly due to problems with long waiting time when ordering, shipping and having them installed. On the other hand, better equipment has made it possible to install piles between 10 and 20 meters in Longyearbyen.

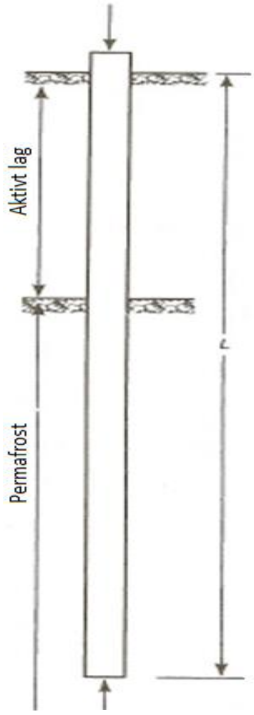


Figure 10: Principle of pile foundation (Rognved et al., 2017).

4.1.3 Active Cooling Foundation

This method is an example of active cooling, where cooling pipes are placed in a layer of sand or concrete. On top of this layer, the building is constructed, and by circulating a refrigerant through the pipes the ground can be kept permanently frozen – preferably kept on cooler temperatures than the permafrost itself. Active cooling foundation is primarily used on particularly important buildings, as for example Svalbardbutikken, Næringsbygget, and Kulturhuset.

In order to ensure low subsidence rates and a long lifetime, this is generally a favourable method. The system is, however, not maintenance-free and is costly.

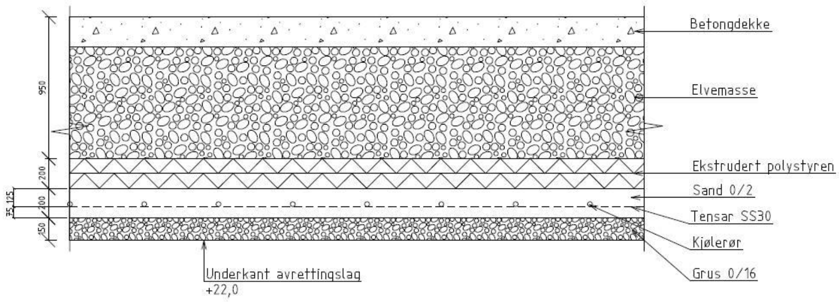


Figure 11: Example of active cooling foundation (Rognved et al., 2017).

4.1.4 Shallow Foundation on Point or Slab

The concept of this method is to dig a hole into the permafrost, where one places a sole or point to set piles on. These holes are then filled with fill masses, and then it is ready to build on. This has been a fairly normal foundation method, but it has been of interest to use other methods in order to minimise the use of concrete, along with the fact that it is time consuming and unfortunate to dig when wanting to preserve the permafrost underneath the buildings. Furthermore, one has to drain the holes that has been dug to avoid accumulation of water.

Due to access of better equipment, pile foundation has grown to be the preferable choice between the two when building on permafrost. Even so, there still exists constructions that are built on this method, which is parts of Forkningsparken, the Post- and Bank building, and Telenorbygget.

One of the advantages of using this technique, is that it is not the vertical stress that is the main force on the building. The soles underneath the piles contribute to this, and it helps decreasing the subsidence. It can therefore be beneficial to use this method when the soil has high salinity and is ice-rich.

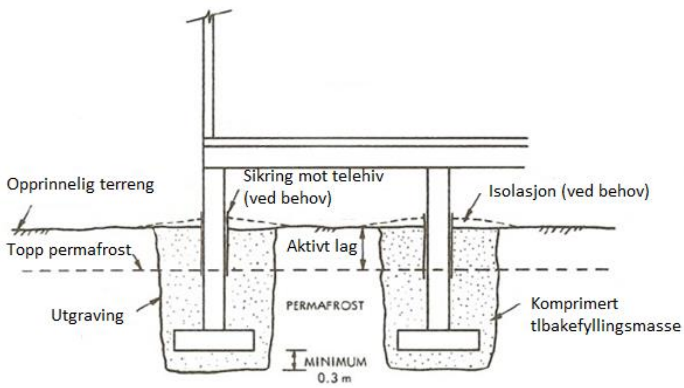


Figure 12: Shallow foundation on point or slab (Rognved et al., 2017).

4.1.5 Passively Cooled Foundation

The passively cooled foundation involves making a foundation with ventilation holes, so that cool air can pass through the foundation to help keep the permafrost constant. It is rarely used in Longyearbyen, but has been implemented some places in Svea. As active cooling foundation, this method also requires some maintenance as the ventilation needs to be closed during summer in order to prevent warm summer air to enter the foundation.

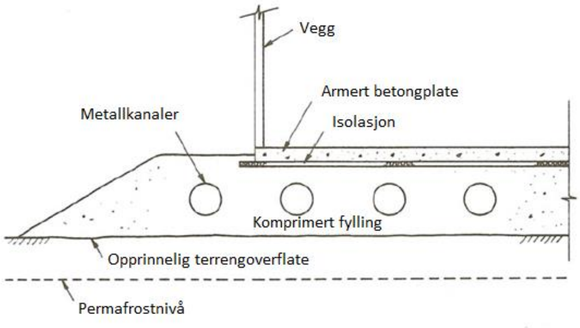


Figure 13: Passively cooled foundation (Rognved et al., 2017).

4.1.6 Multipoint Foundations

This method is a Canadian foundation system that uses a rigid frame of steel and aluminium to lift the building up. In many cases, the frame can be placed directly onto the ground, without any need of drilling or digging. It has been used in Longyearbyen the last three years. Amongst other are Brakke 5, the terrace outside Radisson Blu Hotel, and the cottage that belongs to Sysselmannsbygningen. This method allows for adjustments of the foundation over time, and it can be a beneficial alternative for relatively simple buildings as barracks or simple housings (maximum 2-3 storeys).

Figure 14: A typical Multipoint Foundation (Rognved et al., 2017).

4.2 Permafrost Behaviour and Failure Modes

The strength and deformation characteristics of frozen soils are dependent on soil type, temperature, density, ice content, unfrozen water content, salinity, stress state and strain rate. Thawing of frozen soil, or even increase in the temperature of frozen soil, may lead to deteriorating strength and deformation characteristics, potentially accelerated subsidence and possible foundation failure (Instanes, 2001).

If not executed correctly, construction activity may lead to warming of permafrost and to damage and even failure of foundation soils and structures. For infrastructures on permafrost it is often difficult to see the difference between the effect of possible climate change and the effects of other factors that might contribute to construction failure. Reasons why the structures might fail due to other factors than climate change are (Humlum et al., 2003);

- The actual conditions in the area are different than the assumed conditions.
- The design of the structure did not consider the appropriate load condition, active layer conditions, and permafrost conditions.
- The contractor did not carry out the construction according to the design.
- The maintenance programme was not carried out according to plan.
- The structure is not used according to design assumptions.

Even though most structures fail due to human errors rather than climate change, it is a fact that temperatures have gradually risen since post industrial times (Instanes, 2001). This will result in permafrost weakening in the long run. The weakening of permafrost due to temperature change can in general be expressed in terms of its strength and its creep behaviour (Etkin, Riseborough, & Paoli, 1998);

- Strength of the soil; which refers to the soils ability to resist applied force. In frozen soils, loss of strength might be the most serious problem associated with warming soil. Even if the soil does not thaw entirely, it loses a lot of its strength if it is warmed towards 0°C. A frozen soil has a higher long-term strength than when unfrozen. It has been shown that ice-rich silty soil increases by 1°C from -7°C will lose 7.5% of its strength, compared to from -3°C which will lose 15% of its strength.
- Creep; is the plastic time-dependant deformation of soils under load. After long periods (months or longer), soil creep will cause soil movement at very small loads. Creep rates also increase significantly when the temperatures approach 0°C. Engineered structures that must take creep into account, such as structures on piles, may be compromised if creep rates increase due to soil warming. It has been estimated that an increase of 1°C, from -2°C to -1°C for example, will result in approximately 3.5 times higher creep deformations.

These two factors will later be known as the bearing capacity and the thaw subsidence. Together with the strength and creep of the soil, saline permafrost, which is common along the coasts of Svalbard, represents an interesting engineering challenge. In Humlum et al. (2003) it is said that “the pile load carrying capacities are reduces by at least 50% at salinities as low as 5 ppt, by 60% to 75% at 10 ppt, and by as much as 90% at 15 ppt." (where ppt refers to parts per thousand). Salt also decreases the freezing point of the soil pore water and increases the unfrozen water content for a given temperature. The saline issue contributes to effects on the infrastructure in two ways; the ad-freeze strength between the frozen soil and the pile surface is reduced due to the presence of saline pore water, and piles in saline permafrost will experience larger deformation in the designed life of the piles.

How much load the piles can handle over time and with climate change has been reviewed by Rognved et al. (2017). A typical soil profile has in this experiment been used from Longyearbyen, which is ice/water rich, silty, and sandy. Figure 12 shows that a 20-meter-long pole underneath a vertical load of approximately 2100 kN in 1986 was calculated to get 5 cm of subsidence after 30 years (2015). To achieve the same level of subsidence after 30 years, the load had to be reduced by 1480 kN and 920 kN when the building is installed in 2016 and 2036. It is worth mentioning that Figure 12 uses RCP4.5 as a baseline.

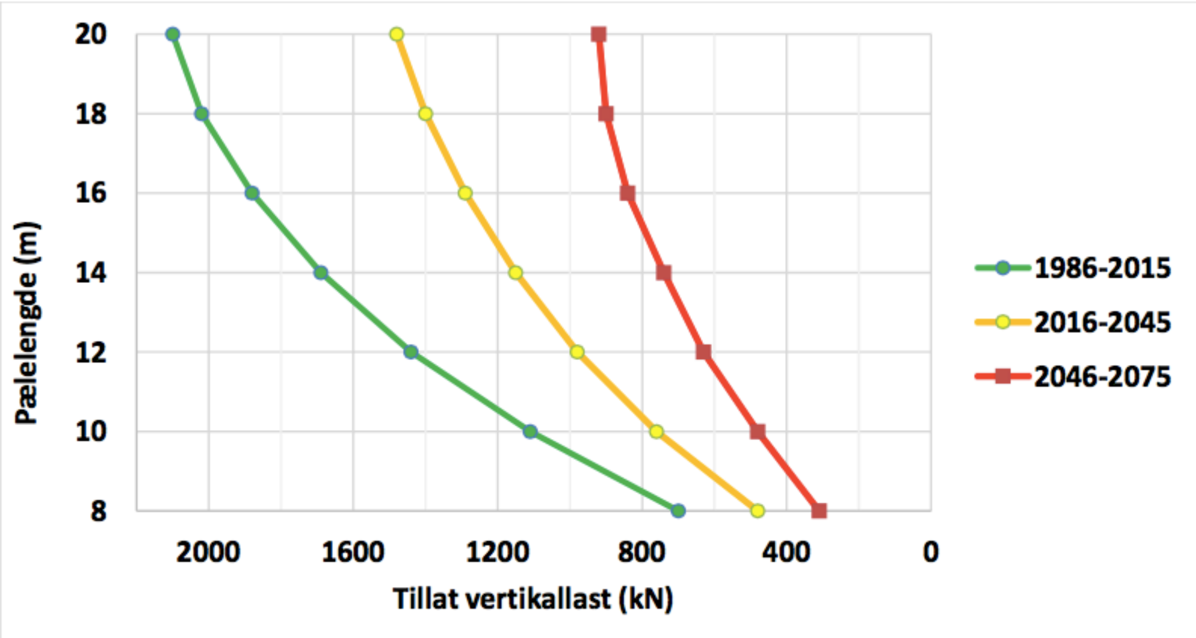


Figure 15: Reduction in allowed vertical load on piles. Vertical axis is the length of the piles (m), horizontal axis shows the allowed vertical load (kN) (Rognved et al., 2017).

Figure 12 shows potential for subsidence of a building with the foundation of 1.5 m x 1.5 m. When installing such a foundation in 1986, the building will experience 5 cm of subsidence during its lifetime of 30 years. If the same building is installed in 2016, 2036, and 2046, the building will experience a subsidence of 9 cm, 11 cm, and 26 cm respectively. According to (Rognved et al., 2017), the bearing capacity in the last case will be reduced to a level where the load will lead to destruction of the building. Which means that with subsidence between 11 cm and 26 cm, the foundation can not handle any more stress and a failure will occur.

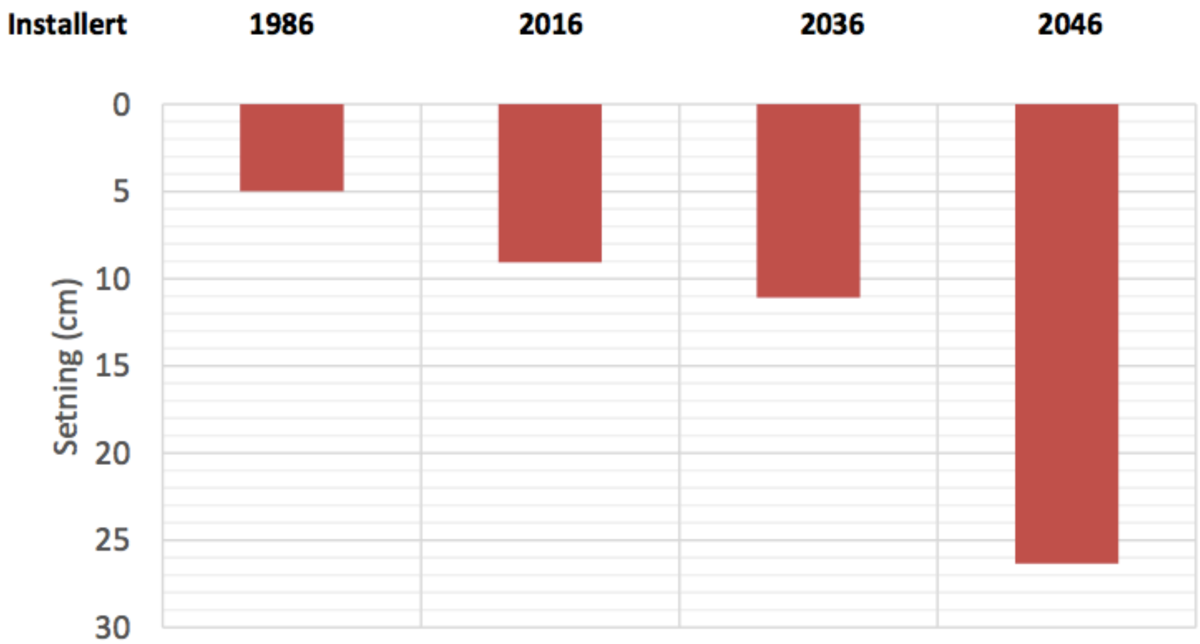


Figure 16: Subsidence of a 1.5 m x 1.5 m foundation installed at different time periods in order to see change in subsidence and bearing capacities (Rognved et al., 2017).

The data from Figure 12 and Figure 13 does only show calculations and is not connected to a specific building. It does, however, according to Rognved et al. (2017) show an illustration of how the foundation will respond to changes in temperature over time. In Chapter 6, estimations of how this might affect thaw subsidence and bearing capacities will be presented.

Design criteria for foundations on permafrost should be based on the probability of occurrence of the warmest air temperature to which the foundation soils will be subject to during the lifetime of the structure (Instanes, 2001). Based on statistical analysis of historical meteorological data; thermal analysis is carried out of the structure, the foundation, and the permafrost. Historically, there has been an increase of the air temperature, so this will normally be considered during the planning and constructing phase.

Even though there has been extensive research on permafrost and climate change, and how it will affect buildings; the lifetime of a residential building is usually no longer than 30-50 years. Within this time frame, the structure should function according to plan with normal maintenance cost. In continuous permafrost, it is believed that climate change will not pose an immediate threat to the local infrastructure (Streletskiy et al., 2019). However, it is difficult to quantify the climate change, and hence difficult to predict the impact on infrastructure (Instanes, 2001).

4.3 Ground Conditions Today

Through a collection of different reports recording the ground conditions of most of the "city parts" or divisions presented in Chapter 2, data has been collected to make a vulnerability assessment that is as accurate as possible. As already mentioned in Chapter 2, some of the areas have already been made and the author has added some. Important buildings that have been examined specifically will also be included in the sections of their respective area.

In some of the pre-defined areas there has also already been made an estimate of how the climate change might affect the given area, this will also be included here. For the divisions that the author has made, assumptions about the ground conditions have been made based on the surrounding area This will be further examined in Chapter 5.4 about assumptions. All areas and their information will be summarised in Table 3 at the end of this chapter.

4.3.1 Skjæringa

The ground conditions on Skjæringa is mostly known through examinations from Sysselmannsgården. Ground condition examinations executed in 2008 tell that it mainly contains sand and gravel over silt and clay. The salinity in the area is established to be between 0,1% and 0,4%, and the water content to be between 14,7% and 29,6%. Even though examinations near Sysselmannsgården showed bed rock at 8 meters, large variations are expected here. The active layer seems to be between 1 and 2 meters thick (Instanes & Rongved, 2017).

Sysselmannsgården is partly built on shallow foundation on slab and partly built on steel piles. On the parts built on shallow foundation on slab, no large deformations are expected due to climate change. It is however a concern that the active layer thickness will increase further than the bottom of the slabs, and this can potentially result in a breach in bearing capacity. When it comes to the part of the building with pile foundation, the extent of damage is dependent on the length of the piles, and this is not known. However, it is believed that they are approximately 9 meters. If this is the case, some movement within the building must be expected (Rognved et al., 2017).

Sysselmannsgården has experienced further damage even though extensive renovation has been done with implementation of steel piles to bed rock. Statsbygg has an ongoing case here in order to minimise future thaw subsidence (Rognved et al., 2017).

Svalbard Kirke is evaluated as a very important building, and extensive maintenance work has already been recommended. It is not known what type of foundation that the church is built on, but as far one can see, tree piles have been used. This is not viewed as a suitable technique for an important building, and it is expected large movement of the building along with increasing rot damage due to a warmer climate (Rognved et al., 2017).

4.3.2 Melkeveien

Melkeveien is an area that has not yet been developed, but it is planned to become a residential area in the future. There has unfortunately not been registered any salinities values for this area, but one can assume that it is the same as for Skjæringa, which was between 0,1% and 0,4%. Same goes for the water content at 14,7% to 29,6%. Based on information from 8 boreholes in the area, bed rock is found between 9-19 meters below surface. From the boreholes, some ice was also discovered (Pedersen, 2017). Nothing was said from the report about active layer thickness, therefore, information from Skjæringa has been used instead.

4.3.3 Sjøområdet

Mostly covered by river delta, Sjøområdet lies on hard clay. It has not been done any examinations of the ground, but it is believed that the soil is of poor quality for buildings, and that the buildings here will experience large deformations. It is further expected high temperatures and salinity in the ground due to the location close to the fjord (Rognved et al., 2017). Since there are no data of the salinity for this area, records of salt content in Elvesletta Nord is used instead, which is between 0.6%-3.0% (Gregersen, 1995). Water content have not been recorded either, therefore data from Bykaia (west of Sjøområdet) will be used instead, which is between 25%-30% (Mikalsen, Norddal, & Grønsberg, 2017). Active layer thickness has not been mentioned either, so information from Sjøskrenten will be used, which is approximately 2 meters.

4.3.4 Sjøskrenten

As Sjøområdet, Sjøskrenten is mostly covered by river delta, and consists mostly of sandy gravel. The ground condition examinations do not say anything about the salinities here either, therefore the same assumption is made as for Sjøområdet, using data from Elvesletta Nord with 0.6%-3.0% (Gregersen, 1995). The water content has been examined, and an estimate of 5%-10% was made. No bed rock was found, and active layer thickness was estimated to be approximately 2 meters thick. If recommendations are followed regarding building techniques and foundation methods, there should not be large movements of the buildings even with climate change (Schwartz, 2010).

4.3.5 Midtre Elvesletta

Most of the data from Midtre Elvesletta is retrieved from examinations done in 1995 (Gregersen, 1995). Boreholes that is located along a profile from Svalbardhallen in the south to the sea in the north, tell that this area mostly consist of gravel at the top, and underneath there are sand and clay before hitting bedrock at 26,5-28 meters. The salinity is estimated to be approximately 1.0%, and the water content to be 26%-36%. In the future it is believed that in order to have buildings free of thaw subsidence, piles to bedrock or active cooling foundation are the only options. Ground subsidence might be a problem due to large icing potential (Pedersen, 2016). Nothing is said about active layer thickness, but it is assumed that it is approximately 1 meter.

4.3.6 Elvesletta Sør

Data from Elvesletta Sør is based on the same report as Midtre Elvesletta (Gregersen, 1995). It has the same composition as Midtre Elvesletta, with gavel at the top, and sand and silt underneath. The salinity is found to be between 0.3%-1.0%, and the water content to be between 5%-30%. There are no recommendations for future structures in this area.

4.3.7 Forskningsparken

Located on old river delta, Statsbygg (2002) examined the ground conditions and discovered that the top layer contained gravel, sand and silt – whilst underneath there was silty clay. The salinity was determined to be between 0.2%-3.5% where it increases with depth. The water content was found to be between 10%-30%. The active layer is estimated to be 1,5 meters, but there are no measurements of temperature here.

This area is only supposed to be used for UNIS and Svalbard Museum, and therefore only future recommendations for this building has been made. According to Rognved et al. (2017) large deformations are not expected for the structure. There is however, concerns that if the permafrost gets much warmer underneath the foundation – movements in the building can become an issue.

4.3.8 Sentrum

The city centre is located south of Forskningsparken and consist of many buildings that are important for the Svalbard community. The area consists of fillings and sand, silt and clay. Measured salinities are between 0.4%-2.7%, and water content is 22%-40%. The active layer is approximately 1.5 meters thick (Instanes & Rongved, 2017).

In the future, foundation methods such as point, slab foundation, or active cooling can be considered as alternative method in order to prevent movements. Slab foundation can on the other hand be problematic if active layer thickness exceeds the depth in which they are placed.

The post and bank office is a building that have received special attention when executing vulnerability evaluations. During inspections, it has been ascertained that there will most likely not be any dramatic changes to the building. There is however, the same concerns as for Forskningsparken that the active layer will increase to depths lower than the slab foundation (Rognved et al., 2017).

4.3.9 Nedre Lia

Nedre Lia is an area created by the author, and there is therefore no ground condition research done here. Because of this, it is assumed that this area will look something like a combination between Sentrum and Elvesletta Sør. It is then believed that the ground conditions will contain of gravel, sand, silt, and clay. Lia would also have been included if there was any valuable data from this area. The salinity will be set to 0.3%-2.7%, and the water content to between 10% and 40%, retrieved from Sentrum and Elvesletta. The active layer thickness is based on data from Sentrum, at 1.5 meters.

This area consist mostly of residential buildings, and according to Rognved et al. (2017) these are the most vulnerable buildings as they mostly are built on fairly short piles. They are then exposed to large subsidence both because of decreasing bearing capacities and thaw subsidence. On a long-term basis, one must expect to build new foundations and/or replace the buildings completely.

4.3.10 Lia

Lia is located in the slope underneath Sukkertoppen and is highly exposed to snow avalanches. Bedrock has been found at between 2-8 meters, and the whole area is dominated by solifluction. No records of either salinity or water content have been found. But due to a fresh water flow through this area one can expect lower salinities than for example by the city centre, it is assumed that it is between 0.3%-1.5%. The water content is assumed to be high, at 20%-40%. The active layer thickness is by read reports estimated to be between 1.5-3 meters, but there are some areas that does not hit the frozen layer until 13 meters. This may be due to water constantly flowing through the area.

The buildings here are also residential, and due to the strong influence by solifluction, all structures shall be well founded to the bedrock. Strong piles are required due to the massive forces of the moving active layer (Nerland, 2018).

4.3.11 Nordre Lia

This area is like Nedre Lia made by the author. It mostly has the same issues as Lia, because it is located at the same height with the same slope processes (solifluction). Therefore, it is assumed that this area is more or less similar to Lia.

4.3.12 Gruvedalen

As Lia and Nordre Lia; Gruvedalen is located on the slope beneath Sukkertoppen. This area is not as exposed to snow avalanches as Lia, but it is some concerns regarding the stability of the active layer that lies above. There have not been recorded salinity and water content here either, but it is assumed that it can be a combination between Forskningsparken, Lia and Sentrum. Salinity is likely to be more similar to Lia, due to the altitude, and is therefore set to be 0.3%-1.5%. The water content is believed to be not as high as Lia because there is not as much water flowing through, it is assumed that the water content will be 10%-35%. The active layer thickness is estimated by reports to be 1-2 meters thick, and bedrock is found at 2-9 meters (Instanes & Rongved, 2017).

Gruvedalen is a rather large area with residential buildings. Due to solifluction, it is recommended that piles to bedrock is used, the same as for Lia (Rognved et al., 2017).

4.3.13 Haugen

No examinations have been done for the ground conditions on Haugen. When constructing Spitsbergen Hotel, it was discovered that there were only a few meters to bedrock. One can assume that Haugen will be similar to Lia and Svalbardhallen. It is assumed that salinity will be 0.2%-1.5% and the water saturation will be 12%-27%. Due to the small distance to bedrock, the active layer is assumed to be somewhat thicker than usual; 3-4 meters thick.

Except for Spitsbergen Hotel, this area mostly contains residential buildings. Because of the small distance to bedrock, it is clear that the preferred foundation technique will be piles to bedrock. Large deformations will therefore not likely be an issue for this area, even if the active layer thickness exceeds the piles.

4.3.14 Svalbardhallen

Svalbardhallen and Longyearbyen School is located in this area. Tuft (1995) examined the ground conditions and discovered that it contained gravel with varying amounts of find sand and silt. The salinity of the area is relatively low and is estimated to be between 0.1%-0.4%. The water saturation is also believed to be low with 5%-15% where the saturation increases with depth. Depth to bedrock and active layer thickness is not mentioned in the report by Tuft (1995), but the active layer thickness is believed to be approximately 1.5 meters.

On the existing buildings in the area there has been observed some damage since 1983 (Karlsrud, 1983). It is believed that todays foundation will be able to carry the loads of Svalbardhallen in future climate, but there might be a need for considering enforcing the structure by using additional piles. For other buildings in the area, pile foundations or slab foundations can be viewed as adequate.

Table 3: Salinities, water saturations and active layer thicknesses from all areas in Longyearbyen. The colours represent if the information comes directly from reports for the specific area (green), extrapolated from the closest area (yellow), or extrapolated from areas not that close or just an educated guess (red).

Area	**Salinity, % (min, max)**	**Water Saturation, % (min, max)**	**Active Layer Thickness, m (min, max)**	**Combination of strengths**
Skjæringa	0.25 (0.1,0.4)	17.5 (15,20)	1.5 (1,2)	Strong
Melkeveien	0.25 (0.1,0.4)	17.5 (15,20)	1.5 (1,2)	Moderate
Sjøområdet	2.3 (0.6,3.0)	30 (25,35)	2	Weak
Sjøskrenten	2.3 (0.6,3.0)	12.5 (10,15)	2	Moderate
Midtre Elvesletta	1.0 (0.7,1.3)	20 (5,35)	1.5 (1,2)	Moderate
Elvesletta Sør	0.65 (0.3,1.0)	17.5 (5,30)	1.5 (1,2)	Moderate
Forskningsparken	1.85 (0.2,3.5)	20 (10,30)	1.5 (1,2)	Strong
Sentrum	1.55 (0.4,2.7)	31 (22,40)	1.5 (1,2)	Strong
Nedre Lia	1.5 (0.3,2.7)	25 (10,40)	1.5 (1,2)	Moderate
Lia	0.9 (0.3,1.5)	30 (20,40)	2 (1.5,13)	Weak
Nordre Lia	0.9 (0.3,1.5)	30 (20,40)	2 (1.5,13)	Moderate
Gruvedalen	0.9 (0.3,1.5)	22,5 (10,35)	1.5 (1,2)	Moderate
Haugen	0.85 (0.2,1.5)	19.5 (12,27)	3.5 (3,4)	Moderate
Svalbardhallen	0.16 (0.05,0.27)	10 (5,15)	1.5 (1,2)	Moderate

"Combination of strengths" has been determined by the following rules;

- Green; all conditions are green.
- Yellow; can either be that all conditions are yellow, two green conditions and one red, or two/one condition green and one yellow.
- Red; can either be that all conditions are red, two red conditions and one green, one/two yellow conditions and one red.

Following is also a map similar to the one in Chapter 2, where the areas of Longyearbyen is colour coded according to its "combination of strengths". This is done so that the reader can easily see which areas that have first-hand information, and which areas that does not (Figure 17).

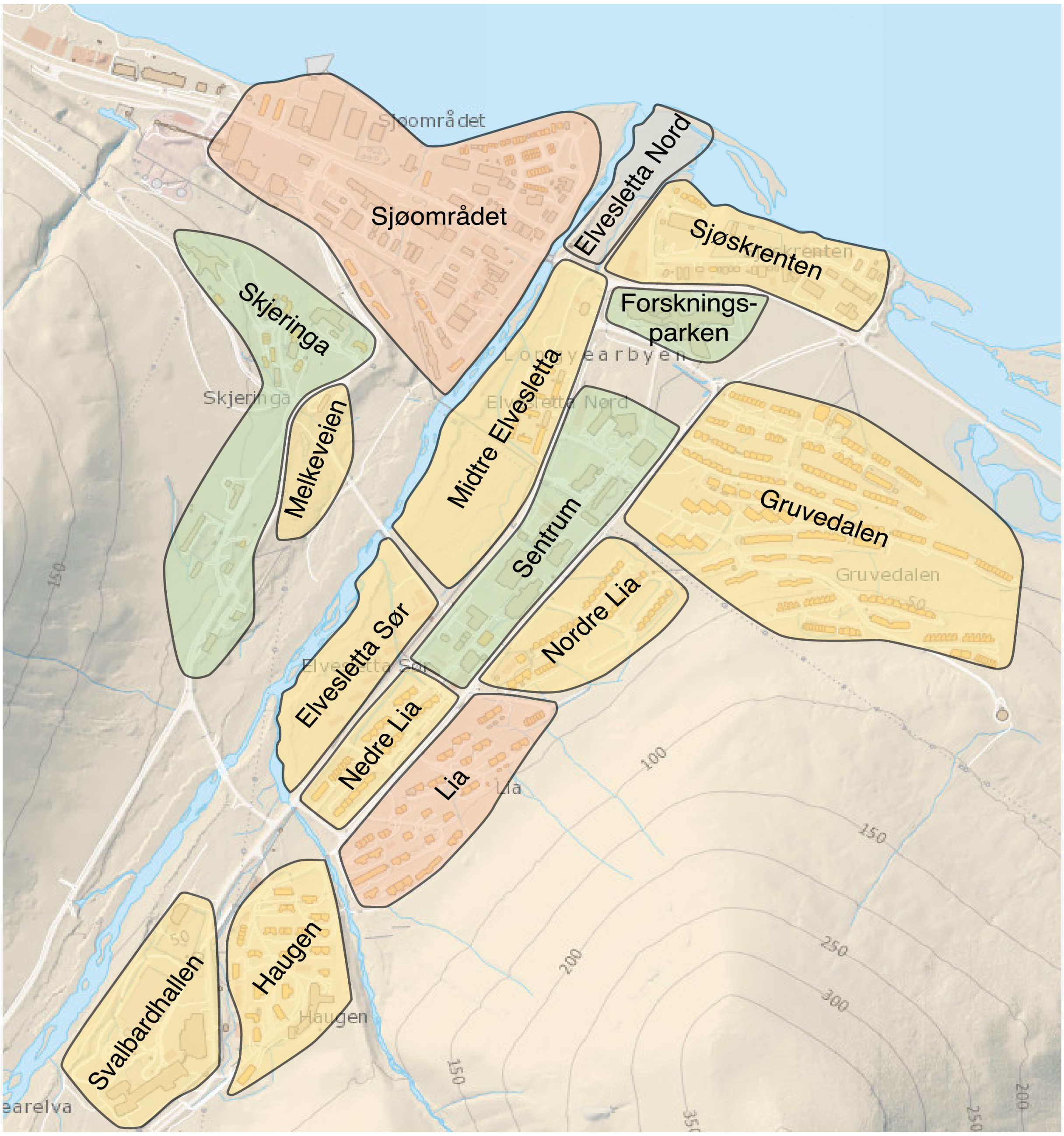


Figure 17: Map of the areas of Longyearbyen, colour coded after the "combination of strengths". Figure: Marie Olsen

5. Method - Vulnerability Analysis of Climate Change Impacts

With a knowledge base regarding likely climate change scenarios and ground conditions in Longyearbyen today in place, it is time to focus on alternative methods to that can be used when performing the vulnerability assessment.

Risk analysis is a well-known field of research that is used to support decision-making under uncertainty, that is, to make sure that adequate measures are taken to protect people, the environment, and assets from harmful consequences from either human activities or natural events. Various methods exist in to perform these assessments, with a goal of systematically collecting information and knowledge, so that one can reach a good and risk-informed decision.

Some considerations that need to be taken into account when selecting the method are the unique challenges connected with executing an analysis of natural hazards. First, there often exist limited data of the event considered, that is – there exists little and/or too crude data to simulate future climate change with a satisfactory accuracy. For the case of this thesis, this is especially true. It is not only difficult to estimate how much the temperature and the precipitation will change, but also how this might affect the soil in permafrost areas and in turn how the change in soil will disturb the foundation of existing structures in Longyearbyen. Examples of uncertainties related to the temperature and precipitation is how much emissions that will be released to the atmosphere during the next 80 years or change in external factors such as solar activity. Examples of uncertainties related to the climate changes effect on permafrost is how the specific soils react to more heat and water, which relies on amongst other type of soil, water content, ice content, salinity, and density of the soil. Uncertainties related to how the foundation reacts to change in permafrost characteristics depends on how certain materials friction reacts to warmer soil, or how the vertical stress changes given the weight of the building.

Because of the many and intricate uncertainties related to the issues of this thesis, and due to the very limited data and models used for the selected area, the selected method needs to be taking these constraints into account. The uncertainties are connected to the climate change and the vulnerability assessment. Whereas the uncertainties about the vulnerability assessment will be more thoroughly examined due to further extent of knowledge regarding this. Uncertainties related to climate change is not within the authors expertise, and therefore the information about this is assumed accurate and taken at face value.

5.1 Identification of Initial Events – Levels of Thawing

As reviewed in Chapter 3, different hazard scenarios of how the climate might look like based on likely climate emissions in the future have been selected. These are called RCP2.6, RCP4.6, and RCP8.5 which represent; “best case scenario”, “middle scenario", and "worst case scenario" respectively. It has already been established that RCP2.6 is highly unlikely, as it relies on a drastic cut of emissions on a world basis by 2020. Therefore, in many modellings and simulations, the estimations from this scenario is excluded, or heavily simplified. Therefore, also here the RCP2.6 scenario will be excluded for the benefit of using the scenarios RCP4.5, RCP4.5 to RCP8.5, and RCP8.5.

Furthermore, in researched literature, only estimations from RCP4.5, and to some extent RCP8.5, are done for the future permafrost conditions in Longyearbyen. As already mentioned, if it turns out that 2100 looks like RCP4.5, the active layer thickness is estimated to change from 1.5 m to 2.5 m, so in all changing by approximately 1 meter. On the other hand, if 2100 appear to be in between RCP4.5 and RCP8.5, the permafrost is assumed to change drastically and the active layer thickness might exceed from 1.5 to 5 meters, which gives a change of 3.5 meters or more. For the RCP8.4 scenario, a change of more than 5 meters is expected. Of course there are large variations in how deep the active layer reaches today and in the 2100, and it will be very difficult to estimate the future changes of each location (Hanssen-Bauer et al., 2019).

It is also large variations in how the bearing capacity will change, which is dependent on the initial temperature of the permafrost and the geological traits of the soil.

5.2 Selection of Method

A well-known form of risk analysis is the so-called quantitative risk analysis (QRA), which was developed by amongst others the nuclear industry and petroleum industry, and has later been transferred to areas such as mitigating measures for terrorism, food safety, and infrastructure planning (Aven & Renn, 2009). In a classic QRA, the information/knowledge available is systemised, potential threats or hazards are identified, along with analysis of the causes and consequences. Importantly, the QRA aims to convert as much as possible into measurable quantities in order to come up with a comparable result that will make choosing between different measures or actions easier for the decision makers. This will create an overview of risk in the system or organisation related to different activities.

Although the QRA method is an informative way of revealing and categorising different risks related to various activities or phenomena, the method has received some criticism due to the difficulties with quantifying risks where uncertainties are large, or for example when trying to quantify things that are not necessarily quantifiable as the value of a human life or the environment. It is important to emphasise that risk is more than just calculated probabilities and expected values, and one must take uncertainties of the activity into account (Aven & Renn, 2009).

Due to the issues arising when solely using numbers as a representation of risk, more semi-quantitative approaches has emerged. Semi-quantitative approaches can address uncertainties and assumptions to a larger degree because one can describe the issues better with words than numbers, and furthermore, one can give some information beyond the numbers that can provide some insight for the decision makers. In this thesis a similar approach is going to be used, or as Berner and Flage (2016) refers to it, an extended quantitative risk assessment (EQRA). An EQRA here means the use of the traditional QRAs in addition to a systematic qualitative assessment of the strength of background knowledge on which the QRA is based. The background knowledge specifically includes assumptions in this thesis, as there are many of them in this case.

When it comes to choosing exactly which approaches to use, many different alternatives have been considered. Both fragility based and statistical approaches as described by Guikema (2018) have been considered, and each of these methods have their strengths and weaknesses. The fragility curves do for example not require substantial past data. However, it is often not as accurate as the statistical modelling and are often only based on one hazard parameter; which natural hazards rarely are. The statistical approach has achieved strong predictive accuracy in practice, and it can incorporate many hazard parameters. This approach is on the contrary to fragility curves highly reliant on substantial past data. Unfortunately, both methods require more data than is available for Longyearbyen. This results in using a different method that is more straightforward and is already used for the same purpose for all of the Arctic Russia. Furthermore, an assessment of how vulnerable the method will be to changes of the chosen approach will be done in addition of the actual vulnerability analysis.

Before beginning to describe the method, the “IPCCs guideline for assessing climate change and adaption” will be highlighted in the following chapter, because it has been tailored to fit climate change challenges, and it is a framework that is internationally recognised amongst climate change researchers. A small comparison between IPCCs framework and the ISO 31000 risk framework has been included to make it apparent for risk managers/analysts to see that they are quite similar despite the customisation for climate change.

Even though the whole framework is viewed as too comprehensive for this thesis, it is still important to show that it has been considered. Furthermore, some of the parts of the framework will still be used, as it always is when doing risk or vulnerability analysis. Both point 1, 2 and 5, are to some degree covered by this thesis.

After the review of the IPPC guideline, a method by Streletskiy et al. (2019), from now on called The Russian Approach, will be presented as the selected method.

5.2.1 The IPPC Guideline for Assessing Climate Change Impacts and Adaption

There exist multiple different approaches for risk analysis that aim to categorise and systemise the process of risk or vulnerability assessments. In 1994 IPCC published a report that aims to help with the assessment of climate change impact and adaption (Carter, Parry, Harasawa, & Nishioka, 1994). The origin of the report came from the need to identify the possible policy implications that enhanced greenhouse effect at an international level (Carter et al., 1994), and the role of the IPCC framework is described as being "to assess on a comprehensive, objective, open, and transparent basis the scientific, technical, and socio-economic information relevant to understanding the risk of human-included climate change, its potential impacts, and options for adaption and mitigation" (Carter et al., 1994). This framework has been integrated into the Australian and New Zealand Risk Management Standard and are therefore used by amongst others Australian governmental facilities (Jones, 2001).

The IPCC guidelines for assessing climate change impacts and adaption is organised into seven different steps:

1) Definition of the problem; where one should aim to determine what the goals of the assessment are, what one should study, what data is needed, and for how long time frame the assessment should consider.
2) Selection of the method; which should be based on experimentation, impact projections, empirical analogue studies, and expert judgements.
3) Testing the method; to test this, three types of testing activities can be used, and that is feasibility studies, data acquisition and compilation, and model testing.
4) Selection of scenarios; when doing this one should establish the present situation, consider what time frames one should estimate for, projecting environmental and socio-economic trends in the absence of climate change separately. Then project future climate, with a following projection of the trends in the presence of climate change.
5) Assessment of biophysical and socio-economic impacts; firstly, with a qualitative description, indicators of change, and compliance to standards. Later, do a cost-benefit analysis, geographical analysis, and dealing with uncertainty.

6 & 7) Assessment of autonomous adjustments and Evaluation of adaption strategies; these two are described together and focus on the two, broad types of response. These are mitigation and adaption. An adaption strategy has also been described.

The IPCC framework meets its goals by being able to assess climate change impacts and adaptions in a scientific manner, and provides a mode of analysis that enables policymakers and decision makers to choose among a set of adaption possibilities (Carter et al., 1994). The framework is simple in concept, even though it is difficult to execute due to the complexity of climate change, and the need to involve various stakeholders in the assessment. Furthermore, the framework relies on key climate variables that can be expressed through a range between high and low extremes with a given probability distribution, an impact threshold forced by the key climate variables, a conditional probability of that threshold being exceeded, and adaption/mitigation options (Jones, 2001). All of this requires a lot of time and effort from both researchers and risk managers.

This framework is similar in structure to many other frameworks, as for example ISO 31000 (ISO31000, 2018) or COSO (COSO-ERM, 2017), in the sense that it follows the issues with the risks from beginning to end, or from detection to treatment. It basically presents the same bullet points as ISO 31000, only by changing the name and order of some of the points. The first point of IPCCs framework is very similar to ISOs “establishing context”, while number two and three is similar to the “risk analysis” part. Selection of scenarios is similar to ISOs “risk identification”, assessment of impact is similar to “risk evaluation”, and number six and seven switch places with the two last from ISO “risk treatment and monitoring and review”).

The major difference between the two is naturally that IPCCs framework is adapted to fit the specific challenges related to climate change. Even though this framework has been used many times before, the author believes that a full risk management framework is not necessary and too time consuming in order to achieve the goals that are set. Thus, the use of only a risk assessment is viewed as adequate for this thesis. Although some aspects within this framework are used.

Aven and Renn (2015) argue that the the IPCC framework falls short when it comes to the understanding of risk and uncertainty. The risk perspective is not viewed as sufficient when it comes to extreme outcomes and poor knowledge base. Specific measures have been represented in the report in order to address the issues better than in the IPCCs framework, as for example by the use of strength of knowledge assessment.

As a risk management framework, this can be constructive approach. However, in the next section other assessment methods that are not as thorough as IPCC guidelines, ISO or COSO, will be examined. As mentioned, in this thesis, it is not necessary to use a full framework in order to achieve the goals that are set. Therefore, a less complex method will be selected, called The Russian Approach (Streletskiy et al., 2019). This will be reviewed and adapted to the specific issues of Longyearbyen.

5.2.2 The Russian Approach

Streletskiy et al. (2019) published a method where they estimated the total value of fixed assets built on permafrost in the Arctic Russia, such as structures, buildings, pipelines for oil and gas, roads, and railways. They did this by dividing the Arctic Russia into nine large areas, based on their administrative regions.
Their method was first based on estimating the total costs by the assumption that there are areas with constant permafrost (90%), discontinuous permafrost (50%), and sporadic permafrost (10%). The total cost then becomes;

- $TC = 0.9*C + 0.5*D + 0.1*S$

Where TC is the total cost, C is the costs related to the constant permafrost, D is the costs related to the discontinuous permafrost, and S is the costs related to the sporadic permafrost.

Further they consider the two largest contributors to risk to buildings and infrastructure associated with climate change to be ground subsidence and bearing capacity. Ground subsidence is the phenomenon where the underlying ice melts and freezes over repeatedly, it can cause deformations of the surface of the ground and hence also the buildings. This already happens in todays climate conditions, but when the active layer thickness becomes more prominent, so does the volume of water in the layer; which results in more movement in the ground from season to season. Streletskiy et al. (2019) has chosen to use the following equation, which is based on the change of active layer thickness and the ice content.

- $S = dZ * I$

Where S is the thaw subsidence, dZ is the change of active layer, and I is the ground ice content.

Bearing capacity is highly dependent in the permafrost characteristics. Climate change will affect this considerably and is an important factor when considering infrastructure on permafrost. In the report by Streletskiy et al. (2019) the information about the bearing capacity has been retrieved from another report calculating the bearing capacity for the different areas of the Arctic Russia by the use of intricate equations based on many different soil conditions in the permafrost. They also assume that the piles are 10x0.36x0.36 m all over Russia, which is a quite large assumption for such a big area. They end up with a table that presents various changes of climate and permafrost, that looks like Table 4 below, which shows the first three districts in the original table.

Table 4: An example of changes in climate change and permafrost characteristic in the study regions by 2050-2059 relative to 2006-2016. Only 3 out of 9 district are selected to show their approach (Streletskiy et al., 2019). MAAT is mean annual air temperature, MAGT is mean annual ground temperature, and ALT is active layer thickness.

District	MAAT, °C (min,max)	Precipitation, mm (min, max)	MAGT, °C (min, max)	ALT, m (max)	Bearing Capacity, % (min, max)	Ground Subsidence, cm (min, max)
Komi Republic	3.61 (3.19, 4.08)	84 (63,96)	3.49 (2.98,4.03)	0.50 (0.68)	-32 (-17,-54)	12 (3,29)
Nenets AO	3.90 (3.39,4.84)	75 (60,94)	3.85 (3.35,4.77)	0.39 (0.74)	-33 (-21,-45)	14 (3,29)
Khanty-Mansi AO	3.35 (3.10,3.54)	48 (28,85)	3.08 (2.92,3.24)	0.18 (0.42)	-31 (-12,-48)	7 (3,18)

By these steps this method managed to produce a somewhat crude estimate of the total costs of climate change using the RCP8.5 scenario. In this thesis, the first part where total costs are estimated, will not be included due to lack of information about the value of the various structures. This can, however, be done quite easily if one wishes to, and has access to necessary data.

To adapt this method to become applicable in Longyearbyen, one need to make some adjustments due to for example different soil properties. Therefore, in the next section it is included what needs to be changed and also some difficulties one might meet when using this method.

5.3 Adaptions for Longyearbyen of The Russian Approach

There must be some adaptions when implementing The Russian Approach to Longyearbyen. Local changes that need to be done in regards to the permafrost in Longyearbyen is mainly due to the salinity of the soil. As already mentioned, salt represents an engineering challenge, in the sense that the pile load bearing capacities are reduced with a great deal with increasing salinity. The salinity will reduce the capacity by at least 50% at 5 ppt, by 60% to 75% at 10 ppt, and by as much as 90% at 15 ppt. In Figure 18, a linear representation is presented of the bearing capacity based on the numbers given above. A linear approach will be easier to use when attempting to find the numbers needed for the method. It can obviously be changed if one wishes to or new and better information about the salinities effect on the soil is discovered. This figure shows that for every ppt salt added to the soil, the pile load carrying capacity will decrease by 3%. Later in the thesis, % of the salinity will be used in stead of parts per thousand, where for example 35 ppt is the same as 3.5%.

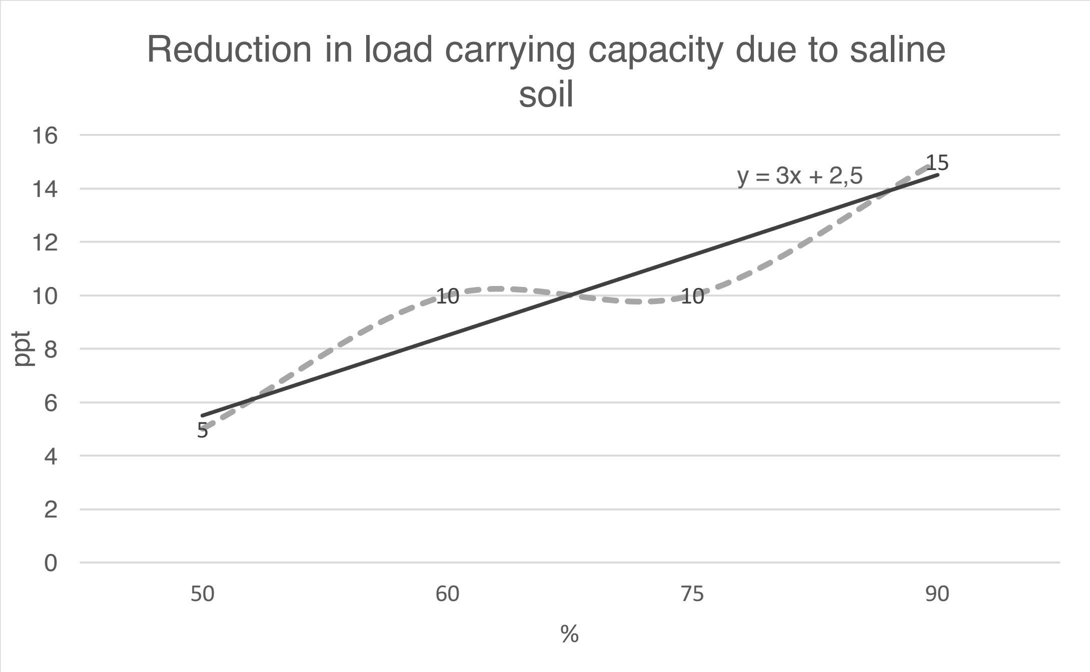


Figure 18: Projection of how the bearing capacity will be reduced due to an increase in salinity. Salinity is given in ppt, and bearing capacity in %. The stapled line shows the projection of the reduction in bearing capacity. The straight line shows a simplified representation of the reduction in bearing capacity, for easier calculations. Graph is based on the numbers presented above with the % of reduction of capacity and salinity, from Humlum et al. (2003).

In addition to reducing the bearing capacities, salinity also affects the freezing point of the water contained in the permafrost. When salt water freezes, it precipitates so that the salt remains outside of the water molecule (one can boil sea ice and use it as drinking water). This means that some of the water containing salt in the soil will never freeze, and hence the thaw subsidence will decrease with increasing amount of salt.

It is clear that the salinity of the soil needs to be integrated into the equation for thaw subsidence from the previous chapter, and probably also water content as well as it plays an important role in the thawing and freezing of the active layer. When salinity (X) is increasing, the thaw subsidence (S) should decrease because when one has more salinity; less water freezes and hence, one gets less thaw subsidence. Underneath it is presented an equation that takes into account both salinity (X) and water content (W). In addition, a constant, c, is added in order to adjust S so that the output values become more representative. The term of the equation, (10-X), is made so because of the argument above about increasing salinities gives decreasing thaw subsidence. Other approaches were also considered as an option, but these was discarded due to unrepresentative numbers during testing. c is unknown, but a tornado diagram will be created (in Chapter 5.4) for the equation to see how sensitive the value of the constant is, along with the other variables.

- $S = dZ * (10-X) * c * W$

Here S is the thaw subsidence (cm), dZ is the change in active layer thickness (m), X is salinity (%), and W is water content (%), c is a constant associated with X. Notice that the equation will not give sensible values if the salinity exceeds 10%, but none of the areas in Longyearbyen has more than maximum 3,5%, so that will not pose as a problem.

Both reduction in bearing capacities and subsidence has been evaluated to some extent by Rognved et al. (2017), which has been reviewed in Chapter 3.5.2. Bearing capacity has, however, been shown as very difficult to estimate even for small areas, and the uncertainties for even the experiments themselves are large. Therefore, it is not a desired choice to use experiments from even nearby areas, but as this is the only choice for know it will be used as a baseline.

Nonetheless, some numbers must be used, and because of these calculations based on Figure 12 and Figure 13 from Chapter 3.5.2 will be used to find estimations of how much reduction in bearing capacities is going to happen, how much reduction a building can handle, how much thaw subsidence is going to happen, and also how much subsidence a building can handle. This will be presented in Chapter 6. These calculations obviously give room for many assumptions, whereas the actual assumptions will be presented in Chapter 6, and the methodology of how the assumptions will be categorised and managed will be presented in the next section.

5.3.1 Assumptions

As in all risk or vulnerability assessments, one must establish a great deal of assumptions in order to handle the uncertainties. Assumptions are an inevitable part of the quantitative risk assessment. An assumption may be made as a simplification, to avoid spending unnecessary time on assessing the uncertainties. It can also be made an assumption due to lack of knowledge. Naturally, the assumption is justified if there is a low degree of belief that the actual conditions will deviate from what has been assumed, and if the deviation will have a low impact on the assessed risk level. A low belief in deviation can however be a result of lack of knowledge, and not a result of what actually is the case.

In order to manage all the assumptions, it can be constructive to categorise them in a table (see Table 8 and 9), where the “assumptions” are listed along with the “assumption justification” and the “strength of assumption justification” (Flage, Aven, & Berner, 2018). The strength of assumption justification is classified to be either weak, moderate, or strong. The classification is based on a qualitative assessment of the potential for assumption deviation in a negative direction. An example is the assumption that the 11-year cycle of the sun is constant; this phenomenon has been studied for several decades, and with help from past geological data one can estimate that the cycle has been stable for a long time. In the future the cycle might change because it is not known how the sun behaves throughout its lifetime, but it is considered highly unlikely that the cycle will change any time soon and hence this would be classified as “strong”.

When listing the assumption, the settings from above will be included in order to assign the criticality of the assumption. In this thesis, the assumptions are going to be divided into two main categories, the first one containing assumptions regarding climate change, and the second one regarding the vulnerability assessment.

In the end a combination of strength of assumption justification and sensitivity analysis will be presented. This is done by setting colours on the bars in the tornado charts from the sensitivity analysis, based on the colours from the strength of assumption justification. For Figure 21, the variables that are presented in the chart can be based on several assumptions, then the following arguments are followed in order for the bar to receive their colour;

- Green; all assumption justifications have to be strong.
- Yellow; none of the assumption justifications can be weak, some can be green.
- Red; at least one assumption justification need to be weak.

For Figure 22, there is a similar approach as above, it follows the selected colours in Table 3 from Chapter 4. How the colours have been determined is explained below Figure 3, where the given colours reflect upon the strength of assumption justification.

Before beginning with the results, a review of how the author conducted this thesis is shown. This is done in order to emphasise what was time consuming and also to show the approach throughout the time spent on the thesis.

5.4 Research Method

The author began the thesis research by collecting information about climate change; to find out what the differences are between climate change research in Arctic regions versus other areas in the world, and how this might affect both local environment as well as global changes. It was discovered that in the Arctic it was extra difficult to estimate future consequences due to lack of previous research and lack of weather stations at Svalbard to estimate changes. This is why it was important to emphasise how the climate change scenarios were estimated, by showing how and which simulations were used and also how they were used together to get as accurate data as possible.

The next step was to investigate how the climate change might affect the behaviour of permafrost. As it turned out, saline permafrost poses a special challenge because the soil behaves as a slow moving liquid, and the bearing capacity and thaw subsidence will be heavily influenced by that. It was discovered that the saline soil response to climate change is not well documented, and the uncertainties are large regarding how it will be in the future.

Quite a lot of effort was spent on retrieving information about ground conditions from various areas in Longyearbyen. First, the author contacted NGI to ask for which areas they had reports from and to also ask for access to the reports if they had them. It turned out that they did have all the reports needed, but in order to gain access, the author had to send e-mails to each of the people or companies responsible for it. So the contacted each of the people or companies responsible for it.

A literature review of both quantitative risk assessment and semi-quantitative risk assessment was done, where the choice fell on the latter because of large uncertainties and hence a need for assessing and categorising assumptions. Fragility based and statistical approach was both considered, but due to lack of data these were discarded in favour of The Russian Approach, which was discovered during literature research on methods used in Arctic climate. This method did not require as much data as the others, but this results in very crude estimations which might not be as favourable as for example the statistical approach.

Based on the required data from The Russian Approach and the available data from the report, data was collected to find estimations of thaw subsidence. However, in order to use The Russian Approach, it needed to be adapted to fit the ground conditions in Longyearbyen. Therefore, it was added a term that would take salinity into account, along with a constant that should regulate the result to give more realistic thaw subsidence.

The bearing capacity was harder to find. Much time was spent on trying to find reduction in bearing capacity due to climate change, but the author found nothing except for an estimation from a community in Greenland. Later on, the author managed to estimate reduction in bearing capacity from Rognved et al. (2017), along with the limits of reduction in bearing capacity and increase in thaw subsidence before failure. These numbers were also difficult to find.

So in short, a lot of time was spent on discovering and retrieving information about climate change because there is much uncertainty and lack of information about the subject. It was also time consuming to retrieve ground conditions from each area, and the general information about failure limits and bearing capacity.

6. Results - Impact Calculations

This chapter will represent the results that have been calculated and estimated using the method from the previous chapter. First, calculations of thaw subsidence along with estimations of active layer thickness and bearing capacities will be presented in tables for each area in Longyearbyen, one table for each RCP scenario. Secondly, a sensitivity analysis of the variables within the equation for thaw subsidence will be shown, and also the sensitivity of the areas based on the ground conditions. Assumptions are listed below this, they are categorised according to assumptions regarding climate change and assumptions regarding the assessment. Finally, a combination of the sensitivity analysis and the assumptions are connected, by presenting the tornado charts with the colours from the strength of assumption justification.

6.1 Calculations

Thaw subsidence has been calculated with the help of the equation developed in Chapter 5.3, using the data from Table 3 and Table 4 in Chapter 4. First, how the bearing capacity will be reduced are calculated, then how much both bearing capacity and thaw subsidence can change before foundation failure. Calculations and a description of how the limits were reached can be seen in the following text and tables.

How bearing capacities are changing is a result of calculations from Figure 12, Chapter 3.5.2, where it can be observed from Figure 12 that the changes from the green line (1986-2015) to the yellow line (2016-2045) is approximately 29%, and changes from the green line to the red line (2046-2075) is approximately 57%. This means that a buildings bearing capacity is reduced by 29% from 1986-2015 to 2016-2045, and reduced by 57% from 1986-2015 to 2046-2075. The previous numbers are found by calculating the difference in % between the green line and the red line and subtracting the value of the yellow line from the green line in order to make the green line into the reference point. This is done throughout the curves, and the numbers turn out the same.

Moreover, the author went one step further, and estimated a new line that goes from 2076-2110, where the reduction in bearing capacities will be as much as 64%. This number is found by looking at the reductions between green line and yellow line which is 29%, and between yellow line and red line which is 28%. The author made the assumption that the next step will be 27%, and then the reduction becomes 64%. This means that the reduction in bearing capacity will decrease by almost 64% in the RCP4.5 scenario. As a result of these calculations, the reduction in bearing capacity fell on 60% as a baseline for the RCP4.5 scenario, for the other scenarios, one can expect an even further reduction, but the author has only guessed at these numbers. The numbers for RCP4.5 to RCP8.5 and for RCP8.5 are given to be 80 (70,90) and

100 (85,115) respectively. A larger fluctuation has been given the RCP8.5 scenario because there are larger uncertainties related to this one (because it is further away from RCP4.5 which the calculations are built on).

From Figure 13 in Chapter 3.5.2, one can at least make an estimate of how much change in thaw subsidence and bearing capacity that is possible before foundation failure. It is said that the change in soil will lead the foundation to fail from construction in 2036 vs 2046, which means that between a change in between 11 and 26 cm will lead to failure due to subsidence. Bearing capacity is reduced to such a level that it leads to failure at the same time, and in terms of %, this means that it fails between 54% and 81% in reduced bearing capacity. This is calculated by looking at the difference between installation in 1986-2015, and 2036-2055 and 2046-2065, which lead to the mentioned reductions respectively.

This means that;

- Thaw subsidence can be between 11 cm and 26 cm before failure. For simplicity, the median of the two is used: 18 cm.
- Bearing capacities can be reduced between 54% to 81% before failure. Same as for the change in thaw subsidence, the median will be used here as well: 67.5%.

The calculations are shown in Table 5, Table 6 and Table 7 below, for RCP4.5, between RCP4.5 and RCP8.5, and for RCP8.5 respectively.

Table 5: The results of active layer thickness, thaw subsidence, and bearing capacity based on a scenario RCP4.5.

Area	Active Layer Thickness, m (min, max)	Thaw Subsidence, cm (min, max)	Bearing Capacity, % (min, max)
Skjæringa	1	10.3 (2.2,23)	60 (55,65)
Melkeveien	1.5	15,4 (2.2,23)	60 (55,65)
Sjøområdet	1	13.9 (2.4,19.6)	60 (55,65)
Sjøskrenten	1	5.8 (0.9,8,4)	60 (55,65)
Midtre Elvesletta	1	10.8 (0.47,24.4)	60 (55,65)
Elvesletta Sør	1	9.8 (4.9,21.6)	60 (55,65)
Forsknings-parken	1.5	14.7 (1.5,23.4)	60 (55,65)
Sentrum	1	15.7 (2.1,23.4)	60 (55,65)
Nedre Lia	1	12.8 (1.0,23.4)	60 (55,65)

Lia	1	16.4 (1.9,27.2)	60 (55,65)
Nordre Lia	1	16.4 (1.9,27.2)	60 (55,65)
Gruvedalen	1	12.3 (1.0,23.8)	60 (55,65)
Haugen	1	10.7 (1.2,18.4)	60 (55,65)
Svalbard-hallen	1	5.9 (0.5,11.7)	60 (55,65)

Table 6: The results of active layer thickness, thaw subsidence, and bearing capacity based on a scenario between RCP4.5 and RCP8.5

Area	Active Layer Thickness, m (min, max)	Thaw Subsidence, cm (min, max)	Bearing Capacity, % (min, max)
Skjæringa	3.5	35.8 (5.2,53.8)	80 (70,90)
Melkeveien	4	41.0 (8.2,68.6)	80 (70,90)
Sjøområdet	3.5	48.8 (8.2,68.6)	60 (55,65)
Sjøskrenten	3.5	20.2 (8.2,68.6)	80 (70,90)
Midtre Elvesletta	3.5	37.8 (1.6,85.3)	80 (70,90)
Elvesletta Sør	3.5	34.4 (1.7,75.6)	80 (70,90)
Forsknings-parken	4	39.1 (3.9,62.4)	60 (55,65)
Sentrum	3.5	55.0 (7.4,81.8)	80 (70,90)
Nedre Lia	3.5	44.6 (3.4,54.6)	80 (70,90)
Lia	3.5	57.3 (6.8,95.2)	80 (70,90)
Nordre Lia	3.5	57.3 (6.8,95.2)	60 (55,65)
Gruvedalen	3.5	43.0 (3.4,83.3)	80 (70,90)
Haugen	3.5	37.5 (4.1,64.3)	80 (70,90)
Svalbard-hallen	3.5	20.7 (1.7,40.9)	80 (70,90)

Table 7: The results of active layer thickness, thaw subsidence, and bearing capacity based on a scenario RCP8.5

Area	Active Layer Thickness, m (min, max)	Thaw Subsidence, cm (min, max)	Bearing Capacity, % (min, max)
Skjæringa	3.5	61.4 (8.9,92.2)	100 (85,115)
Melkeveien	4	66.5 (9.7,99.8)	100 (85,115)
Sjøområdet	3.5	83.2 (14.1,117.6)	100 (85,115)
Sjøskrenten	3.5	34.7 (5.6,50.4)	100 (85,115)
Midtre Elvesletta	3.5	64.8 (2.8,146.2)	100 (85,115)
Elvesletta Sør	3.5	58.9 (2.9,129.6)	100 (85,115)
Forsknings-parken	4	63.6 (6.4,101.4)	100 (85,115)
Sentrum	3.5	94.3 (12.7,140.2)	100 (85,115)
Nedre Lia	3.5	76.5 (5.8,140.2)	100 (85,115)
Lia	3.5	98.3 (11.6,163.2)	100 (85,115)
Nordre Lia	3.5	98.3 (11.6,163.2)	100 (85,115)
Gruvedalen	3.5	73.7 (5.8,142.8)	100 (85,115)
Haugen	3.5	64.2 (7.1,110.2)	100 (85,115)
Svalbard-hallen	3.5	35.4 (3.0,70.1)	100 (85,115)

As can be seen from the tables, only the thaw subsidence are the values that varies from area to area. In reality, it is obvious that the bearing capacity will differ, but since there exist no data for each area only one estimate is used. Therefore, one can see that for scenario RCP4.5; the bearing capacity will probably not be reduced to a failure point, even at the upper limit of the fluctuation. For the two following scenarios, RCP4.5 to RCP8.5 and RCP8.5, it is estimated that the foundation will fail even at the lower end of the scale. This goes for all of the defined areas, because they are all defined with the same limits in this thesis.

For the change in thaw subsidence, a sensitivity analysis for each area will be shown in the form of a tornado chart. How sensitive each component is within the thaw subsidence equation will also be shown as a tornado chart to be able to see what components are the most sensitive.

6.2 Sensitivity Analysis

In this chapter, it will first be presented how sensitive the different components within the thaw subsidence equation are; namely, the constant (c), the salinity (X), the water content and change in active layer thickness (dZ). After that, it will be presented how much the thaw subsidence will vary within each area.

The tornado charts of variables within the equation for thaw subsidence are presented in Figure 19. By letting all variables to be set at a median value and then changing the component one at a time, the charts show the minimum and maximum values for each of the variables. A middle line is drawn in order to see what the result would be if all variables was at the middle value. The fluctuations show only the change in the respective components.

Each of the charts represent RCP4.5 scenario, RCP4.5 to RCP8.5 scenario, and RCP8.5 scenario respectively, and Forskningsparken has been used as an example because the fluctuations are the largest for this area. It can be observed that even though the values change, the shape of the graphs do not change. The only exception for this is the change in active layer thickness, which is a reflection of increased uncertainty for the scenarios.

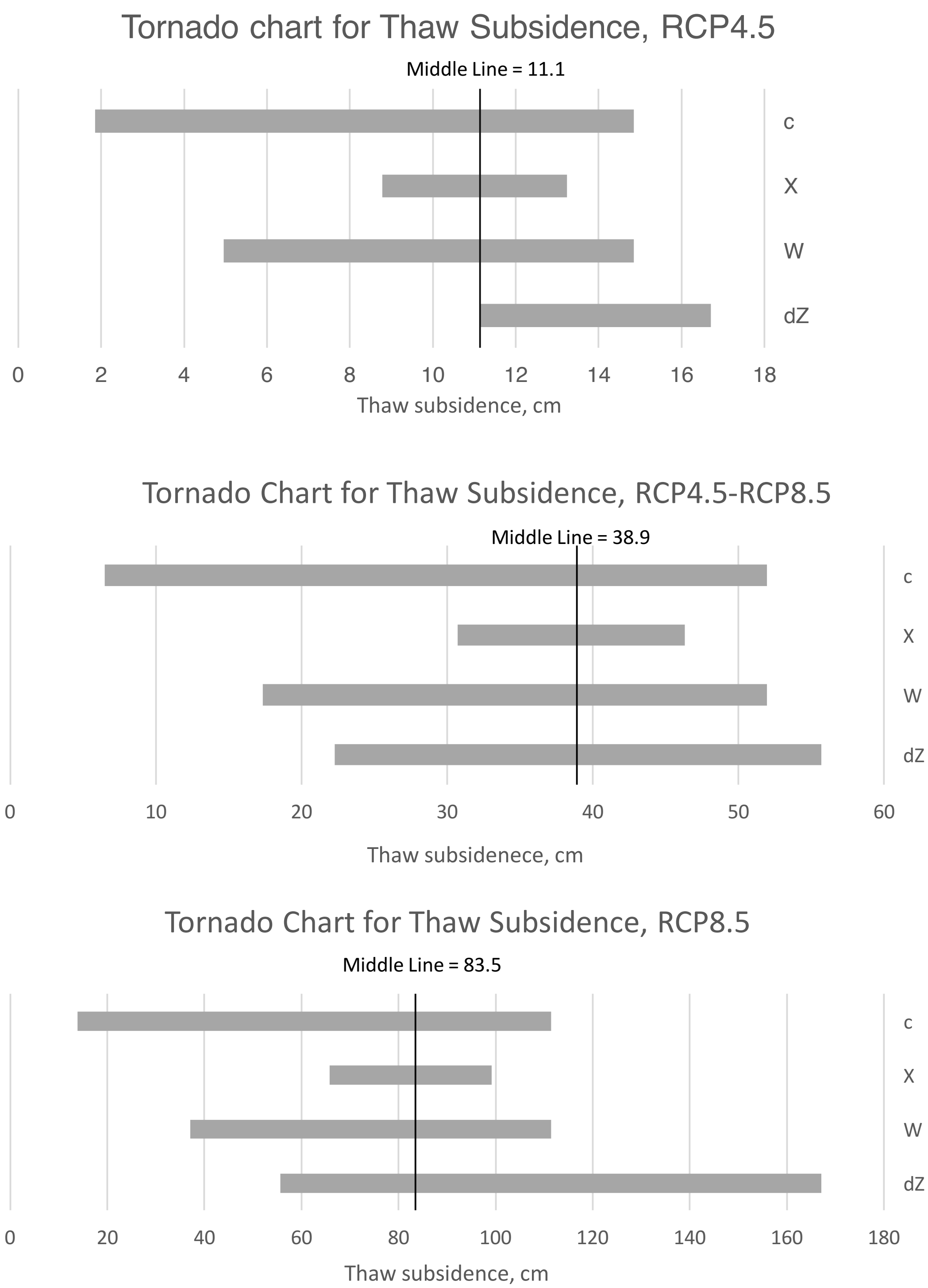


Figure 19: Tornado charts of components within the thaw subsidence equation in scenario RCP4.5, scenario RCP4.5 to RCP8.5 and, scenario RCP8.5. Forskningsparken is used as an example here.

The following charts show the sensitivity of the thaw subsidence within each area for the different RCP scenarios. The fluctuations within each area reflect the minimum and maximum values of thaw subsidence when inserting all minimum ground condition values on one end and all maximum ground condition values on the other as for Figure 13. The failure line at 18 cm shows where the amount of thaw subsidence will lead to failure, and the two on each side shows the minimum and maximum value of the failure line, at 11 cm and 26 cm.

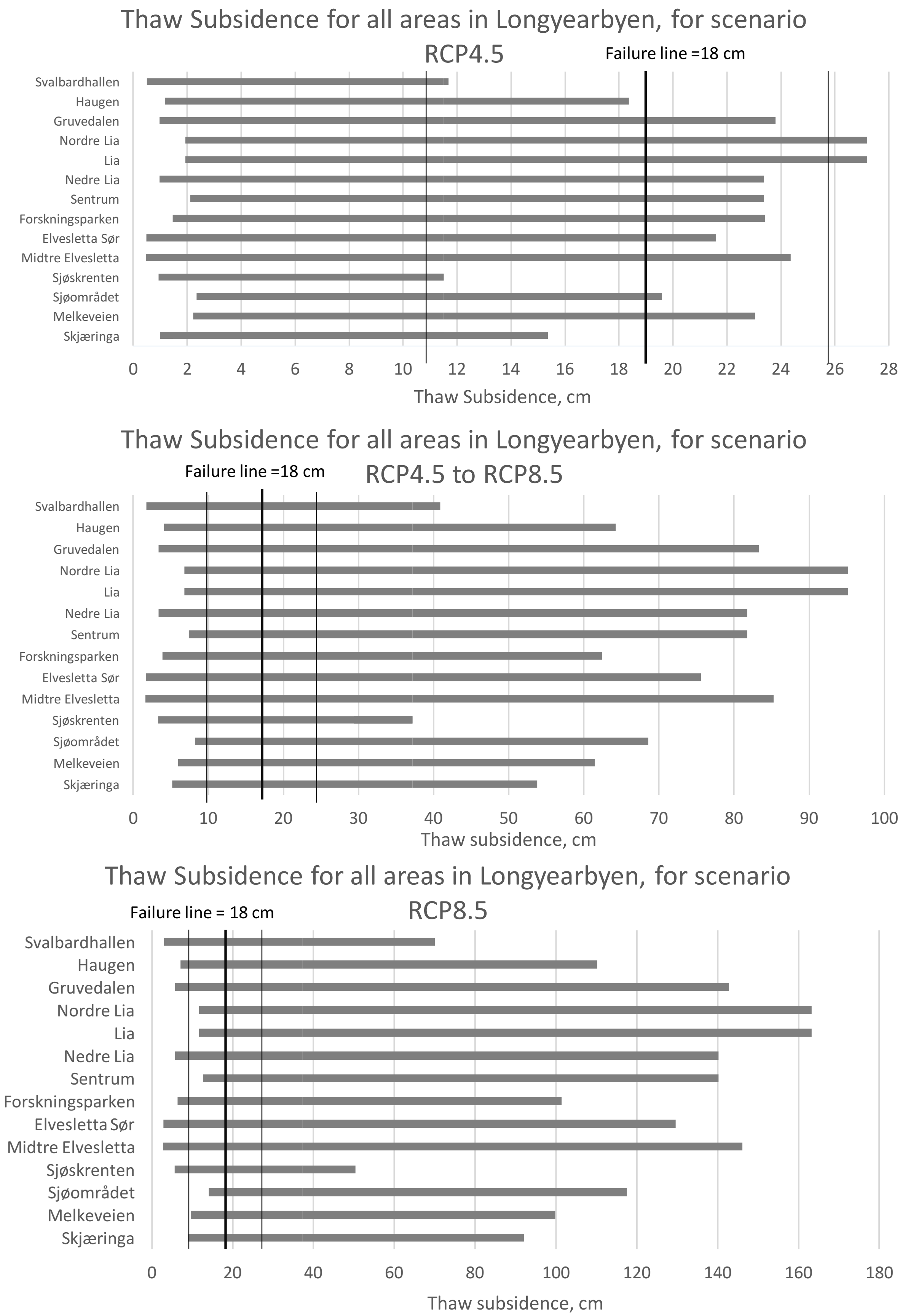


Figure 20: Fluctuation in thaw subsidence for each area in Longyearbyen. Done for each of the RCP scenarios.

As can be seen is that there are large variations of the thaw subsidence within each area, and this is a result of uncertainties for each of the variables that is assessed above. The tornado charts from Figure 20 shows that even with large fluctuations the median points of from RCP4.5 stays within the limits of failure due to thaw subsidence. Furthermore, the bearing capacity will still hold during this scenario (see points in Chapter 6.1). For the other two scenarios, it is quite different for both thaw subsidence and bearing capacity. For scenario RCP4.5 to RCP8.5, the thaw subsidence's vary from being within to limit to above, but even so, the bearing capacity is reduced to such a level that it will lead to failure anyway. When looking at RCP8.5, both the thaw subsidence and bearing capacity will fail for all.

6.3 Assumptions

6.3.1 Assumptions Regarding Climate Change

As already mentioned in Chapter 3.6, uncertainties about climate change can be categorised either according to Aven (2014) or according to climate change researchers (Isaksen et al., 2017). Since these assumptions already are specified, it is difficult for the author to uncover what assumptions that has been made in order to make the different RCP scenarios. It has however to some extent already been highlighted to some degree by Isaksen et al. (2017), and due to this the climate change categorisation will be used (Table 8).

Table 8: Assumptions about climate change.

Assumption
That the given RCP scenarios are representative
That the suns cycle is constant
That the weather and ocean systems are constant
It is known how much natural variations matter
The models give accurate predictions
Climate change affects permafrost as expected
Assume that the sea ice is where the models estimate
State of todays climate is correct

That the different scenarios for the future are correct is highly dependent on a variety of factors regarding for example political agreements, and whether these agreements will be followed or not. And if these requirements are fulfilled it is not certain that the temperature, precipitation and weather patterns are going to be the same as the RCP scenarios predict.

Furthermore, it is impossible to know how much of the climate change that is caused by man-made emissions compared to natural variations. Some experts even argue that the climate change might not be caused by humans at all, or at least more dependent on natural variations than is the popular belief (Humlum, Solheim, & Stordahl, 2011). That the climate has become warmer the last 100 years might or be a result of anthropological emissions or just a part of the larger system within the natural variations, but even so it is important to prepare for the change that is coming.

The assumptions connected to the natural variations itself can in some cases be a quite reasonable assumption, as for example the suns 11-year cycle which have been documented for long periods of time and has been proven to be constant so far (Hanssen-Bauer et al., 2019). Other assumptions connected to natural variations might not be so certain, as for example natural fluctuation of low-pressure and high-pressure systems coming in over the Svalbard Archipelago.

That the models give accurate predictions are for certain not a very safe assumption. There are many reasons for this not to be true, as for example a problem with understanding and be able to simulate phenomena and systems. Furthermore, errors occur when some input data based on other assumptions is wrong from the beginning, and it gets larger the further one simulates into the future. An example of this is the extent of the sea ice, where some of the simulation methods have estimated the location of the limits to be either to far south or to far north. This results in the future temperatures being far to high or low compared to what is realistic. Fortunately, several different types of simulations can to some extent cancel out the model uncertainties, by using their different strengths and weaknesses together to estimate the best predictions. As a result of this, the assumption about the models being correct can to some extent be viewed as more safe than with only one model.

Even though many of the assumptions for climate change are large, one has to accept them in order to proceed with assessments. Everything done in the vulnerability assessment is based on the assumptions made from climate change, and new assumptions even need to be made in order to make the vulnerability assessment possible, which will be shown in the next section.

6.3.2 Assumptions Related to the Vulnerability Assessment

Assumptions related to the vulnerability assessment is easier to do more thoroughly. These assumptions will be categorised in Table 9.

Table 9: Assumptions about the assessment.

Assumption	Assumption Justification	Strength of Assumption Justification
The values from reports on ground conditions are correct	Even though the sources are reliable, uncertainties related to research on ground conditions can be large.	Strong
The values retrieved from other areas with data are valid for another area next to it	This is not necessarily true, but it is the best option.	Moderate
The values retrieved from other areas with data are valid for another area one area away from it	This is not necessarily true, but it is the best option. This is even further away than the previous.	Weak
The areas within each "city part" are homogenous	This is not true, but assessment becomes too cumbersome.	Moderate
The bearing capacities are the same for all areas	No basis for this information. It is the best option at this point.	Weak
Buildings are constructed and used according to recommendations from experts	In Longyearbyen, this can be viewed as believable	Strong
Salinity and water saturation stay the same for each of the RCP scenarios.	Not believed to change, but with increasing precipitation, salinities might decrease due to drainage	Moderate
Reduction in bearing capacities in the RCP4.5 scenario can be estimated from Figure 12	According to structural engineers on UiS, this is correct	Strong
Estimation of reduction in bearing capacities for the other RCP scenarios are correct	No basis for this information. It is the best option at this point.	Weak
The values given from climate change research is correct	Have no more insight than what is written in reports about climate change. It is done much research, but large uncertainties.	Moderate
The chosen constant in equation for thaw subsidence is representative	This is more or less only a guess	Weak
That water saturation and ice content gives the same result for thaw subsidence	Water freezes to ice in permafrost over the winter. However, there are ice lenses that lasts all over summer in the active layer, so it can be some deviations.	Moderate

Reduction in subsidence can be estimated from Figure 12	According to structural engineers on UiS, this is correct	Strong
The estimated active layer thickness for RCP4.5 (dZ) is correct	Many simulations have been executed.	Strong
The estimated active layer thickness for RCP4.5 to RCP8.6 (dZ) is correct	Fewer estimations are made.	Moderate
The estimated active layer thickness for RCP8.5 (dZ) is correct	Even fewer estimations are made.	Weak
The ground conditions used are the only ones relevant for the assessment	No basis for this information. It is the best option at this point.	Weak

The assumptions in Table 9 is mainly connected to whether the values are correct. Some specific assumptions are that some areas do not have the necessary information for the assessment. If there is lack of information about salinity or water saturation in one area, or if there exists no information because the area is made by the author.

For example, Gruvedalen lacked information about both salinity and water saturation. Therefore, based on elevation and the location beneath Sukkertoppen, Lia was selected as the most similar area to Gruvedalen. The salinity of the area was copied, but the water saturation was assumed to be lower due to information about less water flowing through this area compared to Lia, given by Instanes and Rongved (2017). These kinds of assumptions have also been made in Sjøområdet, Sjøskrenten, Lia, and Melkeveien.

Nedre Lia, is an example of an area created entirely by the author, where everything is assumed to be similar to nearby areas. In this case information retrieved from Elvesletta Sør, and Sentrum. Nedre and Nordre Lia are the areas that solely are based on other areas. Even though the Elvesletta areas technically are made by the author, there still exist much data from the whole profile from Svaldbarhallen to the sea and based on these data the information is retrieved.

How certain these assumptions actually are, is not an easy task to answer. Regarding the values in the Table 5-7, it is clear that most of the numbers are very uncertain. Even the numbers provided by reports on each area have many uncertainties, and many factors play an important role in the correctness of the data, as for example the quality of equipment, weather or variations within the soils. The variations within each area can potentially also be large, so the assumption that nearby areas are similar to the relevant area is not viewed as a good assumption.

There has been made some calculations of how the bearing capacity will be reduced for scenario RCP4.5 in Longyearbyen. However, estimations of bearing capacity are very cumbersome work, with large uncertainties even for small areas. On the basis of this, it is not desirable to use values from only one soil profile even when it is from

Longyearbyen. But a decision needs to be reached, and the numbers are necessary in order to do so.

It is clear that there are many, and quite large assumptions sometimes with incredibly weak strength of assumption justification. This uncovers that there is a need for more research on certain areas. An example is that there is a need to increase the knowledge base for how saline permafrost will be affected by climate change, which in turn will increase the strength of assumption justifications for several other assumptions. Such as assumptions made for ground conditions, bearing capacities, and the equation for thaw subsidence.

6.4 Assumption Criticality Assessment

In EQRA, it is often emphasised the importance of comparing the strength of knowledge with the sensitivity analysis. In this case it has not been done any strength of knowledge assessment, but it has been done assessments of the strength of the assumptions. Assumption criticality depends on the strength of assumption justification and the assumption sensitivity. The following charts show the sensitivity of the variables in the thaw subsidence equation, and the thaw subsidence of the different areas in Longyearbyen. In these charts, the bars have been colour coded in order to reflect the strengths of assumption justifications that the variables are based on. The other RCP scenarios show the same trend as RCP4.5, but with more uncertain assumptions, which will make the colours change to yellow and red.

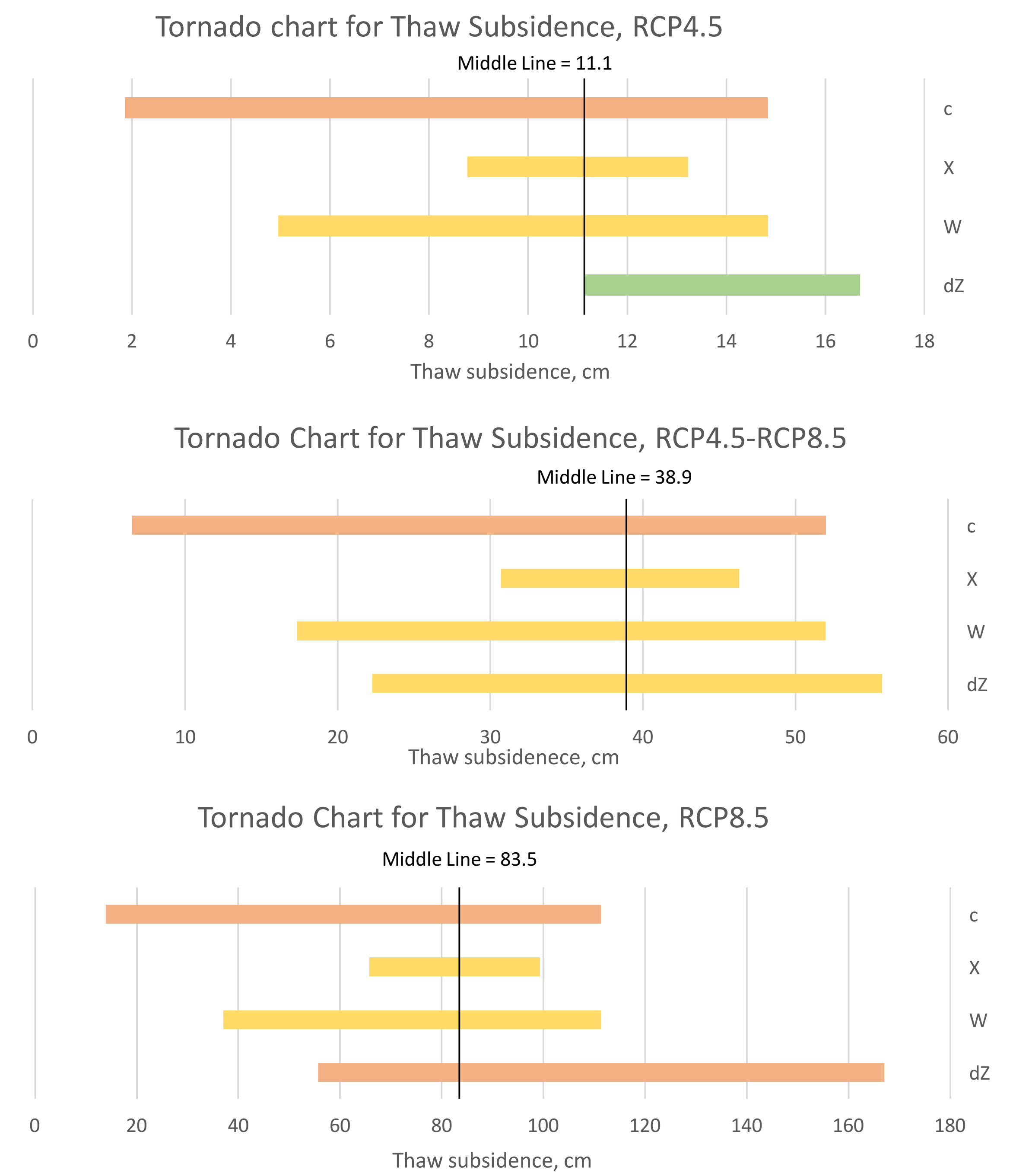
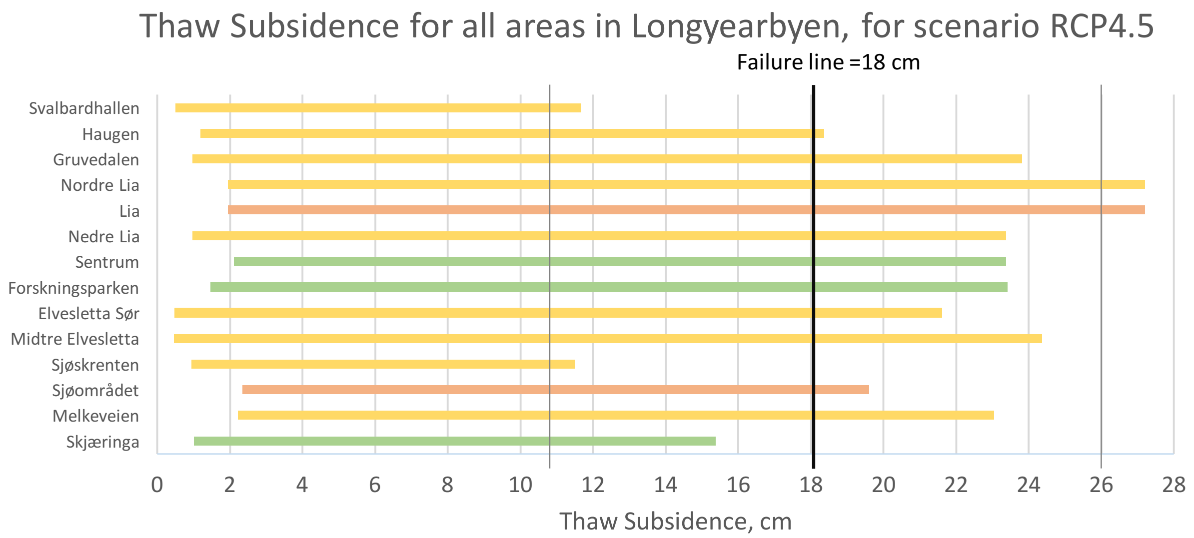
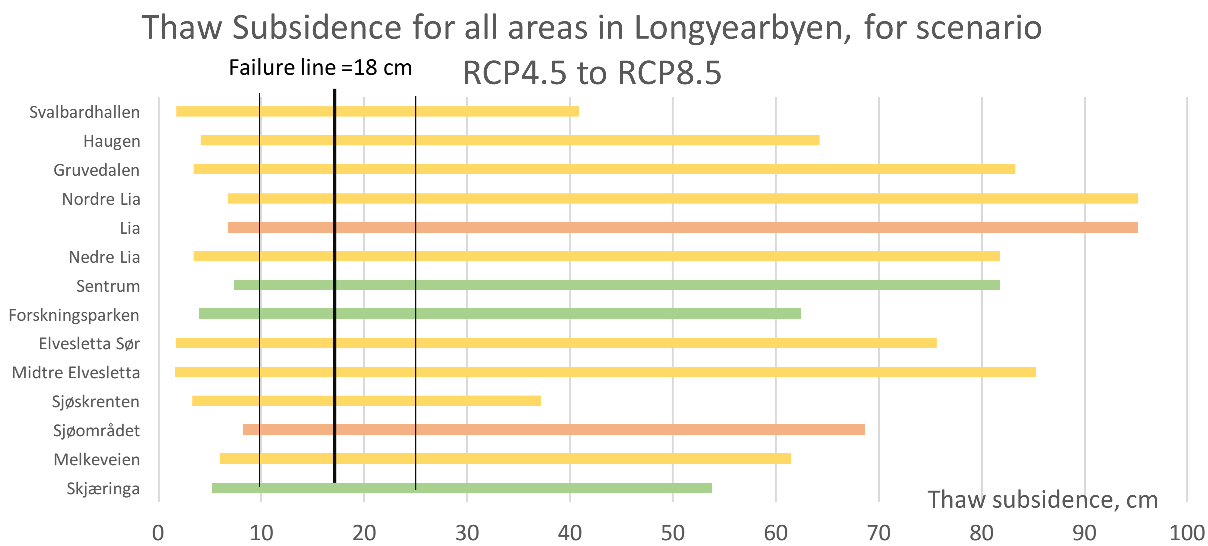


Figure 21: Sensitivity of variables for equation of thaw subsidence.

The colours represent the assumptions made to be able to estimate the variable. Green colour would be that all the assumption justifications are considered as being strong. Yellow colour is that the assumption justifications is considered as moderate. Red colour is that the assumption justifications is considered as weak. Example from Forskningsparken.

As can be observed, c is the variable that is the most sensitive and has the weakest strength of assumption justification. However, as RCP scenarios become more severe, the change in active layer thickness (dZ) becomes longer and also the colours change.





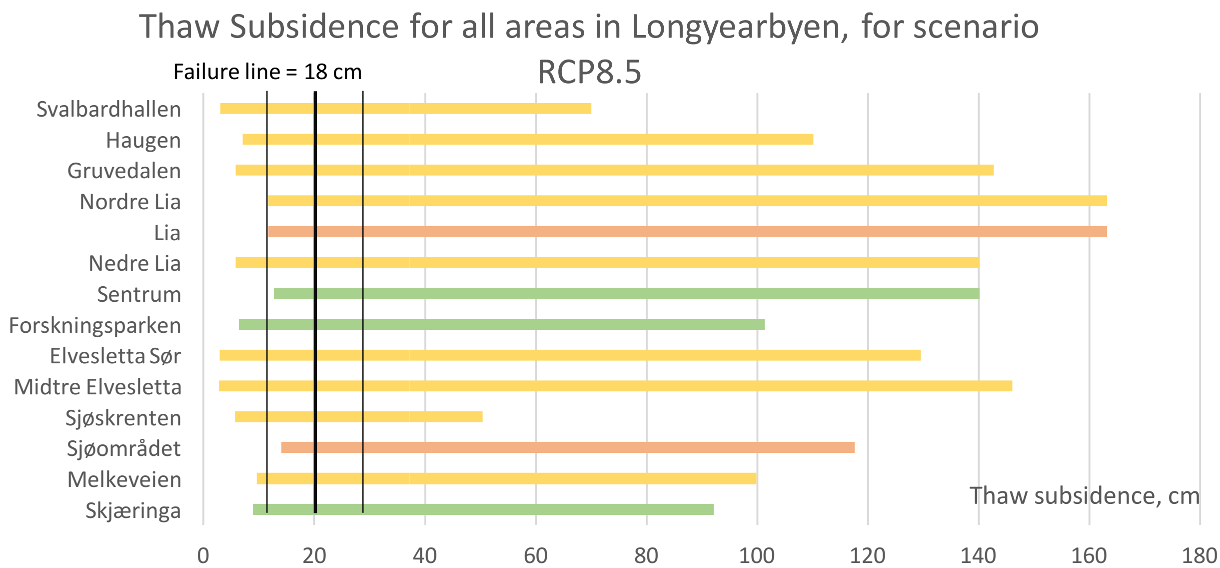


Figure 22: Thaw subsidence for each area in Longyearbyen.

The colours represent a merging of where the different information is retrieved from. It represents if the information comes directly from reports for the specific area (green), extrapolated from the closest area (yellow), or extrapolated from areas not that close or is just an educated guess (red). The failure limit is shown through the three lines, where the middle is a median, and the other two are upper and lower limits.

There is no obvious correlation between the strength of assumption justification and the sensitivity. This is due to another assumption which states that ground conditions that lack data are the same as nearby areas. As an alternative, one could possibly make larger fluctuations for the areas that does not have their own data, but this has not been done for the sake of simplicity.

It is however, a very evident sign of where one needs to be concerned regarding future implications regarding climate change. Shown in Figure 23 with areas. From the assessment is shows that the areas Lia and Nedre Lia is most vulnerable to climate change, whereas Svalbardhallen, Sjøskrenten and Skjæringa is the least vulnerable.

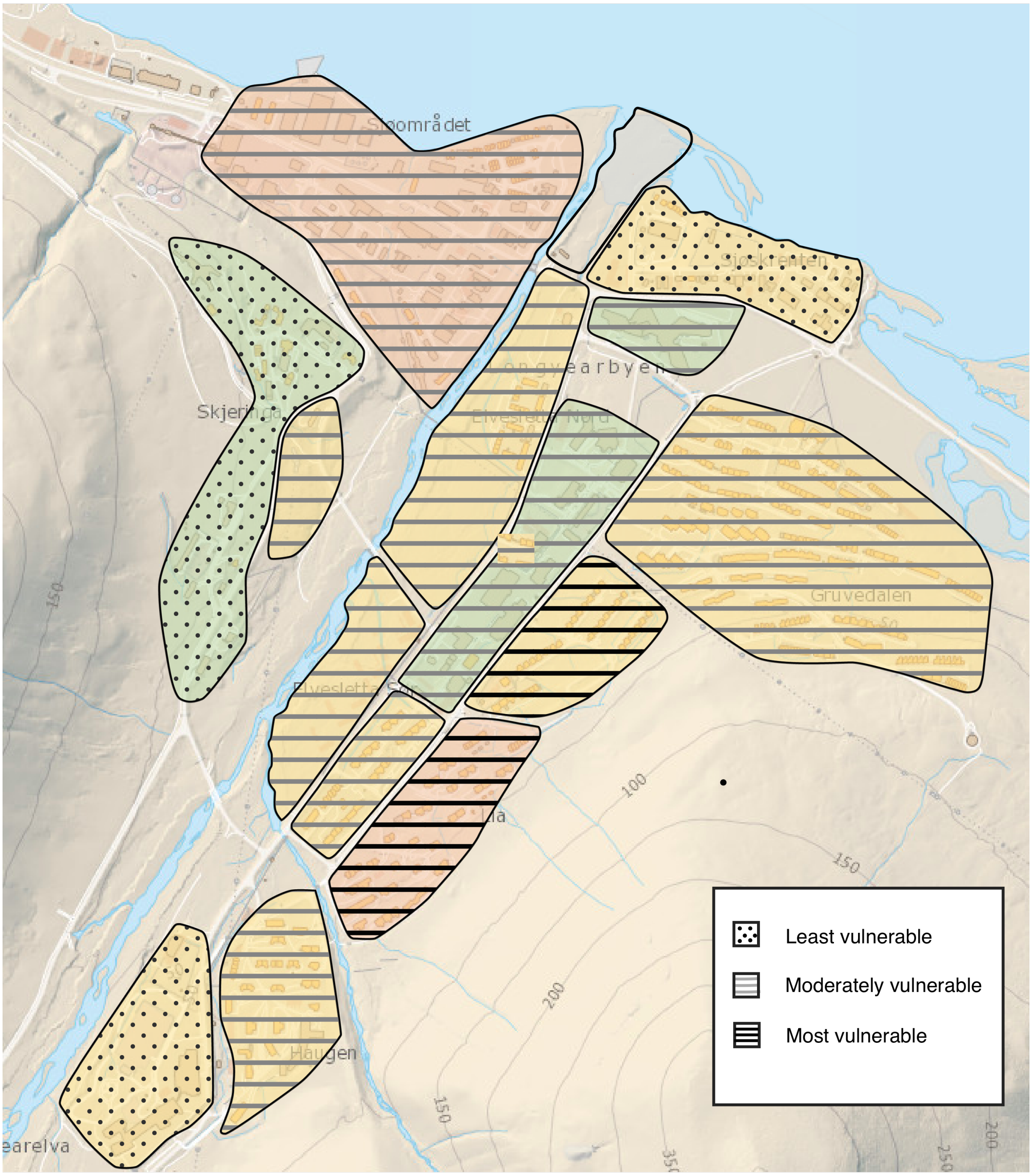


Figure 23: Map of areas in Longyearbyen, colour coded after "combination of strengths" and shaded after the possible severity of consequences. Figure: Marie Olsen

7. Discussion - Climate Change and the Response of Longyearbyen

This chapter contains a discussion of what and how this thesis has contributed to the risk management implications, and if it has uncovered the need for risk mitigation measures or the need for retrieving more information. This chapter will also reflect around how the thesis has dealt with assumptions, and whether it has contributed to how previous researchers has dealt with their assumptions. In the end, it will be some discussions and recommendations for future research and work.

7.1 Risk Management Implications of the Findings

From a risk management point of view, it can seem difficult to say something about the consequences due to large uncertainties. However, the whole point of risk management is find the balance between creating value and avoid accidents or loss to reach a decision in spite of restricted amount of data or information, and to handle the information/or lack of information in the best possible way. In quantitative risk assessment, where the assessment is restricted by information, it is very important to use methods that highlight the uncertainties, and also choosing a method where it is possible to produce some numbers from the little data that exist.

That is why the choice of method fell on The Russian Approach, because there was need for relatively little data in order to produce values. With the use of a method adapted to the specifics of Longyearbyen and the collected ground condition data, values were produced which revealed some concerns that should be addressed. The concerns can be divided into two parts;

- Locations in Longyearbyen that might be the most critical to climate change.
- Areas of research in the need of further exploration to significantly improve the assessment.

7.1.1 Critical Areas in Longyearbyen

Even though little is known about how severe the consequences of climate change will be in Longyearbyen, measures have fortunately already been put in place to assure the safety of important buildings that exist and to some extent also made recommendations for future constructions. Rognved et al. (2017) has for example made recommendations about renovation for Svalbard Kirke, Sysselmannsgården, and Sysselmannsbygget, based on the earlier damage on the buildings and their foundation. They have also made some general advice regarding new constructions where they recommend longer piles, or using foundation on point or slab. These recommendations are however only general, and it is viewed as rather crude to make such a recommendation for the whole city (which they also have stated). So research must be done on ground conditions before new buildings are constructed in order to ensure its safety for its estimated lifetime.

What has been excluded from the assessment is other geological processes that happens in many of the areas in Longyearbyen. An example of this is solifluction (see Chapter 3.4.1), which affects both Lia, Nordre Lia, and Gruvedalen. Because of the solifluction it is recommended that piles are drilled deeper than normal, or preferably into bedrock. This will make the buildings more resistant to reduction in bearing capacity and increasing thaw subsidence, which is not reflected upon in this assessment. The same goes for Haugen, who is not a subject to extensive solifluction, but bedrock is found after only a couple of meters and the houses are therefore drilled directly into it. This is only one of many uncertainties that exist in this assessment, and this will be discussed to further detail in the following section.

Even the assessment now show that Lia and Nordre Lia are the most critical areas, the uncertainties are very large and it can be uncovered that other areas might be more critical with further research. Areas in specific need of research will be discussed in the next section.

7.1.2 Areas of Research in the Need of Further Exploration

Some obvious areas that should be researched are the reduction of bearing capacities for each area. In this thesis it is only one value for all areas, where the value itself is not accurate. Furthermore, it is not realistic at all that all areas will have the same reduction of bearing capacity. Regarding the equation for thaw subsidence, an examination of the validity of this will also be of great help to the assessment. Especially by testing the constant that have been used, which is more or less just a guess from the authors side. An improvement of the accuracy of salinity, water content change of active layer thickness would also be of great help, especially for certain areas of Longyearbyen.

What can be seen in the RCP4.5 scenario in Figure 22 is that there are some areas that seem more critical than others. From the table it is the values from Lia and Nordre Lia. Gruvedalen and Midtre Elvesletta follows closely. All of the areas show large fluctuations of the thaw subsidence, and even though it looks like the outcome probably will fall within the limit, it might as well go beyond the limit of failure. Furthermore, the limit has a rather large interval as well, which makes the probability of being above failure line larger. The ones that seem to be the least critical is Skjæringa, Svalbardhallen, and Sjøskrenten, but even they can in an extreme outcome (based on the numbers from Figure 22) exceed the failure limit if it turns out that the limit is at its lowest and the thaw subsidence at its highest. It is worth mentioning that even though it is shown as an extreme outcome in the figures, it might not be because the uncertainties are large.

This shows that maybe one of the most critical interval to narrow down is the limits of failure due to thaw subsidence, because that will potentially give more conclusive results in addition to helping the accuracy of all areas compared to just finding ground conditions for one area. That is, it will be much more productive if one manages to narrow down the failure limits for example from 11-26 cm to 16-20, than for example narrow down the interval for salinity in Haugen. Because reduction of interval for the failure limit contributes to the accuracy of the consequences (fail/not fail) for all areas, whilst improving interval for salinity only contributes to that specific area.

Furthermore, if it turns out that the actual failure line is at the upper limit, almost all of the areas are within the safety limit. On the other hand, if it turns out to be close to the lower limit, all of the areas have the potential to exceed the failure line even for the RCP4.5 scenario. The same issue might arise if one receives more accurate data for the bearing capacities as well, but hopefully research regarding the areas will also give more accurate information about the limits as well as for the areas in Longyearbyen. Other areas that also have the most potential to contribute to the accuracy is to find information about ground conditions of Sjøområdet and Lia, so that the need for extrapolating data decreases. The other areas without their own data can also be a great contribution, but Sjøskrenten and Lia are the most critical.

When looking at Figure 22, reviewing the scenarios RCP4.5 to RCP8.5 and especially the scenario RCP8.5, the consequences seem to lead to failure regardless what the limits of bearing capacity and thaw subsidence will be. This means that, if the future turns out to look more similar to RCP8.5 it might not be necessary to research the limits, but rather focus on researching what building techniques that will be stable in that climate. The different focus according to which scenario the future might look like raises the question as to the importance of gaining more knowledge about climate change in the Arctic. It can be very costly to be precautious and built for RCP8.5 if not needed, and it can be very unfortunate to build for RCP4.5 and the buildings fail after for example 10 years due to rapid climate change.

7.2 Treating Uncertainties Using Assumption Justification Assessment

To the authors knowledge, previous researchers have not attempted to list each of the uncertainties or attempting to categorise the assumptions made to execute assessments, both for climate change and for risk/vulnerability of the society of Longyearbyen. They have only mentioned that there are uncertainties, and some have made categorisations of types of uncertainties regarding climate change (Hanssen-Bauer et al., 2019), but not going any further than that into specifics. The assessments carried out to present this thesis provide a semi-quantitative method, where assumptions are listed and assumption justifications assessed in order to strengthen the knowledge regarding the weaknesses of the method.

7.2.1 Treatment of Uncertainty Regarding the Assessment

The method is as already said to be crude, which results in quite many assumptions which do not necessarily have the best assumption justifications. An example of this is within the equation for thaw subsidence, where a part of it consist of the term (10-x). This part has no support by research, it is only a product of the author testing out which layout will fit the best according to reasonable thaw subsidence (the author tested (1-x), and (1/x) as well). Moreover, many conditions that will influence bearing capacity and thaw subsidence are not included in the assessment. Examples of conditions are the level of precipitation and the temperature of the permafrost, not only the active layer thickness. It is mentioned that the reduction of bearing capacities change more rapidly if the temperature of the permafrost is closer to 0 °C. Another problem is accumulation of water underneath the buildings, which contributes to more rapid warming than if the area was drained. These are issues that are not accounted for in the assessment, and is a large contributor to errors.

Regarding the ground conditions that the equation is dependent on, it was necessary to make some assumptions. The author does not doubt that the researchers estimated the ground conditions to their best effort, but equipment used to measure such conditions are often not accurate to a satisfactory level and can be biased due to weather. Furthermore, a source of error can be due to the interpretation of the intervals given in the different reports on ground conditions. One alternative to interpret these intervals is that the researchers are uncertain of the actual value due to inconclusive results. Another alternative is that it was a difference in the values throughout the profile that they measured, as for example differences between boreholes or a difference from the top to the bottom of the borehole. The author has assumed that it is the first alternative, but it could very well be the second, a combination, or different alternative from area to area (depending on amount and depths of boreholes).

Assumptions have also been made regarding construction engineering. The author has consulted with some civil engineers on UiS, which confirmed the authors understanding based on research by Rognved et al. (2017) regarding limits and future change of bearing capacity and subsidence. But the consulted civil engineers are not experts on constructions on permafrost, which is quite different from constructional engineering on the Norwegian mainland.

7.2.2 Treatment of Uncertainty Regarding Climate Change

As stated in Chapter 5, the assumptions regarding climate change could not be assessed to an extensive degree because the author does not have the competence to classify their strength of assumption justification. It is, however, interesting to discuss it because it affects the whole assessment of the structures in Longyearbyen, which have already been discussed a bit in the previous section. The problem with predicting the climate change in the Arctic begins with todays weather. On Svalbard there are very few weather stations and the stations that exist have not been operational for a long period of time; there is only one old close to the airport. This results in uncertainties even for the actual temperatures and amount of precipitation even for todays weather, and it makes it difficult to even forecast weather a week into the future. As a result of this, uncertainties regarding climate change in the Arctic will be even larger than for many other areas in the world.

Another reaction of climate change research is that with increasing severity of the RCP scenarios, the uncertainties also increases. That the fluctuation of change in active layer thickness (dZ) is growing from scenario to scenario in Figure 21 (in contrast to the other values) is a reflection of this uncertainty, because the knowledge about how much the active layer thickness is going to change decreases. This can also be observed on Figure 22, when all of the fluctuations are growing.

The growing thaw subsidence with each scenario can also be a result of model error, where larger values for each of the variables give room for larger errors than with values form RCP4.5. Since the equation is viewed as not being too reliable, this needs to be taken into account.

7.3 Further Work

To improve the existing method, collecting more and better data regarding both climate change, permafrost behaviour and response to climate change, ground conditions, and response of ground conditions to climate change can be constructive. This is however, easier said than done. There has already been done extensive research on climate change, and still the uncertainties are very large. The easiest is maybe to discard more research on climate change as an option and accept the uncertainties related to this, and rather focus on other aspects that can be improved. Even though increasing the knowledge about climate change might be one of the most constructive contributions to the assessment. Knowledge about the future climate will help choosing which scenario is the most likely, which in turn will make the analysis done in this thesis less comprehensive. Because, at least according to the results in this assessment, the largest differences in what mitigating measures to chose is if the future is more severe than scenario RCP4.5. In addition, knowing how warm it will be will in turn help making estimations of active layer thickness, which is a large source of uncertainty for the scenarios RCP4.5 to RCP8.5 and RCP8.5.

If looking at only the information one can improve for Longyearbyen, the most critical information to collect is how the permafrost soil responds to climate change, and in turn how this affects bearing capacity and thaw subsidence. Limits and calculations of each area of bearing capacities and thaw subsidence may also be informative since it will help decrease uncertainties and may eliminate/strengthen some assumptions regarding these.

Specific areas that need attention are Lia and Nordre Lia, because they in the present analysis show the largest potential to exceed the limits of thaw subsidence. Other areas are the red areas from Figure 22, which are the areas that do not even have information extrapolated from nearby areas, but rather from areas that are next to them again.

As a result of finding the previously mentioned information, it might be possible to give better recommendations for future constructions, and also know to what extent one needs to restore important buildings. Fortunately, residential buildings and storage locations are only built to last 30-50 years, which makes the consequences of climate change less drastic because the buildings would not last longer than 50 years anyway. Still, new building techniques need to be considered for future construction for them to be able to last for 50 years into the future from today. In addition, if the climate changes more rapidly than expected, construction that was built now might not last as long as predicted.

The next step to develop the method would be to include other slope processes (as avalanches, solifluction), infrastructures (as pipes, roads, electricity), and expand the amount of areas (as the piers and the airport). To estimate costs of damage can also be a future opportunity if one manages to collect data of the values of various buildings. All of this can contribute to estimate more accurate consequences for the community of Longyearbyen. This thesis has many restrictions, and it would be both interesting and constructive to find out on a more precise level than done in this thesis, both with accuracy of what is already included in the assessment, but also by including infrastructures and other areas.

8. Conclusion

This thesis has developed a semi-quantitative assessment of climate change effects on permafrost in Longyearbyen, which is a contribution because as far as the author know, this has not been done to this extent. The method itself was able to be implemented even with little data about climate change and ground conditions of the area, which gave crude results, but nevertheless provided some insightful product.

The IPCC scenarios was chosen to minimise uncertainties regarding future climate, these scenarios are called RCP4.5, RCP4.5 to RCP8.5, and RCP8.5. The first one represents the least severe scenario of the three, the second one are a middle case scenario, and the last one is a worst case scenario. Originally, there was a less severe scenario, called RCP2.6, but this require a substantial decrease of anthropological emissions by 2020, which is viewed as very unlikely.

The main engineering challenges on permafrost are that the moving active layer, along with the freezing and thawing throughout the year, will cause movement within the structure. This results in restrictions regarding allowed loads on the foundation and also the structures lifetime, which is why buildings rarely stand for more than 50 years. Changes of the ground conditions means reduction of bearing capacity and increase in thaw subsidence, this will lead to buildings being more exposed to damage.

Different methods were considered to execute the assessment of vulnerability of the structures. The Russian Approach was selected as the method, because it required little data to achieve results. In order to be able to do the assessment many assumptions had to be established, and on the basis off this it was established a system to categorise these after their strength of assumption justification.

In general, there are large fluctuations in the results due to uncertainties, and it shows that there is growing uncertainty with increasing severity of the scenarios. The results from different RCPs uncover that there might be need for different focus with shifting scenarios. With the RCP4.5 scenario, there is a bigger need for research of failure limits of bearing capacity and thaw subsidence, whilst in the case of the other two scenarios more efforts may be put into research regarding construction methods for a warmer climate, along with recommendations for how to secure important buildings. Some specific areas should receive special attention, which is due to the fact that the results show that most areas will exceed failure limit for thaw subsidence, and also because it will exceed the failure limit for bearing capacity as well, which is not the case for the first scenario. The most critical areas, regardless of scenario, are Lia and Nordre Lia, as they have the highest potential for thaw.

There is need for more research as a mitigating measure, especially regarding the soils reaction to climate change and hence also the failure limits of bearing capacity and thaw subsidence. This will help increasing the accuracy of at least RCP4.5. There will also be need for finding more information about areas that are critical, and information about areas that lacks required data. Testing the validity of the equation used to predict thaw subsidence is also important, in particular verifying the parameter values used and the term (10-x) added to reflect the salinity of the soil.

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