Student thesis series INES nr 423

Change of water surface area in northern Sweden between 1990 and 2015

Femke Pijcke

2017
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Femke Pijcke
Change of water surface area in northern Sweden between 1990 and 2015
Förändring av vattenytan i norra Sverige (1990-2015)
Bachelor degree thesis,15 credits in *Physical Geography and Ecosystem science*
Department of Physical Geography and Ecosystem Science, Lund University

Level: Bachelor of Science (BSc)

Course duration: March 2017 until June 2017

Change in water surface area northern Sweden between 1990 and 2015

Femke Pijcke

Bachelor thesis, 15 credits, in *Physical Geography and Ecosystem Science*

Supervisor:
Harry Lankreijer
Lund University

Exam committee:
Margareta Johansson, Lund University
Vaughan Philips, Lund University

Abstract

Changes in water surface area (w.s.a.) in Arctic regions have been linked to climate warming and permafrost degradation (Briggs et al. 2014). As permafrost thaws, thermokarst lakes are formed. This causes the surface to get wetter. Although, a drying of the surface has often been observed in areas of discontinuous permafrost. As the climate warms, permafrost starts to thaw from underneath the lakes, causing drainage from below to be possible. The permafrost around lake Torneträsk, northern Sweden, has been degrading over the past few decades (Akerman and Johansson 2008), and a change in surface wetness has been observed (Christensen et al. 2004b).

In this thesis, the change in w.s.a. of the Torneträsk region, as well as its relation to air temperature, precipitation, snow depth and active layer thickness has been investigated by analysing satellite images taken between 1990 to 2015. The w.s.a. in the Torneträsk region has been declining over the past 25 years. This decline however has only been observed in the permafrost free zones and the areas with sporadic permafrost. The areas underlain by continuous and discontinuous permafrost observed an increase in w.s.a. However, no significant relationships were found between the change in w.s.a. and climatic factors, since the study was too short.

Key words: Permafrost, thermokarst lakes, climate change, northern Sweden, remote sensing

Popularised summary

The Arctic region has experienced a rapidly changing climate and this has major influences on the characteristics of this region. Air temperatures have been rising in most areas of the Arctic region since the 1960's, with an acceleration in rising air temperatures measured since the 1980's (Serreze and Walsh 2000; Smith et al. 2005). The warming of the Arctic triggered changes in the cryosphere, including a warming and degradation of the permafrost, as well as a thickening of the active layer above the permafrost (Hinzman et al. 2005). This causes changes in the water surface area (w.s.a.) of Arctic regions, as this have been linked to climate warming and permafrost degradation (Briggs et al. 2014).

Climate warming causes the permafrost, in areas underlain with ice-rich permafrost to thaw and degrade, resulting in the formation of thermokarst landscapes. Permafrost is soil, rock, sediment, or any other earth material with a temperature that has remained below 0 ºC for two or more consecutive years (Walsh et al. 2005), and as temperatures rises, the ice within the ice-rich permafrost melts resulting in collapses and subsides of the surface, forming a thermokarst landscape.

Thermokarst lakes are found within a thermokarst landscape. They are formed after the ground subsides due to the thaw of ice-rich permafrost (Luo et al. 2015). The size of the lakes can change over time due to a continuation of permafrost thaw, variations in climate such as precipitation and evapotranspiration, or due to lake drainage caused by taliks (an area of unfrozen ground surrounded by permafrost) and eroding gullies (Yoshikawa and Hinzman 2003; Smith et al. 2005; Karlsson et al. 2012; Luo et al. 2015). The development of thermokarst lakes causes the surface to get wetter. However, a drying of the surface has often been observed in areas of discontinuous permafrost. As the climate warms, permafrost starts to thaw from underneath the lakes, causing drainage from below to be possible.

In this thesis, the change in w.s.a. of the Torneträsk region, northern Sweden, as well as its relation to air temperature, precipitation, snow depth and active layer thickness has been investigated by analysing satellite images taken between 1990 to 2015. The analysis was split up in three regions; areas underlain by sporadic permafrost (coverage of 0-50%), discontinuous permafrost (50-90%) and continuous permafrost (>90%). As each permafrost type responds differently to climate change.

The w.s.a. in the Torneträsk region has been declining over the past 25 years. This decline however has only been observed in the permafrost free zones and the areas with sporadic permafrost. The areas underlain by continuous and discontinuous permafrost observed an increase in w.s.a. However, no significant relationships were found between the change in w.s.a. and climatic factors, since the study was too short.

Acknowledgments

First of all I would like to thank Harry Lankreijer, my supervisor, for his guidance and help throughout the whole project. In addition, I would also like to thank the Department of Physical Geography and Ecosystem Science, for the past three years. Moreover, I should also thank my parents for their support, not only financially, but also mentally.

Secondly, I would also like to thank Kjersti Gisnås for the data about permafrost type distribution in Scandinavia, and Margareta Johansson for the data of the active layer depth in the Abisko region. I thank her also for the useful and detailed feedback she gave on my thesis as well as Vaughan Phillips as my second examiner.

Last but not least, special thanks to amazing ninja Neija and classmates, who have supported me throughout these demanding months (and years) and where I enjoyed multiple fikas with. All of them are simply amazing, and my bachelors would not have been the same without them.

Table of contents

1. Introduction

The Arctic region has experienced a rapidly changing climate and this has major influences on the characteristics of this region. Air temperatures have been rising in most areas of the Arctic region since the 1960’s, with an acceleration in rising air temperatures measured since the 1980’s (Serreze and Walsh 2000; Smith et al. 2005). The warming of the Arctic triggered changes in the cryosphere, including a warming and degradation of the permafrost, as well as a thickening of the active layer above the permafrost (Hinzman et al. 2005).

Climate warming causes the permafrost in areas underlain with ice-rich permafrost to thaw and degrade, resulting in the formation of thermokarst landscapes. This changes ecosystems, causes soil collapses (resulting in damaged houses, pipelines and roads) and leads to changes in hydrologic processes. Furthermore, the degradation of permafrost accelerates biochemical decomposition which can lead to an increase of greenhouse gas emissions to the atmosphere (Walsh et al. 2005). This enhances climate changes, forming a positive feedback loop.

One of the features formed as ice-rich permafrost thaws are thermokarst lakes. Thermokarst lakes are developed as ground subsides, due to the thaw of ice-rich permafrost. This forms a depression which can fill up with water, resulting in an increase of water surface area (w.s.a.). However, in many regions, thermokarst lake drainage has been observed, causing a drying of the surface. This drying or wetting of the surface causes the ecosystem to change and new types of vegetation to grow (Smith et al. 2005).

This thesis examines the changes in w.s.a. in the Torneträsk region, northern Sweden. This region is underlain by discontinuous permafrost, and a degradation in permafrost has been observed in the past few decades, as well as a thickening of the active layer (Akerman and Johansson 2008). Thus, as the hydrological processes are controlled by the presence or absence of permafrost, and the thickness of the active layer; a change in w.s.a. could be expected (Yoshikawa and Hinzman 2003).

Satellite images were analysed over a 30-year time period to see if any changes in w.s.a. were present. In addition, several climatic factors, such as precipitation, air temperature, active layer thickness and snow depth were analysed, to see if they had any influence on the w.s.a. The analysis was split up over the different permafrost types (sporadic, discontinuous and continuous permafrost) to see if there were any differences in response to climate change.

1.1 Permafrost

Permafrost is soil, rock, sediment, or any other earth material with a temperature that has remained below 0 ºC for two or more consecutive years (Walsh et al. 2005). It covers 24 % of the northern hemisphere in the boreal sub-Arctic and Arctic regions (Zhang et al. 2003). The permafrost thickness can vary from a few decimetres up to hundreds of metres (King 1986).

The layer above the permafrost, called the active layer, thaws and refreezes seasonally (Akerman and Johansson 2008). During summer, when air temperatures are above zero degree Celsius, the layer on top of the permafrost thaws. Whilst in winter, when air temperatures drop below zero, it refreezes. The active layer thickness varies between a few decimetres in peat, up to several metres in well drained materials (Johansson et al. 2011). Its thickness is dependent on several factors, such as climate, vegetation cover and soil type.

Water can move freely within the active layer during summer when the upper soil is unfrozen. The frozen layer underneath, the permafrost layer, hinders the waterflow from moving freely within the soil, and is thus controlling lake-groundwater interactions, moisture conditions, soil temperature, ground stability and vegetation near lakes (Briggs et al. 2014). Therefore, permafrost degradation enhances the waterflow, since it thickens the active layer and can potentially reactivates the ground and soil water. Ice-rich permafrost restricts the soil moisture to percolate to the deeper groundwater zones, causing wet surficial soil in permafrost regions (Yoshikawa and Hinzman 2003). However, the soil in permafrost free zones will be drier, since vertical percolation is not restricted. These drier conditions have an impact on the ecosystem, occurrence of fires and the sensible and latent heat flux.

Permafrost can be split up into four different classes depending on the spatial coverage of the permafrost (Gisnås et al. 2017). Isolated permafrost underlays 0 to 10 % of the land surface, sporadic permafrost 10 to 50 %, discontinuous permafrost 50 to 90 % and continuous permafrost 90 to 100 %. Discontinuous and sporadic permafrost are only found in certain places within the landscape; for instance, in shady areas or northern slopes, due to its lower air temperatures (Wunderground.com 2017). The Torneträsk region, the study area of this thesis, is mainly situated in an area of discontinuous permafrost. Here, discontinuous pemafrost is mainly found above the tree line, or at lower altitudes on the north facing slopes or in areas with little snow cover (Johansson et al. 2006a). Continuous permafrost is found in places where temperatures stays low enough to keep the ground frozen all year around, such as in mountainous areas or at higher latitudes.

About 4.3 % of the land surface in Sweden is underlain by permafrost, which is about 21 910 km^2. The permafrost mainly occurs in the northernmost regions of Sweden as well as on the mountainous areas in the West. Most of the permafrost in Sweden is sporadic as it counts for 78 % of the total permafrost area. The sporadic permafrost is found in regions below 750 m a.s.l. About 20 % of the permafrost in Sweden is discontinuous and 2 % is continuous. The discontinuous permafrost is generally found in areas which have a mean annual air temperature between -1.5 ºC and -6 ºC. Continuous permafrost is only present on higher altitudes in the mountains where the mean annual air temperature is below -6ºC (King 1986). Though, this is just a guideline, e.g. in Abisko discontinuous permafrost is found even though the mean annual air temperature is above -1.5 ºC. Here the presence or absence of permafrost is mainly determined by physical parameters such as topography, soil type and hydrology as well as by climatic parameters such as snow cover (Johansson et al. 2006a).

Permafrost in Sweden has been degrading over the past three decades. And an acceleration of increasing thickness in active layer has been observed (Akerman and Johansson 2008). The degradation has been linked to an increase in air temperature, thawing degree days and snow depth to some extent. And as climate predictions of the area suggest an increase in precipitation and air temperature, a continuation of permafrost degradation can be expected.

1.2 Thermokarst landscapes

Thermokarst topography forms as ice-rich permafrost thaws or massive ice melts, either due to natural or anthropogenic causes, and the ground surface subsides into the resulting voids (Yoshikawa and Hinzman 2003). These landforms are most common in the sub-Arctic regions where temperatures above -1ºC are frequently found. Those areas are mainly underlain by discontinuous permafrost where intra- and sub-permafrost water flow is often observed.

According to Shur and Osterkamp (2007) there are several processes which cause thermokarst development. Firstly, thaw subsidence of the upper permafrost as well as water accumulation on the soil surface, caused by an increase of active layer thickness. Secondly, permafrost degradation with retreat of the permafrost table. Finally, enlargement by thermal subsidence and thermal erosion of lakes resulting into thermokarst landscapes.

The formation of thermokarst topography results in the consolidation and deformation of the soil surface and forms specific forms of relief such as collapsed pingos, sinkholes, pits and thermokarst lakes (Jones et al. 2013). Thermokarst lakes are formed after the ground subsides due to the thaw of ice-rich permafrost (Luo et al. 2015). The size of the lakes can change over time due to a continuation of permafrost thaw, variations in climate such as precipitation and evapotranspiration, or due to lake drainage caused by taliks (an area of unfrozen ground surrounded by permafrost) and eroding gullies (Yoshikawa and Hinzman 2003; Smith et al. 2005; Karlsson et al. 2012; Luo et al. 2015). Taliks can be found underneath lakes, as the water bodies can transfer the heat better to the underlying ground than other land cover types. This enhanced heat flux triggers the permafrost to thaw more rapidly forming a talik or thaw bubble underneath the lake (Heslop et al. 2015).

Previous studies have shown that the water surface area of thermokarst lakes tend to decrease in areas with discontinuous permafrost (*Appendix* A). No single answer can be assigned to this observation, though it is thought to be caused by lake drainage. Ice-rich permafrost starts to thaw irregularly due to climate warming, forming taliks (a layer of unfrozen soil above the permafrost and below the pond) in the depressions. When taliks grows to a size that completely penetrates the underlying soil or connects to a subsurface layer that allows continued drainage, the pond may then begin to drain. Though, in some cases, the w.s.a. in areas of discontinuous permafrost increased (Labrecque et al. 2009).

Other studies focusing on areas with continuous permafrost observed a general increase in water surface area (*Appendix* B). This increase might be explained by the fact that permafrost thaw causes lake expansion (Smith et al. 2005). This lake enlargement is mainly lateral, and is commonly induced by the thaw of ice-rich permafrost along the sides of the lakes (Luo et al. 2015). Wind is a main driver of this phenomenon. During the ice-free seasons, the prevailing wind causes wave erosion on the sides parallel to the wind direction, expanding the lake. In addition, slumping of lake shores can cause lake expansion since it exposes the massive ice to solar radiation, enhancing the melt of ground ice. This phenomenon of lake expansion could be expected to increase with climate change. Since higher air temperatures will lead to; a longer open water season with thinner lake ice, an increase in active layer thickness and enhanced thaw of ground ice; causing more rapid lake expansion (Luo et al. 2015).

1.3 Previous studies

Previous studies have shown that the permafrost type influences the w.s.a. coverages, and its changes (Appendix A&B). The majority of research were done in areas of discontinuous permafrost, and these found mainly a decrease in w.s.a. Firstly Yoshikawa and Hinzman (2003) found that the w.s.a. in Council, Alaska declined between 1950 and 2000. Their explanation of the decline was assigned to the formation of taliks. As the ponds grew lager due to permafrost degradation, large taliks were formed, which penetrated the permafrost, causing the ponds to drain. Moreover, Smith et al. (2005) made the same observation in Siberia between 1973 and 1998. Here, a decline of w.s.a. of 13 % was observed in the discontinuous permafrost zone. About 9 % of the lakes in the area of discontinuous permafrost drained away completely, and are now re-vegetated. Also here permafrost degradation and drainage is said to be the cause of the lake drainage. Labrecque et al. (2009) measure a decrease of 3.5 % in w.s.a. in northern Yukon, Canada between 1951 and 2001. In general all of the larger lakes decreased in extend, whereas the smaller ponds increased. There was an increasing trend in w.s.a. within the area until 1972, but the w.s.a started decreasing after this. Labrecque et al. (2009) connected the change in w.s.a. to a drier and warmer climate, since the climate within the area changed around the 70'ies from cool and moist climate to a hotter and drier climate. Finally Riordan et al. (2006) found a decline in w.s.a. of 11.6% in Alaska from 1950 till 2002. It is assumed that the decrease in w.s.a. was caused by increased drainage, or due to increased evapotranspiration during a warmer and extended growing season.

There was a general increase in w.s.a measured in areas of continuous permafrost. Smith et al. (2005) found, that in Siberia between 1973 and 1998 the w.s.a. increased with 4 %. This was linked to permafrost degradation, as the degradation causes the soil to collapse, forming a depression which fills up with water. On the Tibet plateau, where continuous permafrost is found, Luo et al. (2015) measured an increase in w.s.a. as well. In general, all the lakes increased with about 13 % in surface area, whereas the smaller lakes even increased with 60 %. This increase has been linked to the increase in air temperature and P-ET ratio. However, Hinkel et al. (2007) observed a drainage of 50 lakes in northern Alaska between mid-70'ies and 2000. There is no clear explanation for this decrease in w.s.a., though it is thought to be caused by human activities.

1.4 Aim

The aim of the report is to look at the change in water surface area in the Torneträsk region, in northern Sweden. The drivers behind the changes such as climatic changes and the change in permafrost will be investigated in order to find possible relationships between the water surface area and climatic factors. A distinction between continuous, discontinuous and sporadic permafrost will be made to look at a possible trend difference between permafrost types and water surface area.

1.5 Hypothesis

It is expected to see a decrease in water surface area in northern Sweden since most of the area is underlain by discontinuous and sporadic permafrost. At the same time, in the mountainous areas in Sweden, where continuous permafrost is found, an increase in water surface area might be expected.

1.6 Study area

The study area is situated in the Torneträsk region (*Figure* 1). This region is located in the sub-Arctic region of northern Sweden, with an average air temperature of -0.2 ºC and 338 mm of precipitation per year (measured between 1985-2015, Abisko) (*Figure* 2). Both the air temperature as well as the precipitation have been increasing between 1985 and 2015. The area has a strong W-E climate gradient, meaning there is a maritime, wet climate in the west (~900 mm yr^{-1}) and a drier continental climate toward the east, where Abisko has a precipitation shadow (~300 mm yr^{-1}) (Vonk et al. 2012).

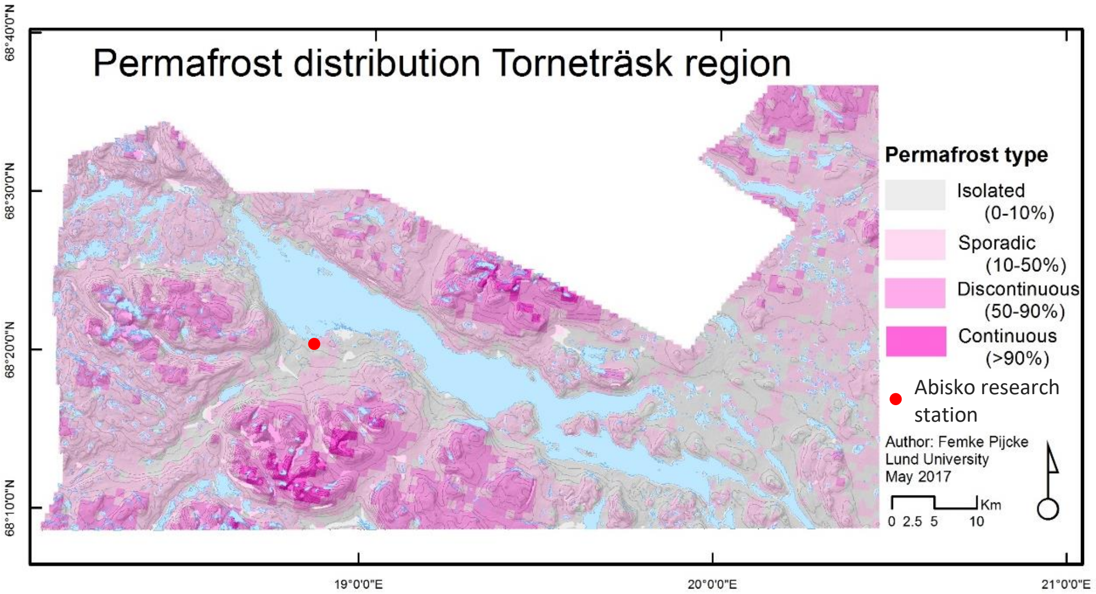


Figure 1: Map of the study area, its permafrost cover and lake coverage. (Gisnås et al. 2017).

The study area is about 3700 km^2, wherefrom 68 % is underlain by sporadic, discontinuous or continuous permafrost. The sporadic permafrost underlays about 49 % of the study area and it is mainly found in areas having a yearly average air temperature above -1.5 ºC (King 1986). Discontinuous permafrost covers 18 % of the study area, and is found in areas having a mean annual air temperature between -6.0 ºC and -1.5 ºC. Continuous permafrost is only found in the highest mountain peaks, and covers only 2 % of the study area.

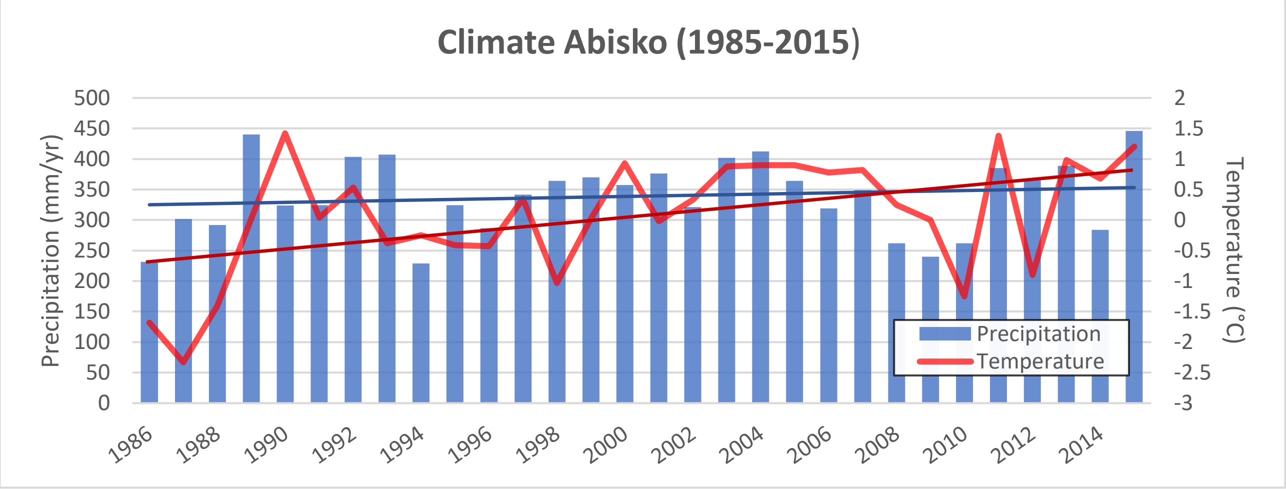


Figure 2: Air temperature and precipitation in Abisko (SMHI). For both an increasing trend is found over the past 30 years.

Around 14 % of the study area is overlain by small lakes and ponds, wherefrom the biggest lake is Torneträsk. Lake Torneträsk has an extent of 330 km^2 and an average depth of 52 metres, which makes it the biggest mountain lake of Scandinavia (Vonk et al. 2012). With a depth of 182 metres at its deepest point, the Torneträsk lake is the second deepest lake of Sweden. Besides Torneträsk is one of the bigger lakes in Sweden, most of the lakes and ponds within the area are rather shallow. Most of those lakes are found in the sporadic and discontinuous permafrost areas, as they are formed by permafrost degradation, forming thermokarst lakes. However, on high altitudes where the continuous permafrost is found, very little thermokarst lakes are present due to the thin soil layer. Most of the permafrost is found in the bedrock, and no ice-rich soil layer is present to cause permafrost degradation resulting into the formation of thermokarst lakes.

The study area has an elevation ranging between 289 and 1791 m a.s.l. The bedrock in the study area is salic igneous rocks and quartic/phyllitic hard schists (Sundqvist et al. 2011). The soil in the area is rather shallow with 5 to 10 metres depth in the lower regions and bare bedrock on the mountain tops. Boreal (birch) forests and mires dominate, with occasional pine forests. Tundra vegetation such as heath, dwarf birch and other shrubs occupy the mid-altitudes, whereas the higher altitudes are sparse in vegetation or snow covered (Vonk et al. 2012). The tree line is between 500 – 600 m a.s.l.

2. Methods

The methodology of this thesis is split up in two main parts. The first part consists mainly of digitising satellite images and delineating lakes and ponds. These digitised layers are then connected to the permafrost map of Sweden (Gisnås et al. 2017), to make a distinction between continuous, discontinuous and sporadic permafrost. In the second step significance tests are performed to look for any correlation between the change in w.s.a. and air temperature, precipitation, snow depth and active layer thickness.

2.1 Data used

For the analysis, satellite images were examined to look at the change in w.s.a. Climatic, snow and active layer thickness data were needed to compare the change in w.s.a. so possible correlations could be investigated.

Satellite images were used to detect all the lakes and ponds in the study area. The images were acquired from USGS and Saccess (U.S. Geological Sourvey. 2017a.; Saccess 2017), and were taken by six different satellites as seen in *Appendix* C. The satellite images were carefully selected, so the maximum cloud coverage was only 10 %. All the satellite images were taken from a time period between July and mid-September so the influence of seasonal variability on the w.s.a. would be as little as possible. The satellite images were taken from the summer months since the w.s.a. extent is highest during this time, and all the lakes are at this time of the year more or less visible due to the absence of snow cover.

There were eight satellite images found which fulfilled all these requirements, covering a time span of 25 years. Their resolution differed between 30x30 and 10x10 metres, therefore some of the images were downscaled in further analysis, so comparisons could be made. An overview of the image resolution for each year can be found in *Appendix* C. The satellite images are processed using ArcMap 10.3.1 (*ESRI 2001. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute*).

The data for air temperature, precipitation and snow depth was retrieved from the Abisko Scientific Research Station. The air temperature data as well as the precipitation data were both measured in Abisko at 2 metres height. The snow depth was measured daily at ground level. The Abisko Scientific Research Station is located at 388 m a.s.l. at 68.3557ºN, 18.8206ºE.

The active layer thickness was measured yearly in the third week of September for nine measuring stations around Torneträsk region, and was retrieved from Akerman and Johansson (2008). The active layer was measured between 500 m a.s.l. and 350 m a.s.l., where mainly sporadic permafrost is found. The permafrost distribution data over Scandinavia was modelled by Gisnås et al. (2017). The CryoGRID1 model was used to estimate the permafrost regions around Scandinavia as well as the permafrost type. As mentioned before, the sporadic permafrost was defined by a permafrost coverage of 10 to 50 %, discontinuous permafrost had a coverage of 50 to 90 % and continuous permafrost had a coverage of >90 %. The resolution of the permafrost layer was 1x1 kilometre.

2.2 Workflow

Step 1

All the satellite images were classified into two classes; water bodies and land area. The class probability tool was used as a supervised classification system in order to make these two classes. This decision was made after evaluating all of the interactive supervised classifications systems available in ArcMap 10.3.1; the "Maximum likelihood classification", "Iso cluster unsupervised classification" and "Class probability" were compared to each other. The Class probability tool had with 67 %, the highest accuracy on average for all of the years as discussed further on in section 2.3.

A training data set was made for every single year, as to make the Class probability tool work. These training data sets were then used in the class probability tool so the lakes and ponds could be delineated. Since many small polygons were shaped by this procedure the aggregation tool from the ArcMap 10.3.1 toolbox was used to aggregate all of the polygons closer than 30 metres from each other. A threshold of 30 metres was taken since the resolution of the satellite images was 30x30 m.

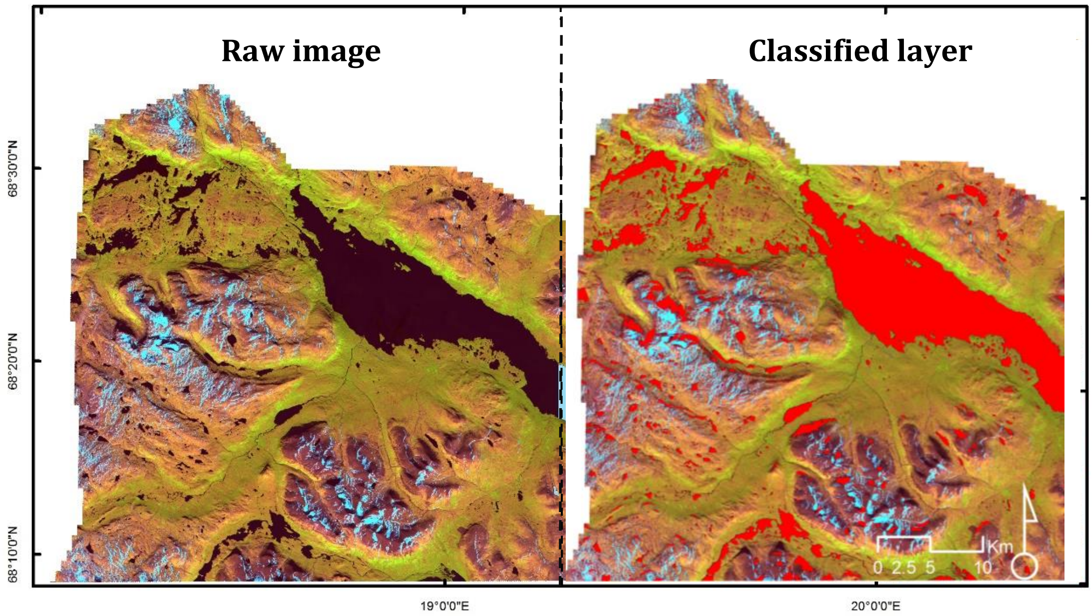


Figure 3: Overview map of the West side of the study area. On the left an example of a satellite image used to classify the lakes is found. On the right hand side the same satellite image is seen, overlain by the final layer of the classified lakes in red.

After auto-classifying the satellite images, manual adjustments were made to the layers, so all the lake layers could be compared to each other. Due to a difference in resolution, the smallest area which could be mapped from the satellite images with the poorest resolution (30x30m) was 600m^2. Therefore, all lakes smaller than 600m^2 were excluded from all the lake layers. Shadows caused by the mountains and clouds were also excluded from the lake layers, as well as rivers. The rivers were excluded since they were not classified very accurately and they were barely visible on the older satellite images. Finally, some of the bigger lakes were redrawn if they were not classified correctly, since these types of errors would have a large influence on the final result. An example of the lake layer can be found in *Figure* 3. All of the harmonised layers were then clipped to the permafrost layer so a distinction between sporadic, discontinuous and continuous permafrost could be made (Gisnås et al. 2017). A buffer of 500 metre around the sporadic permafrost was made since some of the bigger lakes radiated heat and thus no permafrost is seen around them. The 500-metre buffer was chosen since the raster of the permafrost layer had a 1x1 kilometre resolution.

Step 2

In the final part of the analysis, correlation tests were performed to look at any significant relationships between the water surface area and climatic factors such as air temperature, precipitation, snow depth and active layer thickness. In total seven different parameters were analysed. The r^2-values as well as the p-values were calculated in MATLAB (MATLAB 6.1, The MathWorks Inc., Natick, MA, 2000). Trends are assumed to be significant for p-values ≤ 0.05.

Two different parameters for the influence of air temperature on the w.s.a. were analysed. Firstly, the four spring months (April/ May/ June/ July) just before the satellite images were taken, were used in order to see how air temperature influences the w.s.a. The winter season has no major influence on the hydrology in the area since the monthly average air temperatures are below zero causing most of the lakes, especially the smaller ones, to be frozen throughout the whole season and no evaporation would occur. However, there still might be water loss due to sublimation. Secondly the annual air temperature was taken so the change in yearly air temperature could be investigated. The months used for calculating the yearly averages used the mean monthly air temperature from August till July, so only the air temperatures measured before the satellite images were taken, influenced the analysis.

Three precipitation data sets were used to look at the influence of precipitation on the w.s.a. Firstly the sum of the winter and spring (October - July) precipitation was taken so the effect of the snow and rain fall could be examined. Secondly, the yearly precipitation was taken from August till July to have an overview how yearly precipitation influences the w.s.a. Finally, the rain fallen between the end of the winter season (May) and July was looked at, to examine the effect of rainfall on the w.s.a. In the end the active layer thickness as well as the snow depth were compared to the w.s.a. to see if there was any correlation found. The snow depth used the same time frames as the annual air temperature and annual precipitation taken from August till July.

2.3 Data evaluation

Evaluation datasets were made to investigate the accuracy of the auto-classification systems. Here three randomly chosen areas were taken, spread over the study area, each with areas of 1x1 kilometre. These three areas were thereupon manually classified before they were auto-classified. For the auto-classification three different tools available in the ArcMap 10.3.1 toolbox were compared to each other. The respective tools were "Maximum likelihood classification", "Iso cluster unsupervised classification" and "Class probability". Each tool was used to classify the three default areas and were then compared to the default layer which was manually classified. Hereof it was found that the Class probability tool had the highest accuracy (*Appendix* D). All the auto-classified layers gave an underestimation of the lake surface area. Therefore, default data sets were made for each year to see how much the actual w.s.a. differed from the auto-classified one by using the Class probability tool. The error calculated here was then used to adjust the auto-classified layers for each year to a number closer to reality. A table of the average error measured for each year can be found in *Appendix* E.

3. Results

The results consists of five main parts; firstly the data accuracy of the overall study area was examined, so the lake layers for each year could be compared to each other (3.1). Secondly the change in w.s.a. was examined for the sporadic permafrost zones, and was then compared to the climatic data (3.2). The same was done for the discontinuous and continuous permafrost (3.3, 3.4). Finally, all permafrost zones were compared to each other (3.5).

3.1 Data accuracy

The auto-classification tool did not fully cover all the lakes and ponds in the study area, therefore all the classified layers were adjusted to the evaluation data set. The following bar chart shows how the total w.s.a. changed after adjusting the original layer (*Figure* 4).

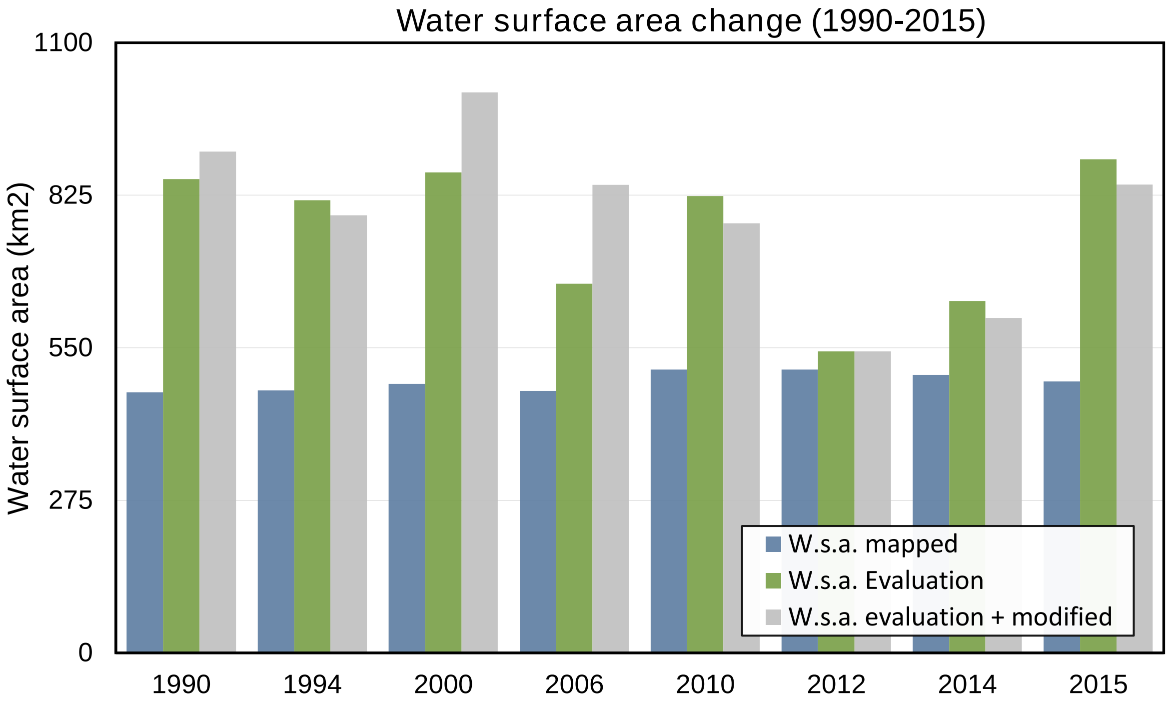


Figure 4: Bar chart of the total w.s.a. calculated for the Torneträsk region. The blue bars show the total w.s.a. calculated after the use of the class probability tool. The green bars represent the total w.s.a. after the mapped w.s.a. was adjusted to the default data set. The grey bars show the w.s.a. of the final layer which is used in all of the analysis parts of this thesis. It is the classified layer, adjusted to the default data set and manually edited afterwards.

The total mapped w.s.a. without any adjustments made was on average 56 % lower than the w.s.a. obtained after adjusting the w.s.a. layer to the evaluation data, and even 61 % lower than the manually modified one. The manually modified layer has 5 % more w.s.a. than the one which was only adjusted to the evaluation data without modifications made.

In the manually modified layer, the one which is used for all analyses further on in this thesis, the highest w.s.a. coverage was found in year 2000 with 1011 km^2 of w.s.a. coverage, followed by year 1990, where the w.s.a. covered 903 km^2. The lowest w.s.a. coverages were seen in 2012 and 2014, 544 km^2 of the area was covered by water in 2012 and 603 km^2 in 2014.

3.2 Sporadic permafrost in the Torneträsk region

The sporadic permafrost area has an average w.s.a. coverage of 286 km^2, with a decreasing trend over time (*Figure* 5). The highest coverage of w.s.a. was in the year 2000, followed by 1990. The two years with lowest w.s.a. coverages are seen in 2012 and 2014. The w.s.a. in 2012 was about 43% lower than it was in 2000.

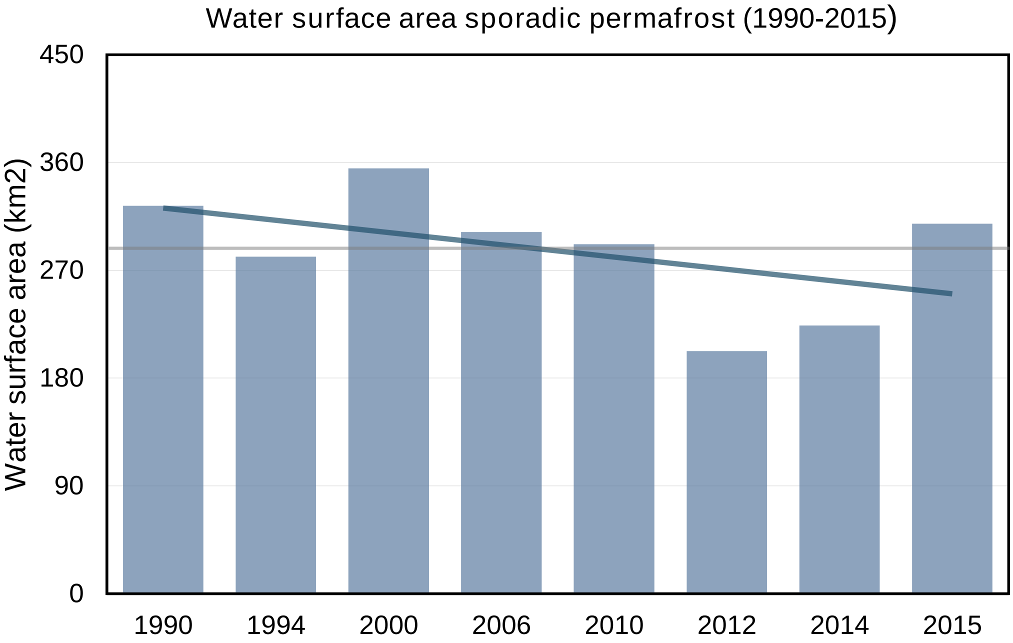


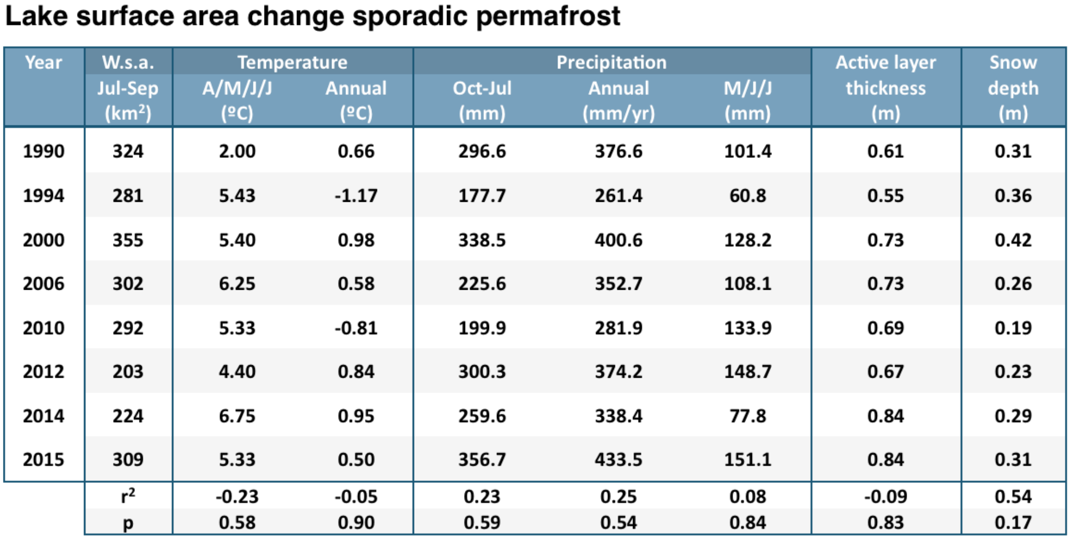
Figure 5: Bar chart of the total w.s.a. in the sporadic permafrost zones Torneträsk region. The grey line represents the average w.s.a. coverage in km^2 for the sporadic permafrost area, Torneträsk region. The blue line is the trend line for the change in w.s.a.

No significant relationship was found between the w.s.a. and both, the annual air temperature, as well as the spring air temperatures (*Table* 1). The p-value for the w.s.a. vs. the annual air temperature was 0.9, and the p-value for the w.s.a. vs. the spring air temperature was 0.58.

The rainfall in the spring season did not seem to have influenced the w.s.a. at all. The annual (p=0.54) and winter precipitation (p=0.59) had a lower p-value than in spring season (p=0.84), however it was still insignificant.

There was no significant relationship found between the active layer thickness and the w.s.a., and no trend could be seen. The snow depth versus the w.s.a. had a r^2-value of 0.54, but with a p-value of only 0.17, no significant relationship could be proven.

Table 1: W.s.a. in the sporadic permafrost zone in the Torneträsk region. together with all of the climatic data measured for each year as well as the active layer thickness. The r² for each correlation with the w.s.a. is given as well as the p-value.



Lake surface area change sporadic permafrost

Year	W.s.a.	Temperature		Precipitation			Active layer thickness (m)	Snow depth (m)
	Jul-Sep (km²)	A/M/J/J (ºC)	Annual (ºC)	Oct-Jul (mm)	Annual (mm/yr)	M/J/J (mm)		
1990	324	2.00	0.66	296.6	376.6	101.4	0.61	0.31
1994	281	5.43	-1.17	177.7	261.4	60.8	0.55	0.36
2000	355	5.40	0.98	338.5	400.6	128.2	0.73	0.42
2006	302	6.25	0.58	225.6	352.7	108.1	0.73	0.26
2010	292	5.33	-0.81	199.9	281.9	133.9	0.69	0.19
2012	203	4.40	0.84	300.3	374.2	148.7	0.67	0.23
2014	224	6.75	0.95	259.6	338.4	77.8	0.84	0.29
2015	309	5.33	0.50	356.7	433.5	151.1	0.84	0.31
	r^2	-0.23	-0.05	0.23	0.25	0.08	-0.09	0.54
	p	0.58	0.90	0.59	0.54	0.84	0.83	0.17

3.3 Discontinuous permafrost in the Torneträsk region

The average extent of the w.s.a. in the discontinuous permafrost area in the Torneträsk region was about 15.5 km². The trend in w.s.a. has been increasing in this area since 1990 (*Figure* 6). Unlike in the sporadic permafrost zone, the greatest extent in w.s.a. was seen in 2015 (20 km²) followed by 2010 (19 km²). The least w.s.a. was mapped in 1990 with a coverage of 10 km². There was a 48 % difference between the 2010 and 1990.

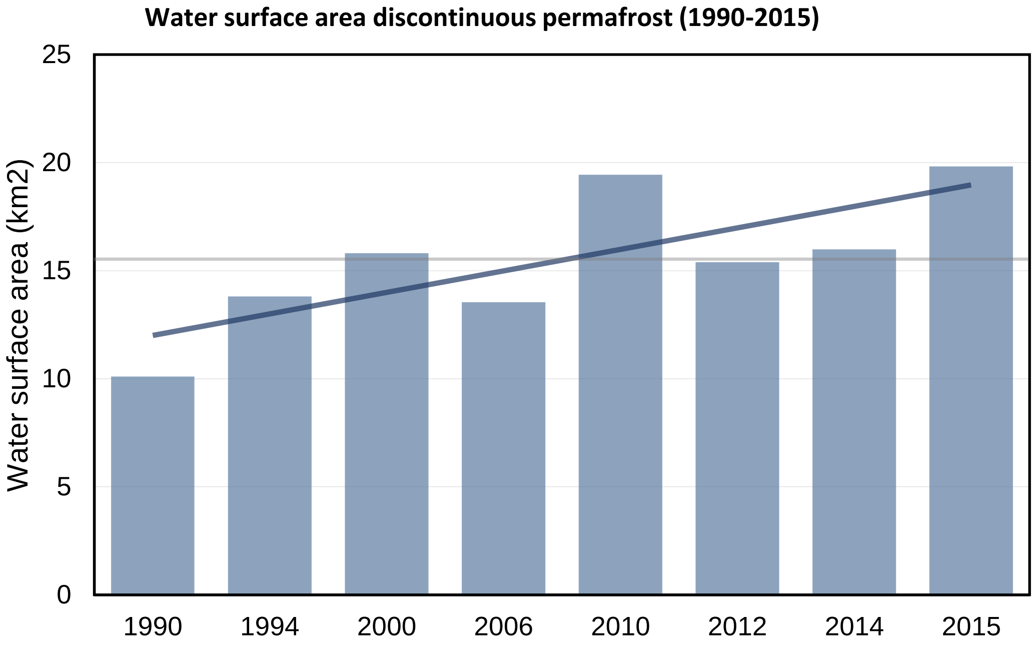


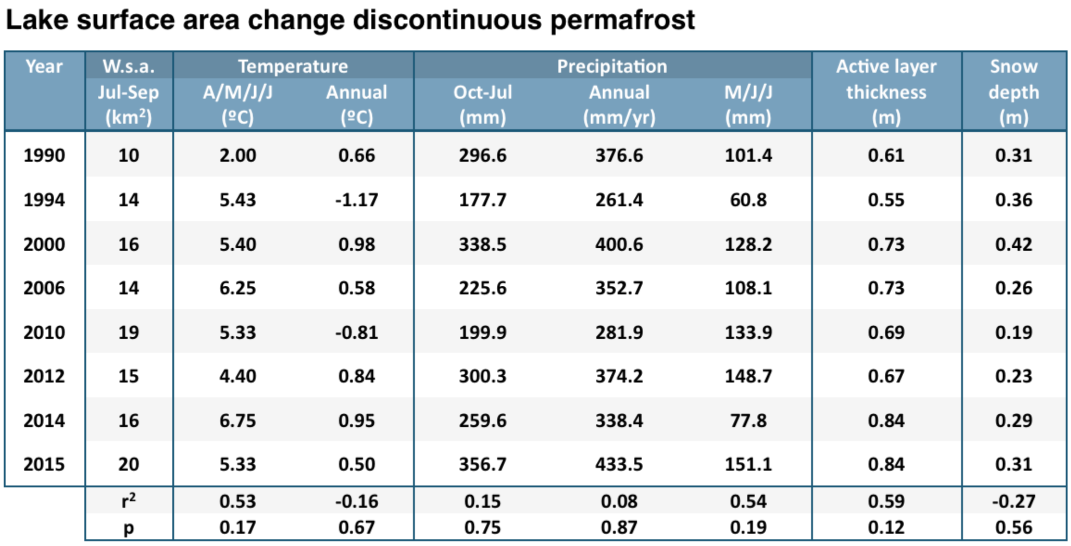
Figure 6: Histogram of the total w.s.a. in the discontinuous permafrost zones of the Torneträsk region. The grey line represents the average w.s.a. coverage in m² in the discontinuous permafrost area. The blue line is the trend line for the change in w.s.a.

There r^2 for the w.s.a. vs. the spring air temperatures in the discontinuous permafrost zone was 0.53, though no significance (p=0.17) was found (*Table* 2). A weak downwards trend to no trend was found between the w.s.a. and the annual air temperature.

There was a positive trend between the w.s.a. and spring rainfall, but with a p-value of 0.19 no significance was seen; thus the correlation could not be proven. There was no trend for the winter precipitation nor the annual precipitation versus the w.s.a.

The r^2-value for the active layer thickness versus the w.s.a. was 0.59, and the p-value 0.12, which means there was no significance even though the r^2 was rather high. There was a weak negative trend seen for the snow depth against the w.s.a. However, there was no significant correlation.

Table 2: Table of the w.s.a. in the discontinuous permafrost zone in the Torneträsk region. together with all the climatic data measured for each year as well as the active layer thickness. The r^2 for each correlation with the w.s.a. is given as well as the p-value. A p-value below 0.05 means there is a significant relationship between the w.s.a. and the parameter (air temperature, precipitation, active layer and snow depth) compared to.



Lake surface area change discontinuous permafrost

Year	W.s.a.	Temperature		Precipitation			Active layer thickness (m)	Snow depth (m)
	Jul-Sep (km^2)	A/M/J/J (ºC)	Annual (ºC)	Oct-Jul (mm)	Annual (mm/yr)	M/J/J (mm)		
1990	10	2.00	0.66	296.6	376.6	101.4	0.61	0.31
1994	14	5.43	-1.17	177.7	261.4	60.8	0.55	0.36
2000	16	5.40	0.98	338.5	400.6	128.2	0.73	0.42
2006	14	6.25	0.58	225.6	352.7	108.1	0.73	0.26
2010	19	5.33	-0.81	199.9	281.9	133.9	0.69	0.19
2012	15	4.40	0.84	300.3	374.2	148.7	0.67	0.23
2014	16	6.75	0.95	259.6	338.4	77.8	0.84	0.29
2015	20	5.33	0.50	356.7	433.5	151.1	0.84	0.31
	r^2	0.53	-0.16	0.15	0.08	0.54	0.59	-0.27
	p	0.17	0.67	0.75	0.87	0.19	0.12	0.56

3.4 Continuous permafrost in the Torneträsk region

The w.s.a. in the continuous permafrost region has been increasing since 1990 (*Figure* 7). The average w.s.a. coverage in the area was 4.3 km^2. From 1990 the w.s.a. rose every single year except from in 2006, where a decrease was seen. The w.s.a. was 0.2 km^2 in 1990 and rose substantially in 1994 where the w.s.a. covered 2.1 km^2. Thereafter a small decline was found in 2006 where the w.s.a. decreased to 1.1 km^2. From there on the w.s.a. has been increasing steadily up till 2015 where the w.s.a. reached its greatest expand of 4.3 km^2, which is 96.5% higher as in 1990.

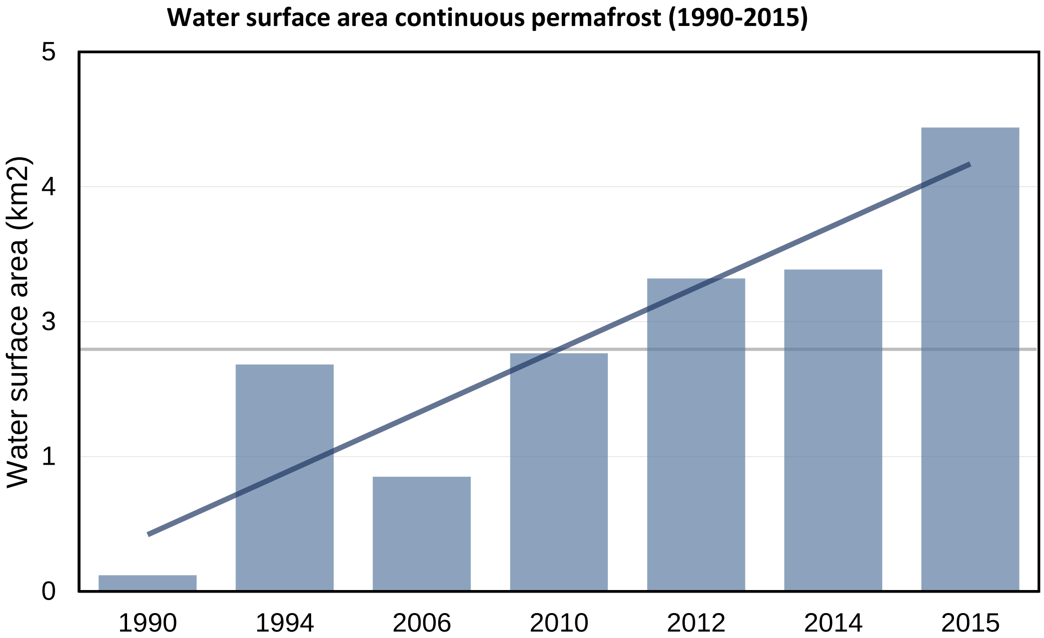


Figure 7: Bar chart of the total w.s.a. in the continuous permafrost zones Torneträsk region. The grey line represents the average w.s.a. coverage in m^2 in the continuous permafrost zone of the Torneträsk region. The blue line is the trend line for the w.s.a. change

There was a positive trend between the w.s.a. and the spring air temperatures, though again no significant relationship was found (*Table* 3). The trend between w.s.a. and annual air temperature was negligible. Also, the trends for the w.s.a. and all precipitation data sets were positive, and showed no significance. The trend for the w.s.a. and active layer thickness was just like the in the discontinuous permafrost zone positive, with a p-value of 0.14, which is also insignificant. No trend nor significance was found between the w.s.a and snow depth.

Table 3: W.s.a. in the discontinuous permafrost zone in the Torneträsk region. Together with the climatic data measured for each year. The r^2 and p-value for each correlation with the w.s.a. is given.

Lake surface area change continuous permafrost

Year	W.s.a.	Temperature		Precipitation			Active layer thickness	Snow depth
	Jul-Sep (km^2)	A/M/J/J (ºC)	Annual (ºC)	Oct-Jul (mm)	Annual (mm/yr)	M/J/J (mm)	(m)	(m)
1990	0.2	2.00	0.66	296.6	376.6	101.4	0.61	0.31
1994	2.1	5.43	-1.17	177.7	261.4	60.8	0.55	0.36
2006	1.1	6.25	0.58	225.6	352.7	108.1	0.73	0.26
2010	2.2	5.33	-0.81	199.9	281.9	133.9	0.69	0.19
2012	2.9	4.40	0.84	300.3	374.2	148.7	0.67	0.23
2014	3.0	6.75	0.95	259.6	338.4	77.8	0.84	0.29
2015	4.3	5.33	0.50	356.7	433.5	151.1	0.84	0.31
	r^2	0.50	0.06	0.40	0.28	0.40	0.61	-0.02
	p	0.25	0.90	0.38	0.54	0.38	0.14	0.96

3.5 Overview

Looking at *Table* 4 the total w.s.a. of the entire study area has been below average since 2010, whilst the opposite trend was seen for the continuous and discontinuous permafrost areas. The trend for the sporadic permafrost areas was also declining. The year 2015 was above average for all layers, especially for the discontinuous (28%) and continuous (92%) permafrost zones, just like in 2000. The w.s.a. in 2012 was, for all years, below average but for the continuous permafrost zone where the w.s.a. was 29 % above average.

Table 4: Table of the anomalies of the mean w.s.a. N/D means there was no data available for that year.

Total area	Total area	Sporadic	Discontinuous	Continuous
Average w.s.a.	**789.03**	**286.00**	**15.49**	**2.24**
1990	15%	13%	-35%	-93%
1994	0%	-2%	-11%	-6%
2000	28%	24%	2%	N/D
2006	7%	50%	-13%	-53%
2010	-2%	2%	26%	-2%
2012	-31%	-29%	-1%	29%
2014	-24%	-22%	3%	33%
2015	7%	8%	28%	92%

Table 5 shows how much the climatic data for each year differed from the mean of the climatic data for all years, so the w.s.a. of each year could be compared to the climate parameters for every single year. It is found that the mean annual air temperature in the area is above zero degree Celsius (0.32 ºC), and the spring air temperatures are around 5 ºC. Most of the precipitation in the area fell in winter/spring season, whereas almost half of the annual precipitation fell between May and July. The average active layer thickness was 0.71 metres, and the average snow depth was about 0.3 metres.

Table 5: Table of climatic data and active layer thickness for each year analysed, together with the total w.s.a. for each permafrost type. N/D stands for no data available.

Year	Temperature		Precipitation			Active layer thickness	Snow depth	W.s.a. Sporadic	W.s.a. Discon.	W.s.a. Con.
	A/M/J/J	Annual	Oct-Jul	Annual	M/J/J					
1990	-61%	109%	10%	7%	-11%	-14%	5%	324	10	0.2
1994	6%	-470%	-34%	-26%	-47%	-22%	22%	281	14	2.1
2000	6%	210%	26%	14%	13%	3%	42%	355	16	N/D
2006	22%	83%	-16%	0%	-5%	3%	-12%	302	14	1.1
2010	4%	-356%	-26%	-20%	18%	-2%	-36%	292	19	2.2
2012	-14%	166%	11%	6%	31%	-5%	-22%	203	15	2.9
2014	32%	200%	-4%	-4%	-32%	19%	-2%	224	16	3.0
2015	4%	58%	32%	23%	33%	19%	5%	309	20	4.3
Mean	**5.11**	**0.32**	**269**	**352**	**114**	**0.71**	**0.3**			

4. Discussion

The w.s.a. coverage changed differently over 25 the past years, depending on the permafrost type within the area. The sporadic permafrost zone had a decline in w.s.a. over 25 years period. This observation corresponds to previous researches done in areas with sporadic permafrost (Smith et al. 2005). According to Smith et al. (2005), this might be because of lake drainage. As mentioned before, lakes could drain as the permafrost gets thinner and breaches beneath the lakes, causing drainage to the sub surface. This explanation could be considered as possible because a small increase of precipitation was measured in the study area, meaning the decline in w.s.a. can not be caused by a decline of precipitation. Also, the increasing air temperatures in the area cause the permafrost to degrade and get thinner. No significant relationships were found between the w.s.a. in the sporadic permafrost zone with the different parameters, therefore no conclusions can be drawn looking at the change in w.s.a. and the climatic factors.

As opposed to many other studies, the w.s.a. in the discontinuous permafrost zone of the Torneträsk region declined over time. However, the increasing trend in air temperature and precipitation were similar. As the permafrost has been degrading over the past few decades, depressions in the surface have been formed due to collapses and slumping (Smith et al. 2005). This might have caused melt water coming from the permafrost to fill up the depressions. The increase in spring air temperature could have enhanced the spring snow melt causing more run off to the lakes. Additionally, the increase in spring precipitation as rainfall could have fed the lakes. The shallow soil layer in the discontinuous permafrost area might be the reason for the increase of w.s.a. As the permafrost thaws underneath the lakes, drainage from underneath could occur. However, if the soil layer is too thin (thus the bedrock is too close to the lake bottom) and not all permafrost around the lake has thawed yet an impermeable layer is formed, preventing the water to drain away (Kane and Slaughter 1973). In this case, the lake will be filled by melt water coming from the ice-rich permafrost, snow melt or rainfall. Kane and Slaughter (1973) found also that if a talik forms below a pond or lake and penetrates the permafrost, it could enable the sub-permafrost groundwater and recharge the lake or pond.

The w.s.a. of the continuous permafrost zone is decreasing just like in the discontinuous permafrost zone. Here the increasing trend was even more visible and a continuous increase has been observed since 1990, only 2006 was an outlier from the increasing trend. All r^2-values were rather low in the correlations, and no trends were observed. As said before the continuous permafrost is found up in the mountains at high altitudes. In those areas only a very shallow soil layer is found and therefore the development of thermokarst lakes is rather unlikely. The increase in w.s.a. is thus not explained for these areas, though the increase in w.s.a. might be caused by depressions being filled up by meltwater coming from glaciers or an increase in precipitation.

No clear pattern between the w.s.a. and the climatic factors were seen (*Table* 5). For example, in 2015 the highest level of w.s.a. was measured for discontinuous and continuous permafrost. During this year, the spring air temperature and active layer thickness were also at their highest. However, in 2014 when the w.s.a. was second highest for continuous permafrost, one of the lowest amount of spring precipitation was measured, which contradicts the trend seen for 2015. Only the active layer thickness seems to have followed a certain trend with the w.s.a. in discontinuous and continuous permafrost areas. Whereas the active layer gets thicker, an increase with w.s.a. could be expected. In 2014 and 2015, the active layer thickness was deepest, where at these times also the greatest extend in w.s.a. was observed. On the other hand, 1990 and 1994 had the shallowest active layer thickness, and also the least w.s.a. coverage. However those patterns could not be statistically proven.

4.1 Consequences of changes in w.s.a.

The change in w.s.a. not only has an influence on the hydrology in the soil, but also influences the ecosystem around the thermokarst lakes, as well as the methane (CH_4) emission to the atmosphere (Hinkel et al. 2005). As the soil gets wetter in the discontinuous permafrost regions, anaerobic decomposition of the organic material causes methane to be released to the atmosphere (Luo et al. 2015). The anaerobic decomposition and methane release will be limited in the continuous permafrost areas due to the lack of ice-rich permafrost and thin soil layer.

Furthermore, the change in soil wetness can influence the vegetation type (Christensen et al. 2004a). Briggs et al. (2014) founds that after lake drainage, the lake beds were overgrown by *Sphagnum* and shrubs. This vegetation cover caused new permafrost to form, as the ecological succession of the scrubs alters shading, infiltration and heat transport. Furthermore, Johansson et al. (2006b) found a shift in ecosystems due to changes in soil wetness, snow cover and winter precipitation. Changes in ecosystems and thus vegetation, effect the net ecosystem exchange and the carbon balance in the long term. A change from hummock vegetation to wet growing plant communities was observed in the sporadic permafrost zone in sub-Arctic Sweden, due to an increase in surface wetness. This caused the growing season atmospheric CO_2 function to increase with 16 % and the CH_4 emissions with 22 %.

4.2 Limitations and possible improvements

The class probability tool was quite inaccurate even though it classified the layers more accurately than the other tools. This might be because of the choice of satellite images. The images were quite coarse causing the borders of the lakes not to be very visible. Also, all of the shallow ponds, were not classified due to their transparency. Therefore, other classifications systems, such as radar classification, might have been more suitable for these type of analysis, since the reflectance of the water bodies could have been included. The main errors in the classification were shadows, which were classified as lakes, vegetation bands around the lakes, and poor resolution. All the lakes which were thought to be shadows were manually removed from the map, though often lakes were present underneath the shadows. This gave an underestimation of the w.s.a., especially in the continuous and discontinuous permafrost areas which are both mainly situated in the mountainous areas. Those areas were already rather small and had relatively little w.s.a. coverage, thus a small mistake in classification due to shadows could have a high impact on the final result. The vegetation around the lakes made it hard to delineate the lakes accurately (Sannel, 2010). The sides of the lakes could be overgrown by vegetation causing again an underestimation of the w.s.a. This problem might have influenced the lakes within the sporadic permafrost zones more than in the other areas, due to more favourable air temperatures and soil conditions for plant growth in these regions.

Not only was the image classification poor, but the climatic data used for the analysis could have been better. The data for precipitation and air temperature were only collected at one point within the research area. This was at 388 m a.s.l., whilst the highest in the study area were at 1791 a.s.l. Since the air temperature declines with altitude, the mean annual air temperature would be much lower up in the mountains than at the measurement station. Further, the active layer thickness was measured over nine points where mainly sporadic and discontinuous permafrost is found. In the analysis of this thesis the numbers of the change in active layer thickness of the discontinuous permafrost areas were also used for the continuous permafrost zones. This might not have been very accurate since continuous permafrost responds differently to climate change than discontinuous permafrost. Romanovsky et al. (2010) found that especially in areas of ice-rich permafrost, the continuous permafrost warms faster than the discontinuous permafrost. This is caused by the latent heat effect: as the water melts within the ice rich permafrost close to 0ºC, latent heat is released. This causes a cooling effect on the soil, slowing down the rate of the increase in temperature. The snow depth just like the precipitation and air temperature, was measured at the measuring station in Abisko. Abisko is located within an area of rain shadow at relatively low altitude and is thus not very representative for the whole study area. The use of more measurement stations at various altitudes and locations, covering all permafrost types would have been more accurate for the analysis.

Several parameters were used to look for any correlations between the w.s.a. and climatic factors. There were more parameters, which could have been looked at, but this was not done due to time and/or data limitation. According to Briggs (2004) the vegetation cover has an influence on the w.s.a., where Turner et al. (2014) says the evapotranspiration (E-T) might influence the w.s.a. The E-T was originally looked at but due to limitations in data availability for longer time periods these were excluded from the final results. The Thornthwaite equation (Pereira and Paes De Camargo 1989) was used to estimate the evapotranspiration in the area, but due to negative monthly air temperatures for most of the year the equation was unreliable. The equations only take the monthly air temperatures into account, but it does not include the air temperatures below ºC, air humidity nor wind. Sublimation was not looked at either.

To wrap up, a decline in w.s.a. has been observed in the sporadic permafrost zones, whilst there was an increase seen in the areas with discontinuous and continuous permafrost. Even though no significant results were found, it is possible the w.s.a. in the discontinuous and continuous permafrost zones were connected to permafrost degradation. Therefore, a future increase in w.s.a. could be possible, since climate is changing and permafrost keeps on degrading. The lack of significant results within the analysis is possibly caused by the lack of enough suitable satellite images. On the other hand, the difference between the results of this analysis and other studies could be because of different conditions, such as different response to climate change, soil type, soil depth or impermeable layers.

For further researches, it would be advised to use more time series for a longer period, so the influence of climate change would be seen better connected to the change in w.s.a. Also, another and more accurate auto-classification system, e.g. radar classification, could be used to map all the lakes. Even though manual classification is most precise, it is not to be advised to use due to the size of the area, especially if the whole of the permafrost region of Sweden would be mapped. It would also be interesting to look at the change in number of lakes as well as at the aspect of the lake degradation.

5. Conclusion

To conclude, the w.s.a. in the Torneträsk region has seen a decline in w.s.a., though this decline was mainly seen in the permafrost free regions and sporadic permafrost regions. The w.s.a. doubled in the discontinuous permafrost areas, and got 20 times higher in the continuous permafrost area since 1990. No significant results were found in this thesis, and therefore no conclusions should be drown. However, ways to improve the analysis could be discussed.

A better methodology, such as the use of more satellite images with a better resolution would have improved the data accuracy. Also more representative climate date would have favoured the analysis. In addition, a comparison of eight years over a time span of 25 years was too little in order to obtain any significant results and to find any possible correlations.

6. References

Akerman, H. J., and M. Johansson. 2008. Thawing permafrost and thicker active layers in sub-arctic Sweden. *Permafrost and Periglacial Processes,* 19**:** 279-292. DOI: 10.1002/ppp.626

Anderson, L., J. Birks, J. Rover, and N. Guldager. 2013. Controls on recent Alaskan lake changes identified from water isotopes and remote sensing. *Geophysical Research Letters,* 40**:** 3413-3418. DOI: 10.1002/grl.50672

Briggs, M. A., M. A. Walvoord, J. M. McKenzie, C. I. Voss, F. D. Day-Lewis, and J. W. Lane. 2014. New permafrost is forming around shrinking Arctic lakes, but will it last? *Geophysical Research Letters,* 41**:** 1585-1592. DOI: 10.1002/2014GL059251

Christensen, T. R., T. Johansson, H. J. Akerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson. 2004a. Thawing sub-arctic permafrost; effects on vegetation and methane emissions. *Geophysical Research Letters,* 31. DOI: 10.1029/2003GL018680

Christensen, T. R., T. Johansson, H. J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson. 2004b. Thawing sub-arctic permafrost: Effects on vegetation and methane emissions. *Geophysical Research Letters,* 31**:** n/a.

Gisnås, K., B. Etzelmüller, S. Westermann, C. Lussana, K. Isaksen, J. Hjort, A. B. K. Sannel, P. Kuhry, et al. 2017. Permafrost Map for Norway, Sweden and Finland. *Permafrost and Periglacial Processes,* 28**:** 359-378. DOI: 10.1002/ppp.1922

Heslop, J. K., K. M. W. Anthony, A. Sepulveda-Jauregui, K. Martinez-Cruz, A. Bondurant, G. Grosse, and M. C. Jones. 2015. Thermokarst lake methanogenesis along a complete talik profile. *Biogeosciences, Vol 12, Iss 14, Pp 4317-4331 (2015)***:** 4317. DOI: 10.5194/bg-12-4317-2015

Hinkel, K. M., R. C. Frohn, F. E. Nelson, W. R. Eisner, and R. A. Beck. 2005. Morphometric and spatial analysis of thaw lakes and drained thaw lake basins in the western Arctic Coastal Plain, Alaska. *Permafrost and Periglacial Processes,* 16**:** 327-341. DOI: 10.1002/ppp.532

Hinkel, K. M., B. M. Jones, W. R. Eisner, C. J. Cuomo, R. A. Beck, and R. Frohn. 2007. Methods to assess natural and anthropogenic thaw lake drainage on the western Arctic coastal plain of northern Alaska.

Hinzman, L. D., B. Neil, W. Bolton, F. Chapin, D. Mark, F. Chris, G. Brad, H. Robert, et al. 2005. Evidence and Implications of Recent Climate Change in Northern Alaska and Other Arctic Regions. *Climatic Change,* 72**:** 251-298.

Johansson, M., J. Åkerman, F. Keuper, T. R. Christensen, H. Lantuit, and T. V. Callaghan. 2011. Past and Present Permafrost Temperatures in the Abisko Area: Redrilling of Boreholes. *AMBIO,* 40**:** 558. DOI: 10.1007/s13280-011-0163-3

Johansson, M., T. R. Christensen, H. J. Akerman, and T. V. Callaghan. 2006. What Determines the Current Presence or Absence of Permafrost in the Torneträsk Region, a Sub-arctic Landscape in Northern Sweden? *AMBIO - A Journal of the Human Environment,* 35**:** 190-197.

Johansson, T., N. Malmer, P. M. Crill, T. Friborg, J. H. ÅKerman, M. Mastepanov, and T. R. Christensen. 2006. Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing. *Global Change Biology,* 12**:** 2352-2369. DOI: 10.1111/j.1365-2486.2006.01267.x

Jones, B. M., A. Courtney L., K. Joshua C., and G. Guido. 2013. Thermokarst and Thaw-Related Landscape Dynamics—An Annotated Bibliography with an Emphasis on Potential Effects on Habitat and Wildlife. *U.S. Geological Survey***:** 60p.

Jorgenson, M. T., Y. L. Shur, and E. R. Pullman. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters,* 33. DOI: 10.1029/2005GL024960

Kane, K. L., and C. W. Slaughter. 1973. Recharge of a central Alaska lake by subpermafrost groundwater. *International Conference on Permafrost, 2d, Yakutsk, Siberia, 1973. Papers,* 1973**:** 4.

Karlsson, J. M., S. W. Lyon, and G. Destouni. 2012. Thermokarst lake, hydrological flow and water balance indicators of permafrost change in western Siberia. *Journal of Hydrology,* 464-465**:** 459-466. DOI: 10.1016/j.jhydrol.2012.07.037

King, L. 1986. Zonation and Ecology of High Mountain Permafrost in Scandinavia. 131. Swedish Society for Anthropology and Geography.

Labrecque, S., D. Lacelle, C. R. Duguay, B. Lauriol, and J. Hawkings. 2009. Contemporary (1951-2001) evolution of lakes in the Old Crow Basin, northern Yukon, Canada; remote sensing, numerical modeling, and stable isotope analysis. *Arctic,* 62**:** 225-238.

Luo, J., F. Niu, Z. Lin, M. Liu, and G. Yin. 2015. Thermokarst lake changes between 1969 and 2010 in the Beilu River basin, Qinghai-Tibet Plateau, China. *Science Bulletin,* 60**:** 556-564. DOI: 10.1007/s11434-015-0730-2

Pereira, A. R., and Â. Paes De Camargo. 1989. An analysis of the criticism of thornthwaite's equation for estimating potential evapotranspiration. *Agricultural and Forest Meteorology,* 46**:** 149-157. DOI: http://dx.doi.org/10.1016/0168-1923(89)90118-4

Riordan, B., D. Verbyla, and A. D. McGuire. 2006. Shrinking ponds in subarctic Alaska based on 1950-2002 remotely sensed images. *Journal of Geophysical Research,* 111**:** @CitationG04002-@CitationG04002. DOI: 10.1029/2005JG000150

Romanovsky, V. E., S. L. Smith, and H. H. Christiansen. 2010. Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007-2009: a synthesis. *Permafrost & Periglacial Processes,* 21**:** 106.

Sannel, B., and I. Brown. 2010. High-resolution remote sensing identification of thermokarst lake dynamics in a subarctic peat plateau complex. *Canadian journal of remote sensing*. DOI: 10.5589/m10-010

Swedish National Satellite Database comprising satellite image coverages (Saccess). Retrieved 10. April 2017, from https://saccess.lantmateriet.se/portal/saccess_se.htm

Serreze, M. C., and J. E. Walsh. 2000. Observational evidence of recent change in the northern high-latitude environment. *Climatic Change,* 46**:** 159.

Shur, Y. L., and T. E. Osterkamp. 2007. Thermokarst: Fairbanks, University of Alaska Fairbanks.

Smith, L. C., Y. Sheng, G. M. MacDonald, and L. D. Hinzman. 2005. Disappearing Arctic lakes. *Science,* 308. DOI: 10.1126/science.1108142

Sundqvist, M. K., R. Giesler, B. J. Graae, H. Wallander, E. Fogelberg, and D. A. Wardle. 2011. Interactive effects of vegetation type and elevation on aboveground and belowground properties in a subarctic tundra. *Oikos,* 120**:** 128-142. DOI: 10.1111/j.1600-0706.2010.18811.x

Turner, K. W., B. B. Wolfe, T. W. D. Edwards, T. C. Lantz, R. I. Hall, and G. Larocque. 2014. Controls on water balance of shallow thermokarst lakes and their relations with catchment characteristics: a multi-year, landscape-scale assessment based on water isotope tracers and remote sensing in Old Crow Flats, Yukon (Canada). *Global Change Biology,* 20**:** 1585-1603. DOI: 10.1111/gcb.12465

U.S. Geological Sourvey. 2017a. Earth Explorer. Retrieved 10. April 2017, from earthexplorer.usgs.gov.

Vonk, J., V. Alling, L. Rahm, M. Mörth, C. Humborg, and Ö. Gustafsson. 2012. A centennial record of fluvial organic matter input from the discontinuous permafrost catchment of Lake Torneträsk. *Journal of Geophysical Research***:** 1. DOI: 10.1029/2011JG001887

Walsh, J. E., A. Oleg, O. M. H. Jon, T. Jakobsson, J. Oerleman, T. D. Prowse, V. Romanovs, N. Savelieva, et al. 2005. In *Arctic Climate Impact Assesment (ACIA)*, pp. 183-242. New York: Cambridge University Press.

Wunderground.com. 2017. Permafrost. Retrieved 19 April 2017, from https://www.wunderground.com/about/contact-us.

Yoshikawa, K., and L. D. Hinzman. 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. *Permafrost and Periglacial Processes,* 14**:** 151-160. DOI: 10.1002/ppp.451

Zhang, T., R. G. Barry, K. Knowles, F. Ling, and R. L. Armstrong. 2003. Distribution of seasonally and perennially frozen ground in the Northern Hemisphere. *Permafrost. Phillips, Springman, and Arenson, eds. Swets and Zeitlinger*.

7. Appendix

Appendix A: Table of researches done in areas of discontinuous permafrost, together with its findings.

Region	Time range	Observation	Causes	References
Siberia	1973-1998	Decline of 13% w.s.a	Permafrost degradation, thinning of the permafrost layer	Smith et al. (2005)
Alaska	1950-2000	Decline in w.s.a.	Lake drainage due to talik formation	Yoshikawa and Hinzman (2003)
Yukon, Canada	1951-2001	Decline of 3.5% w.s.a. (but increase till 1971)	A warmer and drier climate (or drainage due to stream erosion or bank overflow)	Labrecque et al. (2009)
Yukon, Canada	-	-	Climate changes, the evaporation is exceeding the inflow of water	Anderson et al. (2013)
Alaska	1950-2002	Decline of 4 to 31% w.s.a	Increased drainage as permafrost warms, or increased evapotranspiration during a warmer and extended growing season.	Riordan et al. (2006)

Appendix B: Table of researches done in areas of continuous permafrost, together with its findings.

Extend	Time range	Observation	Causes	References
Siberia	1973-1998	Increase of 4% w.s.a	Filled depressions after collapses	Smith et al. (2005)
Tibet plateau	1969-2010	Increase of 13% w.s.a. all lakes, 60% increase for small lakes	Increase in air temperatures and P-ET ratio	Luo et al. (2015)
N-Alaska	Mid-1970 -2000	Drainage of 50 lakes	Lake drainage possibly caused by human activities	Hinkel et al. (2007)

Appendix C: Table of the satellite images used for each year, together with satellite type as well as its resolution. The missing data for the dates comes from the images made out of a mosaic and are thus collected at several dates.

Year	Date	Satellite	Resolution
1990	15-Jul	L4-L5 TM higher level	30 m
1994	11-Aug	L4-L5 TM higher level	30 m
2000	N/D	Landsat 7 ETM+	30 m
2004	05-Jul	L4-L5 TM higher level	30 m
2006	27-Jul	L4-L5 TM higher level	30 m
2010	08-Sep	L4-L5 TM higher level	30 m
2012	N/D	SPOT 4	20 m
2014	N/D	Landsat 8 SPOT 5	30 m 10 m
2015	N/D	IRS R2 Landsat 8	20 m 30 m

Appendix D: Table of the average accuracy of the "Maximum likelihood classification", "Iso-cluster" and "Class probability" tool. The w.s.a. of the manual classified layer is present in the second column, and the average accuracy of the layers used in all of the analysis is found in the last column. The data accuracy was measured for 1994, 2010 and 2014.

Year	Manual (m^2)	Max. likelihood	Iso-cluster	Class probability	Actual layer
1994	262729	92619	N/D	153353	158135
2010	269982	119535	209828	167782	171702
2014	287425	116893	232165	227164	239304
1994	-	35%	N/D	58%	60%
2010	-	44%	78%	62%	64%
2014	-	41%	81%	79%	83%
Average accuracy	**-**	**40%**	**N/D**	**67%**	**69%**

Appendix E: Table of the accuracy of each layer. The manually mapped w.s.a. is found in the second row, where the automatically classified w.s.a. can be seen in the third row.

Year	1990	1994	2000	2006	2010	2012	2014	2015
Mapped area (m^2)	153666	158135	129460	158531	171702	245197	239304	151781
Classified Area (m^2)	162160	153353	158839	200783	167782	235457	227164	144130
Accuracy	52%	60%	48%	56%	64%	94%	83%	58%

Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.

Studentexamensarbete (seminarieuppsatser). Uppsatserna finns tillgängliga på institutionens geobibliotek, Sölvegatan 12, 223 62 LUND. Serien startade 1985. Hela listan och själva uppsatserna är även tillgängliga på LUP student papers (https://lup.lub.lu.se/student-papers/search/) och via Geobiblioteket (www.geobib.lu.se)

The student thesis reports are available at the Geo-Library, Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden. Report series started 1985. The complete list and electronic versions are also electronic available at the LUP student papers (https://lup.lub.lu.se/student-papers/search/) and through the Geo-library (www.geobib.lu.se)

400 Sofia Sjögren (2016) Effective methods for prediction and visualization of contaminated soil volumes in 3D with GIS
401 Jayan Wijesingha (2016) Geometric quality assessment of multi-rotor unmanned aerial vehicle-borne remote sensing products for precision agriculture
402 Jenny Ahlstrand (2016) Effects of altered precipitation regimes on bryophyte carbon dynamics in a Peruvian tropical montane cloud forest
403 Peter Markus (2016) Design and development of a prototype mobile geographical information system for real-time collection and storage of traffic accident data
404 Christos Bountzouklis (2016) Monitoring of Santorini (Greece) volcano during post-unrest period (2014-2016) with interferometric time series of Sentinel-1A
405 Gea Hallen (2016) Porous asphalt as a method for reducing urban storm water runoff in Lund, Sweden
406 Marcus Rudolf (2016) Spatiotemporal reconstructions of black carbon, organic matter and heavy metals in coastal records of south-west Sweden
407 Sophie Rudbäck (2016) The spatial growth pattern and directional properties of *Dryas octopetala* on Spitsbergen, Svalbard
408 Julia Schütt (2017) Assessment of forcing mechanisms on net community production and dissolved inorganic carbon dynamics in the Southern Ocean using glider data
409 Abdalla Eltayeb A. Mohamed (2016) Mapping tree canopy cover in the semi-arid Sahel using satellite remote sensing and Google Earth imagery
410 Ying Zhou (2016) The link between secondary organic aerosol and monoterpenes at a boreal forest site
411 Matthew Corney (2016) Preparation and analysis of crowdsourced GPS bicycling data: a study of Skåne, Sweden
412 Louise Hannon Bradshaw (2017) Sweden, forests & wind storms: Developing a model to predict storm damage to forests in Kronoberg county
413 Joel D. White (2017) Shifts within the carbon cycle in response to the absence of keystone herbivore *Ovibos moschatus* in a high arctic mire
414 Kristofer Karlsson (2017) Greenhouse gas flux at a temperate peatland: a comparison of the eddy covariance method and the flux-gradient method
415 Md. Monirul Islam (2017) Tracing mangrove forest dynamics of Bangladesh using historical Landsat data
416 Bos Brendan Bos (2017) The effects of tropical cyclones on the carbon cycle
417 Martynas Cerniauskas (2017) Estimating wildfire-attributed boreal forest burn in Central and Eastern Siberia during summer of 2016
418 Number reserved for BSc thesis
419 Clara Kjällman (2017) Changing landscapes: Wetlands in the Swedish municipality Helsingborg 1820-2016
420 Raluca Munteanu (2017) The effects of changing temperature and precipitation rates on free-living soil Nematoda in Norway.
421 Neija Maegaard Elvekjær (2017) Assessing Land degradation in global drylands and possible linkages to socio-economic inequality
422 Petra Oberhollenzer, (2017) Reforestation of Alpine Grasslands in South Tyrol: Assessing spatial changes based on LANDSAT data 1986-2016
423 Femke Pijcke, (2017) Change in water surface area northern Sweden between 1990 and 2015