Department of Geography

Local climate-related impacts in Central Switzerland:

attributable to climate change?

GEO 511 Master's Thesis

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Abstract

Switzerland is prone to many impacts by climate change now and in the future. Especially in mountainous regions natural and human-managed systems are vulnerable to changes in climate, which can result in influential or irreversible changes of the environment. This impacts natural ecosystems, regional economy and society.

While research on methods for future impact prediction is progressing, it focuses less on detection and attribution of already observed impacts. Impacts with a small spatial extent are especially difficult to confidently attribute to climate change. Consequently, there is a lack of established methods and in-depth research for local climate impact attribution. However, climate change has local consequences and development of suitable methods could benefit local climate change adaptation efforts and the overall understanding of impacts of climate change.

This master thesis applies an attribution framework developed by Hansen et al. (2015) to four local observed impact cases in Central Switzerland. It firstly investigates if this attribution framework can be used in practice for very local impact attribution and how it can be adapted to fit local impacts optimally. Secondly, it focuses on attribution of the cases in Central Switzerland, and the characteristics of the impact cases, which facilitate or hinder impact attribution.

The results show that the attribution framework can be adapted to fit local impact attribution and local attribution is feasible for certain cases. However, there are factors, which complicate and hinder a thorough assessment rendering attribution efforts futile. Attribution is feasible for impacts that are linked to a variable showing long-term trend in average climate condition, e.g. increase in average air temperature. The findings also show that attribution is not yet feasible for extreme event impacts or impacts observed over a very short time period on the local level. Generally, if there is a lack of understanding of the underlying processes of the impact or a lack of appropriate, local data, attribution assessments lose accuracy.

Local impact attribution is promising for future climate research especially for regions where natural systems are undisturbed and small, for instance in mountainous regions. This attempt to apply it in practice is potentially a first step to use it as a tool in climate change adaptation planning.

Fig. 1: Case studies in Central Switzerland, Rhone Glacier, Haggenegg, Sittlisalp, Lake trout of Urnersee.

Title image: Four case study sites: upper left: Rhone Glacier with ice cave (Alean and Hambrey, 2008), upper right: Haggenegg (Melanie Graf, October 2016), lower left: Grossbach stream on Sittlisalp (Melanie Graf, September 2016), lower right: Lake trout in Flüelen fish farm (Tierwelt, 2016).

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1. Introduction

> *"Everything changes and nothing remains still [...]*
>
> *you cannot step twice into the same stream"* (Heraclitus, B49a)

This ancient quote from Heraclitus states nicely, that as strongly as we might try to hold on, the world is changing constantly. And while this is a philosophic sentiment, it is important in research as well, to never assume something is as it always was.

1.1 Motivation

In climate research, contemporary climatic change has been a focus for over 30 years now, and it will probably stay at the centre of attention for the foreseeable future. How the influence of humans has changed the climate already and how it will influence it in the future causes concern all around the scientific as well as the political communities (Brown et al., 2011, Zerefos, 2011, IPCC, 2014a).

A primary cause of concern is of course, how this change does affect humans and for us important natural systems now and in the future. A good understanding of these already happening or impending impacts and the system they affect is important to be able to adapt to the change. Therefore, development of methods supporting this understanding should be a priority. A first step in understanding the systems is to be able to differentiate between impacts that are caused by a changing climate and impacts that are occurring due to other causes. These attribution methods can be applied to many different scales and time frames. Most advanced are attribution methods for the global level. Many climate-related impacts, for instance retreating glacier mass because of a climatic trend to higher air temperatures, can be identified with confidence and are well understood (Hegerl et al., 2007, IPCC, 2014a).

Understanding on a smaller, local level is less advanced. Most local studies make projections of possible impacts happening in a region in the near future (Gasner et al., 2010, Tabari et al., 2016). It is encouraging that science is striving to assess these future changes and give us an insight in what might happen. But if we are honest, what we also want to know is: How does it really affect us? Does climate change really change something for me, for my family, my neighbours, my community and my business? Is it possible that it already affects us, without us knowing the cause of some of our problems is climate change?

It is possible and plausible that climate change already affects us in a personal way. However, these local impacts, which have the ability to change our everyday life are not studied systematically yet (Hansen et al., 2015). This is mainly because the attribution of such impacts poses many challenges, caused by small-scale extent, including lack of appropriate data and insufficient understanding of the local system. Also, more often than not, observed local impacts are seen as too small and not worth the effort of thorough investigation. It is much more common to start with the premise of global climate change and assessing what global impacts might mean for the local level, than looking at a local impact and linking it back to climate change.

Working with this perspective certainly yields useful information, but dismissing research on observed changes as fruitless could be short sighted. Especially as individual small-scale impacts can be a first manifestation of a regional trend. Also, local policies and adaptation measures are only effective if they target the correct cause of the impact. If the root cause is an on-going problem like climate change, more long-term adaptation measures have to be found instead of a fixing the problem short-term. Preventive measures to weaken the brunt of future impacts are important, but the impacts already happening need our attention too.

To address this topic in a scientific manner, more suitable methods to approach such local impact attribution have to be developed. Hansen et al. (2015) designed a framework for local impact attribution in their article: *Linking local impacts to changes in climate: a guide to attribution*. The article provides some examples of attribution case studies, which cover small to large regions rather than local impacts. The question therefore poses itself if the framework really is applicable to such observed local impacts. The aim of this study is to shine a light on such local impacts, put them into climate context and find out to what extent attribution is possible.

1.2 Content

The content of this thesis therefore focuses on two points, the attribution framework and local case studies. To provide a scientific basis for both, state of the art findings on global climate change are reviewed, introducing observed impacts and drivers on a local and global scale. A second chapter focuses on climate change impact detection and attribution specifically, outlining globally and locally used methods and defining the research questions. A third introductory chapter introduces the study area, detailing the case studies and the data availability in the area. Based on the scientific background and study area, the research questions are formulated.

Next the methods give a step by step explanation on the attribution framework by Hansen et al. (2015) and how they are adapted to very local cases. It also presents a classification for attribution cases developed for this thesis. Additionally, supporting methods like interviews and field investigations are outlined.

The results are presented through four detailed case studies in Central Switzerland. Each of the cases reports on the observed impact and its local study area. A case specific background chapter is provided to establish the underlying processes and their relation to the climate. Additionally, the local research in the area is reviewed and the case is set into context. After this introduction to the case follows the attribution assessment. The assessment tests hypotheses by comparing the climate trend with the climate-free background behaviour leading to impact detection and attribution. The limitations of the data and analyses used for the attribution assessment are revealed and finally the case is classified according to the developed classification scheme.

In the following, the discussion analyses the results of the case studies following the two main research goals and each of their sub-questions. Finally, the conclusion summarises the findings and gives a short outlook on future research opportunities.

1.3 Case studies

This thesis is based on four case studies, where a local impact was observed in recent years. The cases are located in Central Switzerland at different elevations and with varying degrees of human influence. The first case study is concerned with the glacier retreat of the Rhone Glacier in the Canton of Valais. Secondly, a groundwater temperature rise is investigated in a fish farm in Flüelen, Canton of Uri. The third case processes water shortages on the Sittlisalp also in the Canton of Uri. Another water shortage on the Haggenegg pass in the Canton of Schwyz serves as a fourth and last case. The case studies were all chosen for their connection to climate variables and small spatial extent. They also give an insight into a range of possible climate change impacts and the processes behind them.

1.4 Research goals

The challenges facing local impact detection and attribution are manifold: Systematic observation of the impact is problematic due to its small extent. Measurement networks are often too coarse to observe the impacts and inhabitants seldom report impacts to the local authorities. Therefore, there is a lack of data for many attribution methods that are used on a larger scale. Translating global climate behaviour to local behaviour is difficult and chained to uncertainties. Many attribution methods need detailed and extensive data, unobtainable on a local level. The following chapter 2. Climate Change deliberates on basic understanding and challenges of climate change and local climate change attribution.

Despite, or maybe also because of these challenges, it is important that there is a robust and tested approach to detecting and attributing local impacts. As climate potentially impacts all natural and human systems, a wide range of researchers profit from a guided approach. Hansen et al. (2015) published such an attribution framework, which will be tested in this thesis on four local impact studies in Central Switzerland.

Based on the background knowledge about impact detection and attribution (see 2 Climate Change), the goals and supporting research questions for this thesis are laid out below. The four questions are examined in each of the four local case studies. They are grouped within the two main goals.

Goal 1: Evaluate and adapt a climate change attribution framework for local observed impacts.

Question 1: Is the attribution framework (Hansen et al., 2015) applicable to the attribution of local observed impacts in practice?

Q2: How can the attribution framework be adapted to provide the optimal guide for very local cases?

This first goal addresses a theoretical approach to impact attribution and how translatable it is to cases in practice.

Goal 2: Establish to what extent attribution on local case studies is feasible.

Q3: Is an impact detection and attribution of the cases in Central Switzerland possible and to what extent?

Q4: Which case characteristics (e.g. temporal and spatial scale), facilitate or hinder detection and attribution?

The second goal focuses more on the attribution of the cases at hand. The aim is to look more in-depth into the assessment of the cases. How far it was possible and circumstances that hindered of helped a thorough attribution assessment.

2. Climate Change

"Climate change will have a bigger impact on your family and friends and all of humanity than the Internet has had. [...] Since everyone's family will be affected by climate change – indeed, they already are – everyone needs to know the basics about it, regardless of their politics." (Romm, 2016)

Today, there is a vivid scientific and political debate about the future development of the climate, and probable scenarios are discussed based on extensive research. Most scientists approve of the statement, that it will affect humans massively in the foreseeable future and this validates the immense interest of the scientific community (IPCC, 2014a). However, detecting how climate change already affects humans in everyday life, how "everyone's family" feels the consequences of it is not reported on as extensively yet.

This thesis focuses on the impacts that are already detectable and their attribution to climate change. To understand the importance of this thematic, this chapter gives an overview on global and local climate change and its current and potential impacts. In a short excursus, it introduces important institutions and global agreements on climate change and outlines Swiss and European climate change adaptation and mitigation plans.

2.1. Global climate change

More and more attention is dedicated worldwide to climate change research every year, as the scientific community is increasingly concerned about anthropogenic influences on recent climate. Nowadays, it is widely acknowledged that human actions influence the climate significantly and will continue to do so. If business is carried on as usual, human actions will have an exceptionally large influence.

To recognise if climate changed, past climate conditions were reconstructed through different methods. A particular area of interest is air temperature change as it influences many environmental processes and landscapes. Reliable measurement data for air temperatures have been taken at many sites from 1850 to today. Pre-industrial temperatures, however, have to be reconstructed using borehole isotopes or other proxies like tree ring reconstructions, which can reach farther into the past. Between 1850 and 2010 global air temperature has risen 0.8°C with the main rise occurring since 1975 (Chapman and Davis, 2010). In contrast, temperatures calculated by a hybrid reconstruction of borehole and surface temperatures indicate a rise of 1.1°C by 2000 compared to 1750 (Harris and Chapman, 2001). While the range of reconstructions of temperatures suggest different increase rates that may vary up to 0.5°C, the consensus shows a definite rise in temperatures (Chapman and Davis, 2010).

This rapid change is unprecedented over at least the past millennium. Consequently, the climate-related systems react strongly to the change (Chapman and Davis, 2010). Other important signals than air temperatures also change of course, for example the marine climate signals. The ocean stores the majority of the energy surplus: Only 1 % of the energy surplus in the earths system is stored in the atmosphere, while over 90% of the energy is stored in the ocean. Both of these energy changes contribute greatly to the loss in sea ice extent in arctic regions, to just name one impact. As air temperatures are easily measured and many measurement stations have been established for a long time, it is often used as a main signal of the rate at which the climate changes (IPCC, 2014a).

Another focus in climate change monitoring is put on precipitation amounts and patterns, as changes in parts of the hydrological cycle could potentially harm human and natural systems immensely. Both a significant increase and decrease in precipitation would influence vegetation, ecosystems, water resources and occurrence of mass movements. However, confidences in changes (the certainty, with which scientists are able to detect a change) are mostly low except for mid-latitude terrestrial regions in the Northern Hemisphere where precipitation has likely increased long-term since 1901. However, this applies only for the average of the area, smaller regions like the Mediterranean region are even expected to show a trend to less precipitation in the near future (IPCC, 2014a).

As described above, temperature and precipitation trends over a prolonged period of time are important climate signals as they report on a change in the average condition of the weather. If a change to greater variability of the climate occurs, this produces a greater risk for extreme weather events. Even if no trend in average climate conditions is detectable, the risk for more frequent and more intense extreme weather is concerning, as their spontaneous onset is challenging to adapt to. Particularly concerning for the health of ecosystems and people are, on the one hand, potential periods of high temperatures and droughts. On the other hand, more frequent high-precipitation events, which can trigger natural hazards like flooding, might also become a problem. Hence, a diligent investigation in climate variability changes is also important in detecting if average climate condition changes (Klein Tank et al., 2009).

2.1.1. Climate change forcing and drivers

The climate is never absolutely stable, as many different natural and anthropogenic factors influence it. The energy balance in the troposphere mainly drives the climate. If the energy fluxes are imbalanced, the climate changes. Many different influences have been discussed as the root causes of the recent changes in climate. An influence with the potential to cause change in the climate is termed forcing or occasionally driver. Cyclic processes and irregular processes induce natural forcing. Both long-term cyclic processes such as the Milankovitch-cycles (10^4-10^5 a) and short-term cyclic processes like variability in solar irradiance (up to 10^2 a) or systemic oscillation processes (e.g. El Niño) change constantly. Irregular natural influences like volcanic eruptions can also induce very short-term changes (1 to 3a) (Wanner and Brönnimann, 2000).

The term for non-natural or humanly caused forcing is anthropogenic forcing. The Fifth IPCC Assessment Report deems it extremely likely that anthropogenic forcing through greenhouse gas emissions caused the observed global temperature rise since the mid-20th century (IPCC, 2014a). A larger concentration of the greenhouse gases basically keeps long-wave radiation in the atmosphere instead of it leaving the system and consequently changing the energy balance (Charlson et al., 1992). It also likely has an influence on the global water cycle and very likely cryospheric processes like glacier and sea-ice changes (IPCC, 2014a). There are of course other anthropogenic influences like energy loss through aerosols in the troposphere and land use changes like urbanisation. These may have similar or opposite effects than the greenhouse gases. At the moment they are less prevalent on a global scale, but they can of course intensify or mellow the forcing through greenhouse gases, especially on a more local scale (Wanner and Brönnimann, 2000).

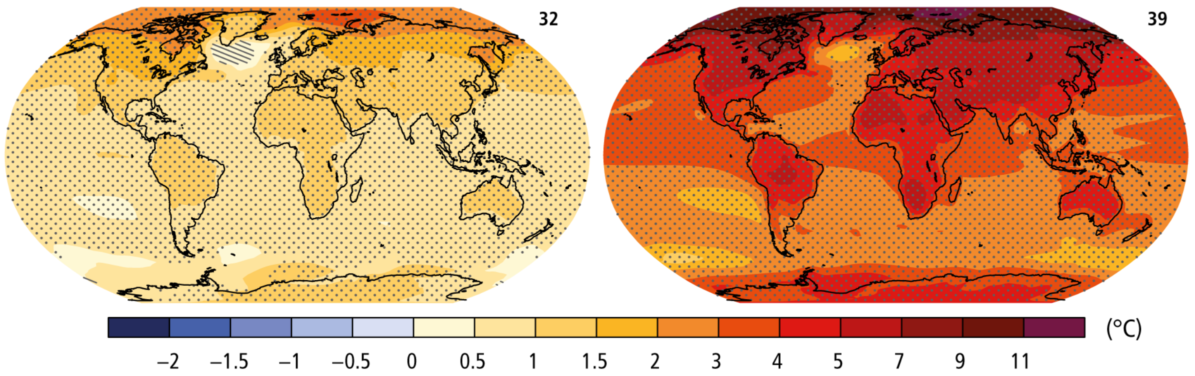
In this thesis the term “driver” is mainly used to describe the causes of the observed impact, instead of a forcing of the climatic change. These can either be climatic drivers or other non-climatic drivers. Even if it is established that the driver of an observed local impact is most likely climate change, one cannot assume that the forcing of the change is automatically anthropogenic. It is very difficult to link local climate impacts to anthropogenic forcing (Hansen et al., 2015).

2.1.2. Climate change scenarios

Current and future greenhouse gas emissions will most likely force the future changes in climate. Depending on the change in emission rates, resulting from a range of economic or population scenarios, different climate scenarios were modelled. If greenhouse gas concentrations continue to rise at current rates or even at increased rates, it would mean an increase in global surface temperature of up to 4.8°C by 2100 compared to 1986-2005. Either way, temperature extremes, will become more frequent and heat waves will be longer and more common. These are just the most probable of consequences; however, it is indisputable that these scenarios would induce an abundance of consequences, not all of them foreseeable (IPCC, 2014a).

Other climate scenarios using an immediate reduction in emission rates project warming in the first half of the 21st century, but limited warming in the second half. This would still lead to significant impacts but the extent would be less extreme. Fig. 2 depicts temperature and precipitation changes by 2100, modelled for two scenarios. While temperatures will follow a distinct long-term warming trend over all regions of the earth, precipitation will likely increase in polar and equatorial regions and decrease in sub-tropic to temperate. The arctic regions are to expect the most drastic changes for both climate signals (IPCC, 2014a).

(a) **Change in average surface temperature (1986–2005 to 2081–2100)**



(b) **Change in average precipitation (1986–2005 to 2081–2100)**

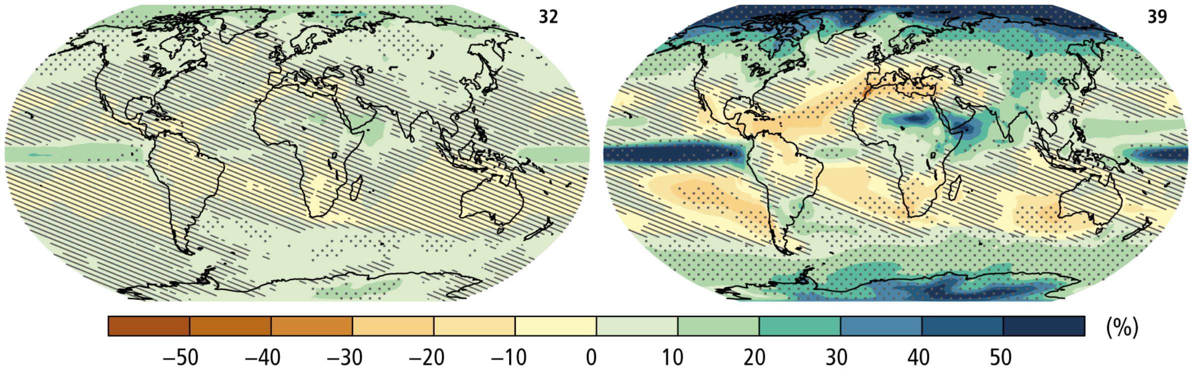


Fig. 2: Global climate changes: temperatures and precipitation.

Global climate changes for the variables temperatures and precipitation by 2100 for a low emission/mitigation scenario (left) and high emission scenario (right) compared to the norm period 1986-2005 (IPCC, 2014a).

2.1.3. Climate change impacts

Climate change impacts are changes in human and natural systems caused by changes in climate. It depends on the system if it is possible to detect impacts. Some systems are more sensitive to outside influences than others and if a large number of factors influence the system, it is difficult to discern the driving influence. Generally speaking, it is easier to observe influences on natural systems namely physical or biological systems. The confidence, if changes in human and managed systems are indeed climate impacts, is generally lower. This is partly due to the dynamic nature of human systems. Also, unique and threatened systems are most particularly vulnerable impacts, as their potential for self-adaptation is low (Cramer et al., 2014, IPCC, 2014a). See also *2.2* Climate change impact detection and attribution*.*

How sensitive an environment reacts to climate change is also dependent on the regional climatic zone as well as the system itself. High-elevation regions for example are vulnerable to changes, as they comprise very diverse ecosystems and are prone to amplified changes. Many biological processes are elevation-dependent due to stratified vegetation and these condensed small-scale climate zones. The mountainous landscape is especially exposed to natural hazards like mass movements and floods. Therefore, such sensitive regions are more vulnerable to climate change impacts (Diaz et al., 2003).

The process of assimilating to climate change impacts is called adaptation. It comprises a set of coping mechanisms of a system to manage changing climate circumstances. Both natural and human systems have an innate ability to cope with changes, however, not all systems adapt at the same pace. The faster and easier a system is able to respond and handle changes, the greater their adaptive capacity. Of course it is also more difficult for systems to adapt if the changes are bigger. If the adaptive capacity of a system is low or the changes occur rapidly, the system has a greater vulnerability (Smit and Wandel, 2006).

Mitigation on the other hand tries to lessen risks through climate change by human action. At the moment this particularly involves reducing greenhouse gases by minimising emissions and increasing sinks (Blanco et al., 2015).

2.1.4. Global and local climate scale

Global trends are calculated from a range of local data series and impacts have been linked to the climate in multiple locations. They represent the average of the local or regional data, with the advantage that small-scale systemic influences average out. Local climate trends and impacts are trickier to detect and attribute, as many non-climatic drivers have to be regarded as significant influences. They are potentially large contributors to changes in climatic signals or could pose as alternative drivers for climate-related impacts. It is also easy to overlook small persistent climate-related changes, which long-term could have large impacts if short-term non-climatic changes overpower their signal is overpowered by. This is often the case if other anthropogenic influences are at work. Ecosystems for example, can be heavily influenced by land-use changes, to a degree where it is difficult to detect a smaller climatic driver. The less disturbed a system is, the easier it is to detect and attribute trends and impacts (Parmesan and Yohe, 2003). The attribution of an impact to climate change on a global level, like for instance melt of glacier ice, can therefore not automatically be applied to every local case. It might be possible that the changes of a specific glacier are more dependent on other, non-climatic drivers (Hansen et al., 2015).

This thesis operates on a local to very local impact scale through case studies. The chapter 2.3.3 Expected climate impacts in Central Switzerland discusses the specific local climate change and observed impacts for the study area of Central Switzerland and the chapter 3.1 Attribution framework elaborates on the identification of a local climate trend*.*

2.1.5. Excursus 1: International climate change institutions and agreements

The large political and scientific challenges in climate change necessitate unbiased reliable assessments of the current research and recommendations for policy makers on how to proceed. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was founded as an international institution centred on climate change research. The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) launched the Panel with endorsement of the UN General Assembly. Since then, five Assessment Reports were published as a collaboration of hundreds of international climate scientists with the latest Report in 2014. These Reports aimed to be all-encompassing assessments of the scientific knowledge on current and future development of the climate. This also includes looking at its impacts on environmental and social systems as well as potential adaptation and mitigation. The Assessment Reports include a synthesis report and a summary for international policy makers to provide a basis for the governments on where to focus adaptation and mitigation measures (IPCC, 2017).

Shortly after the IPCC, the United Nations Framework Convention on Climate Change (UNFCCC) came into action in 1994, with currently 197 member countries. It was initiated after the Rio Convention in 1992 alongside the UN Convention on Biological Diversity and the Convention to Combat Desertification. Its ultimate goal is to stabilise greenhouse gas concentrations in the atmosphere and setting national targets to reduced greenhouse gas emissions are used to master this task. The Kyoto Protocol first set emission reduction targets in 1997, particularly on developed countries, which mainly contributed to past greenhouse gas emissions due to the industrialisation. All participating countries were first bound to adhere to emission reductions in the Paris Agreement of 2015. The aim of the agreement is limiting global air temperature rise to a maximum of 1.5°C compared to the pre-industrial level. Additional to the emission reductions it was agreed upon to amplify financial support of low-greenhouse gas development and to improve climate change adaptation conditions. Each participating country is obligated to submit reasonable emission targets and report on their emissions (UNFCCC, 2014).

2.1.6. Excursus 2: Swiss and European climate change adaptation and mitigation efforts

Switzerland as well as the European Union (EU) approved the terms of the Paris Agreement as of 2016 and are therefore legally obligated to reduce their greenhouse gas emissions (UNFCCC, 2014). The Federal Environmental Bureau (Bundesamt für Umwelt, BAFU) has published their climate change adaptation strategy in two parts (BAFU, 2012a, BAFU, 2014, BAFU, 2015). Many different changes challenge the adaptation, as Switzerland is a country with a very homogenous landscape. The potential for dry spells, prolonged summer heat in cities and decreasing water and air quality through climatic trends are alarming. Also increased risks triggered by extreme events such as flooding and slope instability are a concern. But apart from direct physical impacts that have to be adapted to another, focus is set on better monitoring, research and education of the public (BAFU, 2012a). According to the federal law of CO_2-emission a long-term mitigation target is to contribute to the global goal of less than 2° Celsius temperature rise. In the short-term this means a reduction of greenhouse gas emission of 20% until 2020 compared to the 1990 level (Schweizerische Eidgenossenschaft, 2012).

On a more continental level, the European Union, which all the other European Alpine Countries belong to (apart from Lichtenstein), set slightly less specific goals than Switzerland as a frame for its member states. By 2017 all member states have to submit an adaptation strategy. These national approaches are supposed to follow the EU adaptation strategy adopted in 2013, which focuses on water use efficiency, supporting migration of species in ecosystems and adapting infrastructure to extreme weather events. Their short-term mitigation goals are a cut of 20% in greenhouse gas emissions (compared to 1990) by 2020 as well, while 20% of the energy has to be renewable and energy efficiency should increase by 20% (European Commission, 2017).

Now, while for example improving water use efficiency is an important overall goal for Europe, for many alpine communities sufficient water resources rarely pose a problem. In contrast, they may struggle with other changes in the mountainous environment like permafrost thawing causing hang instabilities (Diaz et al., 2003). It is therefore detrimental to keep the more local environment and their specific adaptation needs in mind when drawing up adaptation strategies.

Today many local governments have plans for adaptation and mitigation, but there is often a struggle to put them into action. This is either due to vague planning or insufficient support from the public or higher government. There is also a certain disconnect between local and higher level governments. Baker et al. (2012) mention in particular the importance of communication between local and higher level government and the inclusion of local communities. And Laukkonen et al. (2009) discuss the importance of a methodology and decision-making tool for local governments. A more unified approach could facilitate the process of setting priorities.

Further, local climate impact studies, instead of projections only, can also contribute to the understanding of the individual needs of a region and where to focus adaptation. A better understanding of local impacts and how to detect and attribute them is therefore important.

2.2. Climate change impact detection and attribution

Detection and attribution of observed impacts is the main focus of this study. *Detection* refers to the identification of a change in the climate. The change in question can be a long-term trend in average condition or variability of any climate signal. *Impact detection* is the identification of a change in a human or natural system where a climate change is present. A change is detected if the system is in a state different from its baseline behaviour where climate change is not present (Stone et al., 2013).

Impact attribution links detected impacts to a climatic driver by considering the magnitude of contribution of the climate to the impact. It determines how important the contribution of climate change was compared with non-climatic drivers. Consequently, attribution requires knowledge about the contribution of all other relevant drivers in the system. The magnitude of attribution can be given quantitatively or qualitatively. Usually the confidence of the attribution is stated additionally. It states how certain the assessment is of the contribution of the drivers (Cramer et al., 2014). This again is not the same as the attribution of climatic changes to anthropogenic forcing, which is a different procedure altogether. It relates a detected change in climate to forcing through anthropogenic greenhouse gas emissions. Attribution to anthropogenic forcing has been an important research topic since the concern about climate change first came up. Especially since it is also a politically controversial subject who or what is responsible for climate change (Hegerl and Zwiers, 2011). For the purpose of this thesis, detection and attribution refers to *impact detection* and *impact attribution* if not otherwise specified.

The term climate change attribution is quite new, as the Web of Science published 75% of all publications titled ‘attribution’ after 2010. The term detection has been used since the 1990s, but around 60% of the publications using ‘detection’ in its title were published since 2010 (the percentage may vary slightly, as the term is used in multiple contexts and not all of them could be excluded) (Web of Science, 2017). Hence, the research area itself is quite new and is probably going to attract more attention in the upcoming years.

This chapter discusses detection and attribution of impacts in current research. It first introduces attributed impacts of globally affected systems. Secondly, it presents methods used in typical attribution approaches and especially for extreme event attribution. Thirdly, the chapter elaborates on challenges posed by local impact attribution as well as some selected methods to address these challenges. Finally, it outlines the research questions of this thesis.

2.2.1. Impacted systems

Firstly, what climate change impacts are present up until today and what are their drivers? Fig. 3 shows a summary of impacts attributed to climate change on a continental level. A changing climate strongly affects physical, biological and human systems. This map depicts detected impacts on theses systems for all continents, how large the contribution of climate change is and the confidence, with which this contribution is found. Most detected impacts belong to the physical or biological systems and less to the human or managed systems. In temperate regions like Europe for instance, the prevalent detectable impacts are impacts on the cryosphere, on wildfires and marine ecosystems. Especially the cryosphere and wildfires are closely linked to increasing temperatures and dry conditions. While in tropical to subtropical regions the impacts are primarily in the hydrological system and terrestrial ecosystems (IPCC, 2014a).

Another already detectable indirect impact is the psychological impact. This thesis does not venture into the attribution of these impacts further, but they should be acknowledged as it also adds to the relevance of research on the subject (Doherty and Clayton, 2011). As research also predicts over 200 million refugees from climate change impacts by 2050, their relocation may also cause cultural disconnect and severe psychological illnesses (Doherty and Clayton, 2011). With early impact detection, better adaptation measures could be planned and some of these secondary impacts prevented. Also awareness of what is and is not happening, and the existence of concrete plans to adaptation can help people gain confidence in a secure future.

The main drivers of the impacts are primary climate variables like air temperature and precipitation. In current research, increasing temperature is the main driver for a large amount of successfully detected impacts. Other climatic changes like increasing or decreasing precipitation trends are also expected to influence the systems, however, detection seems to be less straightforward (Stone et al., 2013). This is largely because temperatures follow a similar trend while precipitation changes are more diverse (see 2.1 Global climate change).

The confidence statement provides an assessment of the certainty with which the impact is attributed. It is noticeable that, even at the quite large continental level, where a lot of research is present, confidence in attribution is not always high. The confidence in the attribution is generally lower if the contribution of the climate driver is minor. Also an impact can be confidently detected in one region with a major contribution of climate change while in an other region the same impact cannot be attributed confidently (IPCC, 2014a). Only because a climate change influences a process in one area of the world, it does not inevitably have the same effect on another region. Similarly, an attributed impact in a region is not necessarily observable in every system of this region. For local level assessments this means, not every observed local impact can be attributed just because on a larger scale this impact was attributed confidently (Hansen et al., 2015).

2.2.2. General detection and attribution methods

In successful attribution assessments it is important to use suitable methods. For large-scale impact attribution there are a few methods used regularly. Some of these methods are presented here to illustrate what is possible in attribution already.

Global analyses usually consist of meta-analyses of more local publications. The continental scale impacts in Fig. 3 are attributed based on a range of scientific publications of the individual regions. The more evidence there is for an impact attribution in a region, the higher the confidence. Parmesan and Yohe (2003) for instance used attribution confidence rates of a range of biological systems to calculate a global fingerprint of climate change impacts on ecosystems. As a result they could draw the conclusion that there is a distinct influence of climate change on the overall behaviours of the systems, without there being the highest confidence in attribution for a single species. This method is best suited for large-scale assessments and cannot be used on local cases (Parmesan and Yohe, 2003).

This global fingerprint should not be confused with optimal fingerprinting. Optimal fingerprinting is the most widely used statistical method for detection of climate signals in recent years (Ribes et al., 2013). It deals with the problem that a trend in climate signals is not easily identified due to the variability of a climate. Instead of using just one climate signal, it looks at a range of signals. The weighted combination of these signals, which produces the best distinguishable signal in the noise of variability, is chosen as a fingerprint. Optimal fingerprinting de-

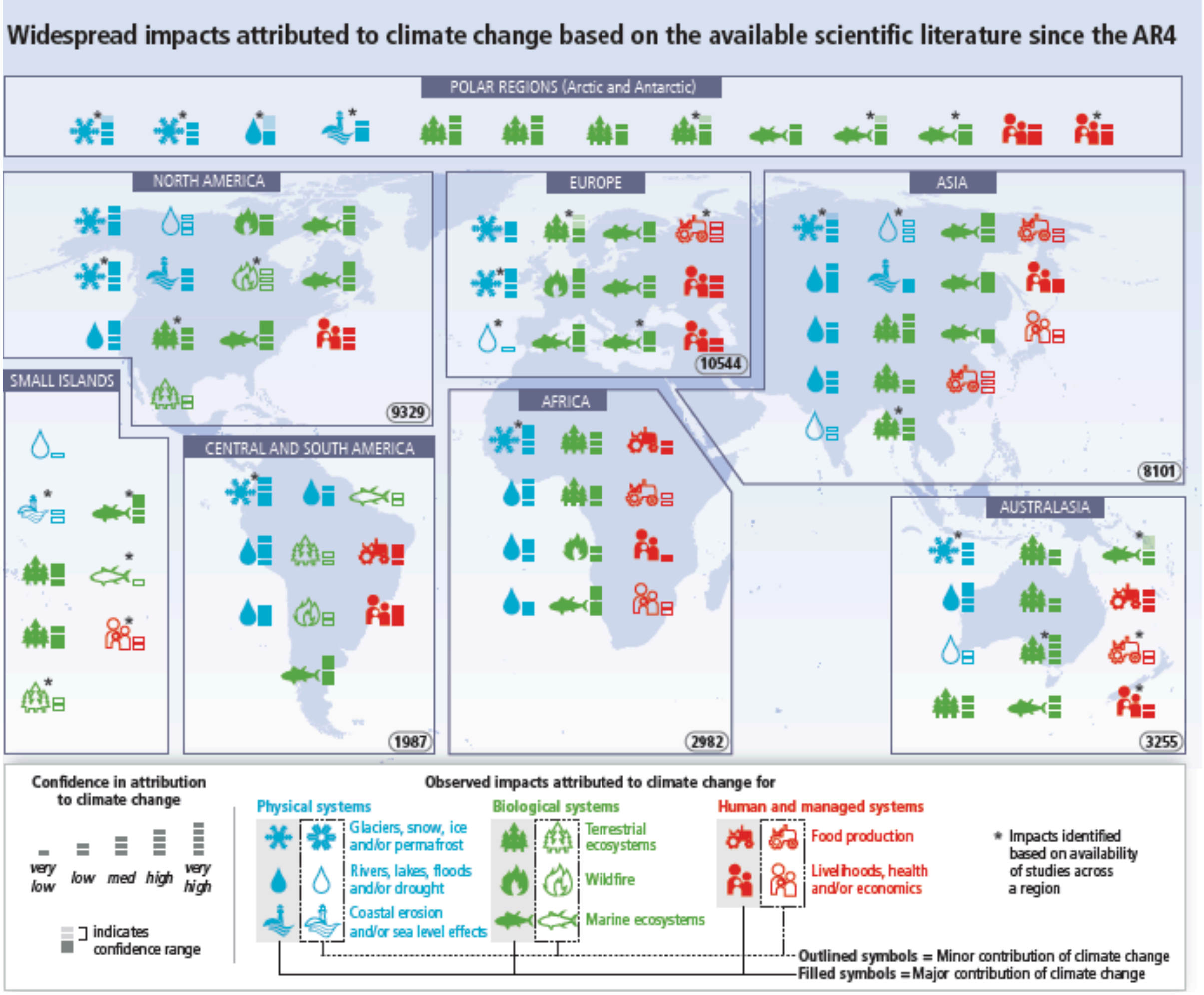


Fig. 3: Attributed impacts on a continental level through meta-analysis.

(IPCC, 2014a)

pends on a range of quantitative signal data and the existence of a natural variability covariance matrix. This dependency on quantitative data can pose problems in a local context, where data is scarcer and data accuracy may suffer (Hasselmann, 1993).

While Hasselmann first mentioned this method in 1979, it has gained in popularity in the last 20 years and is being discussed and adapted to emerging problems (Hegerl et al., 1997, Allen and Stott, 2003, Ribes et al., 2013, Hannart et al., 2014). Hannart et al. (2014) for instance proposed an inference optimal fingerprint model, which addresses the problem of multiple uncertainties fed into a model. Addressing this problem is important as measurement inconsistencies alone can lead to great uncertainties, especially for early measurement series in the late 19th and early 20th century. For surface temperatures there can be inconsistency in measurement setup, change in equipment like thermometers or urbanisation effects around the measurement site, amongst many other error sources. On local assessments such inconsistencies in a dataset often have serious consequences, because less data is available (Brohan et al., 2006).

2.2.3. Extreme weather events

If an impact is caused by extreme events instead of average conditions, attribution methods need adjustments. Both how climate change has influenced the occurrence of extreme weather events and the attribution of resulting impacts have inspired a lot of research recently (Cheng et al., 2012, Angélil et al., 2014, National Academies, 2016). An event is extreme if it is intense and happens infrequently in the region of reference. Extreme weather is spatially limited and often affects local to regional spatial scales. Although it is not an impact itself, it is usually a primary cause of many impacts. Heat waves for instance are already linked to fatalities in the affected communities. Also, large precipitation events can cause natural disasters e.g. flooding, increased occurrence of avalanches or mass movements like debris flows (Easterling et al., 2000, Otto, 2015). The attribution of these events to climate change therefore also attributes its impacts.

The detection of a trend of extreme events is difficult as they are by definition a rare occurrence. Event attribution is possible either if a trend in extreme event frequency or a trend in a related climate variable is found. In the second case, the event has to be linked to a climate variable and a trend has to be found in the variable. This is the more likely approach as the observations often recorded only recent history and it is impossible to estimate the frequency. However, linking the event to a climate variable requires an understanding of the system processes (National Academies, 2016).

Probabilistic event attribution (PEA) is a quite new method for attribution of extreme weather events to climate change. For the attribution, several climate models under the premise of either a (through anthropogenic influence) changing climate or a non-influenced climate are run. The outcome of the models is compared with the observed impact and this assesses the probability of each of the drivers. The higher the probability of the changing climate and the lower the probability of the climate without influence, the higher the confidence in the attribution to the investigated driver (Massey et al., 2015). The more possible variations of the climate are run, the better the estimation. To achieve a large amount of model runs, Massey et al. (2015) used citizen science, where volunteers let models run at home as the required computing power is immense. Mera et al. (2015) applied it to attribute heat waves in California and suggest it can be used as a tool to help distribute adaptation cost to the responsible parties.

Many studies focus on the prediction of extreme event impacts. The methods used in extreme weather attribution are therefore mostly focussed on the modelling scenarios. For local level events Tabari et al. (2016) used statistical downscaling to achieve high-resolution climate models as a base for the analysis of precipitation extremes. They found that higher spatial resolution in models improves precipitation modelling with high-temporal resolution especially. However, the results need careful analysis, as local models may overestimate the signals when compared with measurements (Tabari et al., 2016).

Even though this research topic has gained a lot of attention in research lately, event attribution is very difficult, especially if the event has a small extent. Events best suited for attribution are extreme heat or cold events. Droughts and extreme rainfall are less likely, as it is more difficult to model and underlying processes are less understood. Severe convective storms and wildfires are least likely to be attributed (National Academies, 2016).

2.2.4. Local impact detection and attribution

While attribution on a global to regional scale is aided by various methods, local-scale attribution is more difficult. On a local level impacts similar to impacts in Fig. 3 cannot be attributed to climate change as confidently, as often more detailed information is necessary than is available (Hewitson and Crane, 1996). But investigating what actually happens on a local level is important as it can improve adaptation plans. If past impacts have resulted in loss and damage, questions about financial retribution and policy adaptation also arise. Local communities and governments could be benefit directly from knowledge about causation of impacts (Huggel et al., 2015).

The observation of an impact on the local scale is more difficult than on a larger-scale level. In a well-observed system, some impacts can be observed through systemic measurement and expert reports, for instance through a natural disaster registry. Though, many systems are not as well observed.

In juxtaposition to observations of impacts through scientific reports, climate observations by locals could also help identify impacts. The use of local laymen knowledge is a method rarely used in natural sciences yet, especially in regions with well-established measurement nets. Objectively gathered data with the use of calibrated equipment is preferred over human memories as they are prone to inaccuracies. As a consequence, many researchers underestimate the potential of such local knowledge. Measurement network grids are often too broad to catch changes happening on local scales. The human mind may not be able to record individual climate signals as accurately as some equipment, however, it has the ability to see the changes in processes and environments as a whole. Especially if locals are dependent on natural resources, changes in the availability may be recognised very quickly. The approach has been used mainly in local studies in remote areas where measurement observations are unavailable (Marin, 2010). Marin (2010) used such an approach with a self-subsistent herder community in rural Mongolia, where findings of local knowledge concurred with climatic observations. Moreover, if an impact threatened their livelihood, the local knowledge was more detailed than any other source (Marin, 2010).

Guyot et al. (2006) reported similar findings for two Aboriginal communities in Australia. This data gathering approach is, however, limited to areas where people are living in direct dependency from the land or ocean. Savo et al. (2016) also states that observations by locals can help with adaptation endeavours when impact were detected through measurement observations, as people can point out vulnerabilities in the system they live in.

Another hurdle is the identification of the climate trend, to which the impact has to be linked, for an attribution. Furthermore, an identification of baseline behaviour without climate influence is needed. Apart from direct analysis of local measurement series, downscaling is a widespread method to relate small-scale climate to larger scale climate drivers, for instance through the use of General Circulation Models (GCM). While the practice of scaling data with a spatial context to a better resolution level has been used from the 1960s onwards, the method gained importance in the context of climate change and was developed further. There it aims at linking global climate trends to local or regional climate trends (Hewitson and Crane, 1996). It is a key method predominantly used for climate projections on a regional scale. But it could be used for assessing the climate trends for observed impacts as well (Iizumi et al., 2012).

The two main approaches to model climate at a higher spatial resolution are process based techniques and empirical techniques. Empirical techniques model climate changes based on the premise that the greater scale largely determines the local-scale parameter. A large scale climate pattern would therefore determine the general behaviour on a local scale (Hewitson and Crane, 1996). The implementation of the empirical model can either be statistical or dynamic, with the former being easier to compute but largely dependent on reliable long-term variables. The latter performs better in estimating variability of the climate variable but is restricted due to a limited number of accessible scenarios (Fowler et al., 2007). Statistical downscaling for example has been used to examine past and possible future local precipitation patterns (Chu and Yu, 2010). However, in context with projected impacts all these basic models harbour many uncertainties. Recently, using a set of multi-downscaling models has been proposed as a more reliable approach to impact assessment (Iizumi et al., 2012). For local climate trends this analysis requires specific knowledge about the relationship of the local to the regional and global climate and an abundance of climatic data and parameters, which in many cases is not available. Especially for the analysis of past local climate trends, this approach is not feasible.

While many authors speak find climate impact attribution important (Baker et al., 2012, Cheng et al., 2012) not everyone agrees that local attribution is useful in all cases. Parmesan et al. (2013) argue that efforts to attribute impacts in small ecological systems or for single species are not efficient. They put forward the argument that global meta-analysis is already quite advanced and produces the highest confidence in attribution. Likewise, they point out that there is extensive regional scaled research, where attribution was successful. More local information would not provide more valuable information than larger-scale attribution already has. Instead, the attitude that closer inspection of the system is necessary, before determining if it is impacted by climate change, could delay adaptation efforts. Especially, as adaptation plans have already been designed for many such systems (Parmesan et al., 2013).

2.3. Study area and data availability

The case studies used in this thesis are situated in Central Switzerland (German: *Zentralschweiz* or *Innerschweiz*), which encompasses several cantons on the northern slope of the Alps into the Swiss midlands. Due to its scenic lakes, Alps and rich history, the region around Vierwaldstättersee (*Lake Lucerne*) is a well-known tourist destination (centralswitzerland.ch, 2017). Strictly speaking, one case is not located within what is commonly known as Central Switzerland, but at its border at the eastern tip of the Canton of Valais at the Rhone Glacier. However, the usual use of Central Switzerland is a administrative rather than a landscape-based distinction of the region (Glauser, 2015). So the term is used more loosely here and includes the Furka pass region. Following are a short description of each case and the data used to assess them. Furthermore, the chapter summarises the regional context of Central Switzerland's landscape, climate and the general data availability.

The case studies presented here were chosen because of several reasons. Their situation in Central Switzerland is advantageous because the high density of available climate data in Switzerland provides an optimal basis to assess local observations (MeteoSchweiz, 2017, WSL, 2015). Another important criterion is that they are all of local extent. And of course there has to be a reason to suspect a climate influence on the processes behind the impact.

Rhone Glacier: The first case at the Rhone Glacier investigates glacier retreat over the last 150 years and how it is related to climate variables. The observed impact data used are glacial mass and length changes while the climate variables are summer air temperature and winter precipitation. With the ice cave in the glacier as a famous touristic attraction, mass loss of the glacier can lead to less tourists as well as significant changes in the local ecosystems.

Flüelen fish farm: The second case is located in Flüelen in the Canton of Uri at the eastern lakeboard of the Urnersee (*Lake Uri*, part of *Lake Lucerne*). The observed impact is increasing groundwater temperature at a fish farm where fish eggs are hatched. This leads to challenges on the fish farm and warmer water in the region could also impact the wild fish. The assessment uses groundwater temperatures and Reuss river temperatures from stations in Flüelen to investigate the observed impact and air temperature data from Altdorf for climate data.

Sittlisalp water shortage: The third case is located on Sittlisalp, an alp in a side valley of the Schächen. In 2003 and 2015, two hot and dry years, water shortages in small streams were observed at this site, which impacted the local power plant production. To assess the local water shortage and for climate trends precipitation and temperature data from Altdorf are used.

Haggenegg water shortage: The fourth case is situated at the Haggenegg pass in the Canton of Schwyz. Again there were water shortages observed in 2003 and 2015 affecting the drinking water supply of a local business. Here precipitation data from Erlenbach in the Alpthal and Sattel-Aegeri as well as temperature data from Erlenbach and Einsiedeln are used for the drought assessment.

Fig. 4 depicts a map of the study area with the case sites and the measurement stations of climate and climate-related variables used in the region.. For each case, data from the most suitable stations were chosen, depending on the length of measurement, variables measured and distance to the case site. There are additional stations in the region, but as they are not relevant to the cases, the map depicts only the stations used for the cases.

2.3.1. Landscape

The landscape of the region is quite divers, as it spans over alpine, pre-alpine and flatland areas. Two cases are situated in the Canton of Uri, which is, like the Rhone Glacier, located in the alpine mountain range but also encompasses the lower elevation region around the Urnersee (Lake of Uri). The Urnersee is the most upstream part of the Vierwaldstättersee (Lake Lucerne) and is mostly fed by glacier melt and high alpine precipitation through the river Reuss. The last case is in the pre-alpine Canton of Schwyz, which is located on the northern slope of the alpine mountain range, sharing a border with the Canton of Uri in the south. Schwyz encompasses still quite high-elevation regions, but the landscape is dominated by lower hills and mountains (Swisstopo, 2017).

Central Switzerland and the rest of the European Alps span large elevation differences in the otherwise temperate mid-latitudes of the Northern Hemisphere. Many different systems evolved close to each other because of the elevation differences. These systems are especially vulnerable to changes as they have little room to adapt to influences (Diaz et al., 2003). Geomorphologically, the valleys and other remnants like moraines, indicate that glacier advances from the latest ice age largely formed the landscape in the whole region. Today, in the absence of major glaciers in the region, fluvial and denudative mass movement processes dominate the landscape genesis (Swisstopo, 2017).

2.3.2. Climate in Central Switzerland

Switzerland has a multitude of climatic regions as a result of the Alps running through from west to east. A wet temperate climate dominates with westerly winds bringing moisture from the Atlantic Ocean and the Mediterranean Sea (Burri, 2012).

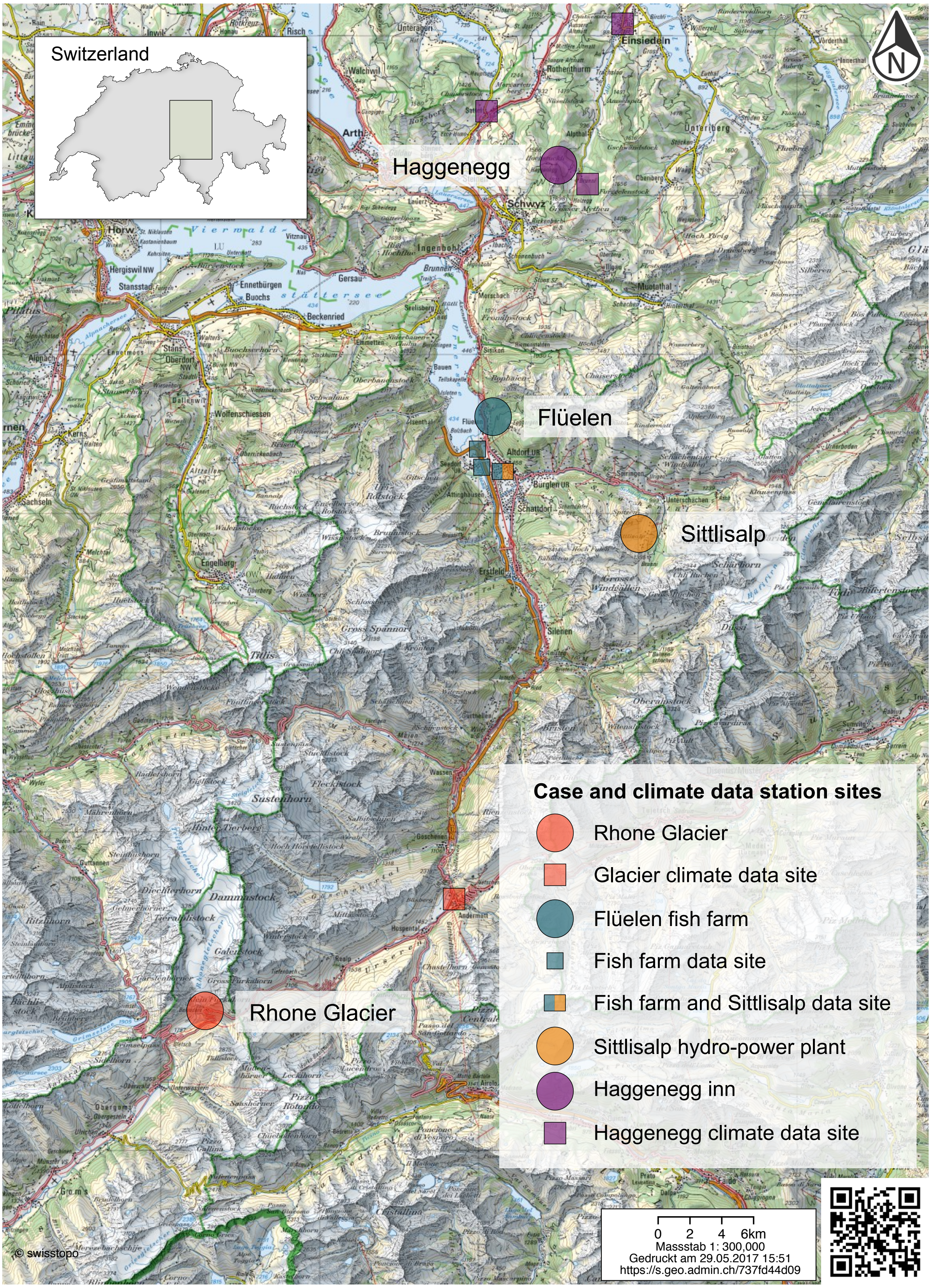


Fig. 4: Map of Central Switzerland with case study sites and measurement data sites.

(Swisstopo, 2017, d-maps.com, 2017)

The Canton of Schwyz has the wet climate of the pre-alps with 1000 to 1500mm precipitation per year. The Canton of Uri and the high-elevation region of the Valais have the very wet climate of the Alps that is characterised by 1500 up to 4000mm precipitation per year. The temperature regime ranges from moderate to high alpine (Burri, 2012). Hence, the temperature in the region is dependent mostly on the elevation and the exposition. Generally speaking, the temperature declines 0.5°C for every 100m elevation and is warmer on southern and colder on northern facing mountainsides (Burri, 2012). The average temperature variation around the year is about 16°C. So the mean temperature at 1500m a.s.l., for instance, is at -5°C in January and 11°C in July. The same range was measured in the northern flatlands, but with around 6°C warmer temperatures (MeteoSchweiz, 2014). The individual case study analyses include more in-depth descriptions of the local climates.

2.3.3. Expected climate impacts in Central Switzerland

The CH2014 (2014) initiative aimed to summarise projected impacts modelled with the Swiss Climate Change Scenarios CH2011. It includes impacts in a range of systems modelled with three different scenarios for short-, medium- and long-term. Projections of a non-intervention scenarios see a quasi-complete loss of glacial ice by 2085. Meanwhile, groundwater temperatures are projected to increase, especially when fed by stream water. In similar projections the runoff regimes change from dominated by snow input to rain controlled, which decreases summer runoff and increases winter runoff. In some cases this may lead to a lack of water resources in summer. Of course the report records many more impacts on health, biodiversity, agriculture, which could be assessed on a local level in the future (CH2014, 2014).

2.3.4. Data availability

Switzerland has a long history of climate data observations, which provides long measurement series for a range of climate variables (MeteoSchweiz, 2017). These long-term observations are an important base for in-depth climate analyses. Climate trends modelled from short time series are sensitive to the natural decadal variability in the climate signals. Cyclic variability through El Niño for example can influence a short-term trend strongly. If a longer time frame is used, these short-term trends likely filter out, however, multi-decadal natural variability cannot automatically be discounted (IPCC, 2014a). The long measurement series fit therefore well, however, climate varies quite strongly in Switzerland, so a measurement does not necessarily represent all locations close by.

There is a range of measurement networks across Switzerland. Most remarkable for climate data is the National Basic Climatological Network (Swiss NBCN) led by MeteoSchweiz (2017), which records five climatic parameters including air temperature and precipitation in 29 ground-stations since 1864. In Central Switzerland there is a NBCN station in Altdorf, UR and another in Andermatt, UR. Additionally, SwissMetNet provides newer automatic measurements for a range of climatic parameters, with a total of 160 monitoring sites (MeteoSchweiz, 2017). The Swiss Federal Office for the Environment (Bundesamt für Umwelt – BAFU) also systematically gathers topographic data through Swisstopo (2017), a range of hydrological data and phenology (BAFU, 2017b). Apart from the national monitoring, many Cantons have their own measurement sites as well as research institutes like the WSL, SLF, EAWAG (WSL, 2015, SLF, 2017, EAWAG, 2017, Kanton Schwyz, 2017).

For attribution it is essential to use the most suitable data for the local setting and process at hand. The extraordinary amount of data available in Switzerland is therefore a great basis for attribution investigations and the case assessments presented here make use of this advantage. Each of the case studies delves more into the specific data and stations used for attribution.

3. Methods

The first research goal in this thesis is centred on evaluating and adapting an attribution approach for local level impact cases to climate change. The methods used in this thesis should provide an optimal basis for a climate change attribution assessment of local cases.

As it is important for local case studies to profit from all data sources possible, the methods to gather and analyse data need to vary to encompass the whole data range. While quantitative data is desirable, qualitative data can be very valuable for the assessment. The main data sources included in this thesis are local knowledge, climatic and glaciological time series and geographical data archives. The local knowledge is attained and analysed through interviews and field investigations. Different digital and literature sources provide the time series and archive data and are assessed with statistical and analytical methods.

The methods are applied to the gathered data according to an integral method framework, which was adapted to local case studies. The framework guides through the attribution assessment in a series of steps. The aim of the framework is to provide a unified approach to attribution for the researcher (See 3.1 Attribution framework).

As in most cases it would be difficult to distinguish between anthropogenic and non-anthropogenic climate change, the cases are evaluated for all climate change inputs. The assessment does not distinguish between the two, except if there is strong evidence of superior fit of one or the other.

3.1. Attribution framework

As the goal is to see if the method framework is suitable for attribution of local cases, it has to be tailored as well as possible to the limited spatial extent. The spatial extent brings many challenges with it, including, but not limited to, fragmented and inadequate data availability. For this reason, the approach to the individual cases and how the data is handled has to be flexible. Whilst the methods depend on the nature of the impact, the data available dictates the methods just as much. Therefore the methods used in the individual case studies may vary strongly from one another.

The framework organises these methods in a series of steps that lead to the attribution assessment. The framework should fit all possible cases, as it does not dictate the methods used, but focuses on unifying the conceptualisation of the cases.

The framework was tailored to a regional to local level by Hansen et al. (2015) and outlines a general design of experiment approach with testing of hypotheses. It follows along the lines of comparative experiments, which tests if two possible influences on an object of interest produce outcomes significantly different from one another. The individual steps of the experimental design are tailored to the concepts of impact detection and attribution. This experimental design is a staple in modern-day (statistical) analysis in many research areas and is seen as a robust approach to more unbiased testing (Montgomery, 2001). Hence, the general setup behind the framework is established in climate science already, but as far as attribution guides for local impacts go, it is unique. In this thesis the scope of the cases is even more spatially limited and transcends to a local to very local level. Therefore slight adaptations to the Hansen approach were made.

To see if the attribution assessments is applicable to the case studies, two main prerequisites have to be met: Firstly, the observed impact has to have a relation to climate change. This relation can be established theoretically in literature or through observations in empirical studies.

Secondly, the case has to be of local extent. The definition of local is somewhat fuzzy, as locality is often perceived as an administrative extent rather than the extent of physical processes. Here, local is defined as the smallest extent of a geographical feature or process. In glaciology, for instance, this could refer to a single glacier or a cluster of glaciers on a single mountain.

If the prerequisites are met the attribution framework can be applied to the case. It consists of five steps that should be executed one after another. For better understanding, short descriptions of an example case illustrate the steps. The impact is an increase in groundwater temperature in an urban area next to a large lake and is loosely based on the premise of the Flüelen fish farm case (see 5. Flüelen fish farm).

3.1.1. First step: Hypothesis formulation

Firstly, for each case a hypothesis and one or more alternate hypotheses are formulated based on the understanding of the system. A hypothesis can be based on observations of impacts in similar systems. It should not be solely motivated by an observed change in climate or the data used in the analysis, as this produces a selection bias. But rather, empirical or theoretical findings in similar systems should support the hypothesis (Hansen et al., 2015).

To adapt it to a very local level, the hypotheses have to be formulated more broadly. This sounds counterintuitive, as we go onto a more spatially limited scale, but are less specific with the hypothesis. Yet the researcher has to keep in mind, that the more spatially limited a case, the more otherwise negligible, small-scale influences have to be accounted for. If the hypothesis concentrates on one specific influence, other important drivers may be forgotten or the research may be biased towards it.

Example: Through understanding of the local groundwater system, the hypothesis is formulated that the increase in groundwater temperature primarily followed an increase in air temperature, heating up the local water bodies.

3.1.2. Second step: Observation of the climate trend

A climate trend is a long-term change (decadal or longer) of a climate signal. To detect a trend, the change, in the mean or the variability for instance, has to be significant in comparison to short-term (annual to decadal) variability (Hansen et al., 2015). Stott et al. (2010) argue that in a non-statuary climate, models of the current climate are needed to understand occurring impacts. In this case the climate cannot only be evaluated using the mean of the commonly used 30 year time frame, but would have to be susceptible to changes on a smaller temporal scale (Stott et al., 2010).

A local climate is influenced directly by local circumstances like turbulence and human behaviour such as land use change, and therefore a local trend can vary strongly from the regional or global climate trend. Therefore a trend may appear stronger on a local scale than a broader scale or may even be reversed. Therefore, it is also more difficult to differentiate between anthropogenic and natural climate change. Even local trends that are compatible with a larger scale climate trend, which could be attributed to anthropogenic climate change, cannot be seamlessly attributed to anthropogenic forcing (Hansen et al., 2015). Thus the case studies do not separate between natural and anthropogenic climate change.

A factor that should not be forgotten is that different local systems react with varying degrees of strength to a climate change, for instance, if ecosystems are involved, the state of disturbance of the system before climate change might be important. Thus, already disturbed ecosystems can react more sensitively to climate changes (Kroel-Dulay et al., 2015).

Something, which has to be kept in mind with local cases, is that often it is not sufficient to focus on the primary climate variable and evaluate whether there is a trend. If other climate signals are suspected to have an influence they should be analysed as well unless there is reasonable cause to neglect them. The term climatic drivers encompasses all influencing climate variables.

An additional intermediary step before the climate trend analysis is the impact analysis. This step connects the local impact to the local climate variables. Local climate trend can vary from the regional climate and usually primarily climate-driven processes can have many further drivers on a local level. Therefore, linking of the impact to climate provides additional assurance that the local climate really influences the local processes to a certain extent. It is not necessary to apply this step according to the attribution framework, but is added here as an adaptation to the local case studies.

Example: For the impact analysis, a linear regression model establishes the connection between the groundwater temperature and the air temperature. It shows that the air temperature predicts part of the variance of the groundwater temperature. The trend analysis investigates both the trend in air and groundwater temperature and finds a comparable significant increase in temperature in both datasets.

3.1.3. Third step: Baseline behaviour identification

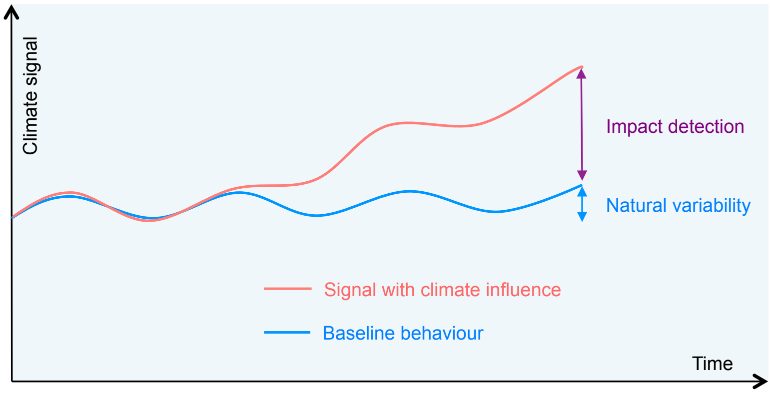
The baseline behaviour is the development of a system if there was a stable climate. This is not to be confused with the natural baseline – the baseline behaviour forced through natural changes – which differentiates between anthropogenic and natural forcing (IPCC, 2014a). Instead it considers all non-climatic drivers, including human and natural processes, which influence the impact but not via the climate. This step is a precursor to impact detection together with the trend detection. As stated in 2.2 Climate change impact detection and attribution, the process of detection mandates the identification of a baseline (Stone et al., 2013).

The identification of the behaviour of a local system in a meaningful way is very challenging because of small-scale influences, whose behaviour most likely has not been recorded. The assumption that the system would be stable (not changing from the starting point of the observation of the impact), if there are no changing influences detectable, is used as a premise in most cases in this thesis. However, care has to be taken with attribution analysis based on this premise, as it harbours uncertainty. The uncertainty stems on the one hand from the lack of knowledge of a system before the start of observation of the impact. It could be that the system has already been thrown off balance before the onset of a detected trend. On the other hand, it is likely that not all possible drivers of the baseline behaviour can be accounted for.

Example: A context analysis establishes if the baseline for the impact in question changed due to non-climatic factors. Here, a geothermal cooling system was installed in the vicinity of the impact site potentially heating up the groundwater. However, the system was installed and taken out of use before the impact observation. As no other influencing factors are present, it can be assumed that the baseline behaviour of the impact has not changed over the duration of observation.

3.1.4. Fourth step: Impact detection

An impact can be detected if a system changes differently from the behaviour expected by a baseline. If in *Step 2* a climate trend was found that significantly differs from the baseline behaviour from *Step 3* it can be assumed that non-climatic drivers cannot explain the trend alone. Fig. 5 illustrates impact detection simply.



Comparison of baseline behaviour and signal with climate influence in a case where impact detection is possible. The baseline behaviour can change due to natural variability as depicted in this figure or through non-climatic drivers. If the behaviour without climate and including the climate trend are identical, no impact can be detected. Schematic constructed after (Hansen et al., 2015).

Fig. 5: Impact detection with baseline behaviour and climate signal.

If the impact has been detected, climate change contribution to the trend has been affirmed. If no impact was detected it rules out climate change as a significant driver. In the latter case the detected drivers, if identified, can be described, but *Step 5: Attribution* has to be omitted (Hansen et al., 2015).

Example: There is a trend in climate connected to a change in the impact signal but the baseline behaviour suggests no change. The system therefore is affected by climate change and an impact can be detected.

3.1.5. Fifth step: Attribution

If there was an impact detected, the contribution of the different drivers to the detected change can be evaluated. Through the impact detection, the involvement of climate change has been affirmed. In the attribution stage the strength of this involvement is assessed. The contribution of each driver is always assessed compared to the other drivers and is not dependent on the size of the impact. Optimally a quantitative estimate of the relative contributions of the drivers can be made. Working on a not very well observed basis, a qualitative evaluation is more adequate (Hansen et al., 2015). A possible quantitative evaluation given to impacts in the IPCC (2014a) report is a distinction between major and minor role in the impact. Both quantitative and qualitative evaluations may be paired with a confidence rating. This can be important as for example a minor influence could still be very clearly attributable and the confidence in attribution therefore high.

Example: As an impact was detected in Step 4, attribution of the impact is possible. It assesses the magnitude of the air temperature as the climate driver to the detected groundwater temperature increase qualitatively. The climate driver is a major driver of the impact in question, as there were no significant non-climatic drivers and the air temperature trend is expected to be closely linked to the impact assessed.

3.2. Classification scheme

After the attribution assessment the cases can be sorted into different classes according to a classification scheme developed in this thesis for local cases. Based on step four and five of the attribution assessment the cases are sorted into one of five classes. This classification is not necessary to see if attribution is possible or not, but it helps to understand and summarise the assessment. It condenses the assessment of detection, attribution and the confidence in it into a user-friendly categorisation.

Step five (*attribution*) compares the drivers of the impact detected quantitatively or qualitatively. The result is an estimate of how large the contribution of the climatic versus the non-climatic drivers are. As it is difficult for such local cases to quantify the influence of the individual driver, most likely the assessments of the cases will be qualitative. The classification scheme presented here therefore bases on qualitative assessments; however, it would work for quantitative assessments as well. Also, if there is no impact detected in step four and consequently there is no attribution, the observed impacts of the cases can still be sorted into one of the five classes. To help with the classification, the classification flow chart in Fig. 6 can be used as an aid.

Class 1: Likely directly related to climate change:

An observed impact is likely directly related to climate change if an impact was detected and the contribution of the climatic drivers is larger or equal to the contribution of non-climatic drivers.

Class 2: Likely indirectly related to climate change:

An indirect relation is found if the impact detected is attributed mostly to non-climatic drivers, but the non-climatic drivers are a result of a climatic change. This may be the case if we have a significant change in temperature or precipitation and the local community reacted to this change.

As an example, an increase in summer temperature may lead to an increased use of ground-heat exchanger for air conditioning in buildings. This could result in warmer ground temperatures as the heat exchanger uses the cooler temperatures of the ground to cool the air, and therefore heats up the surroundings of the borehole.

Class 3: Suspected climate change influence:

If an attribution to climate change was not possible, but an influence of the climate cannot be dismissed, cases are categorised as Class 3. It applies if the non-climatic drivers are exceeding the climatic drivers, but there is reason to suspect that the climate had a minor influence on the case. It is also used if there are large uncertainties in the data or if many approximations and assumptions had to be made to analyse the climate trend or the baseline behaviour.

Class 4: Likely other causes prevalent:

This class is used if the impact detected is very small, and it is impossible to make a good estimate of the magnitude of each contributing driver. It is also used if the contribution of the non-climatic drivers largely exceeds the climatic drivers. In both cases there is a climate influence but it is contributing only to a very small degree.

Class 5: No observable climate change influence:

This class is used for cases where no impact could be detected and there is no suspicion of an influence of climate change up until now. It also applies if there is a strong suspicion that climate change will affect the processes evaluated in the future, but there is no evidence for any impact yet.

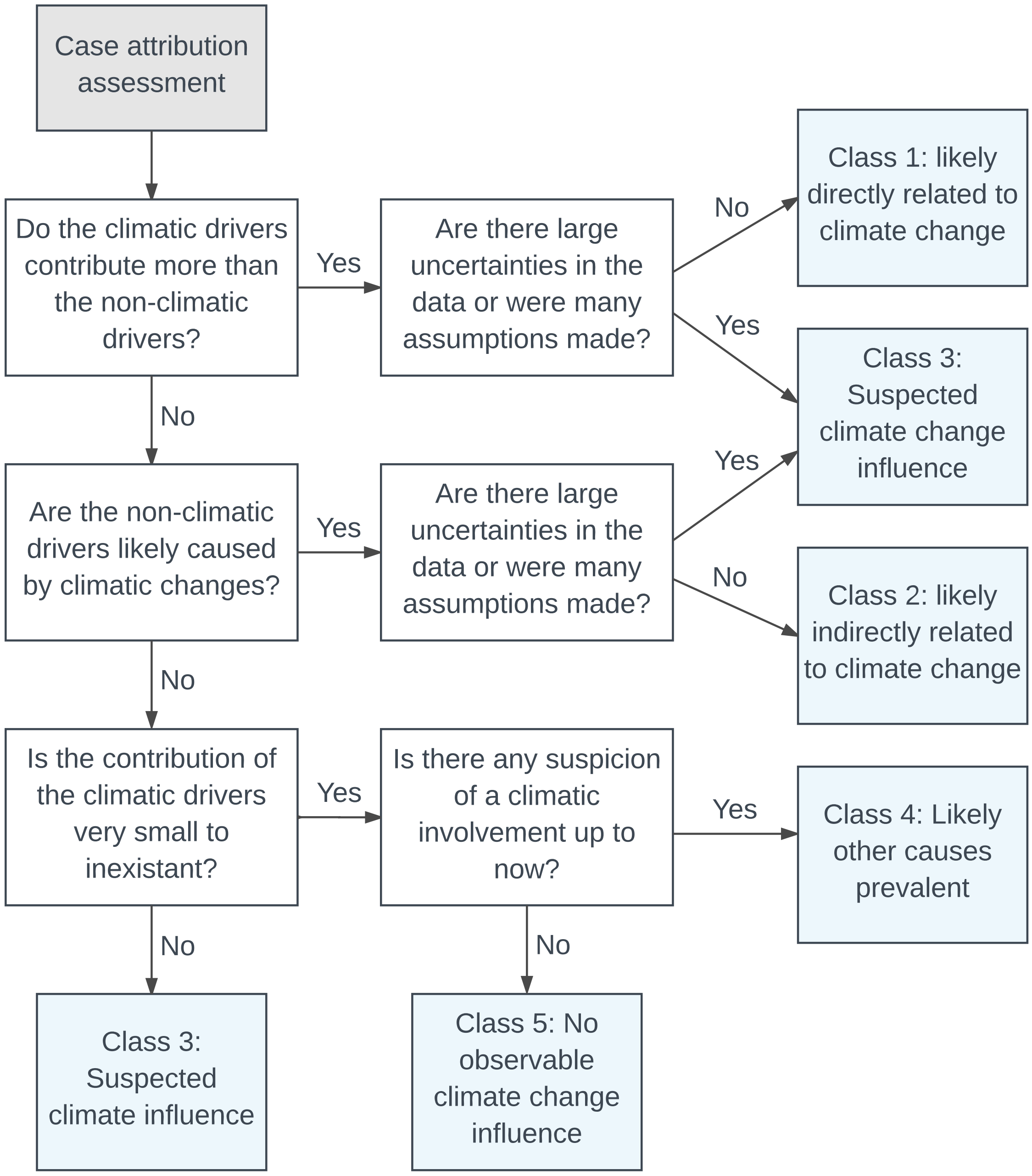


Fig. 6: Classification scheme for attribution cases developed for this thesis.

3.3. Interviews

Before application of the method framework and the classifications, the cases have to be identified and investigated first.

Contacts in different cantonal offices in central Switzerland helped identifying the cases. Also, project managers of adaption projects in the area as well as research institutes were approached. After the identification of a possible case, follow-up interviews are conducted. The aim is to interview the people who are most closely affected by the impact and who observed it. For the cases selected here, these are all people with no geography or climate-science background. The interviews aim to collect information about possible cases either in person or over telephone. In an attempt to use all possible data sources, this use of local laymen knowledge mainly aims at gathering context information on the cases and in some cases facts on the observed impacts recorded by the locals.

The interviews follow a general interview guide approach, encouraging the informants to explain the case and their involvement in it in their own words (McNamara, 2017). A prepared report sheet (see Appendix A: Impact report sheet) is used to record and structure the information given and to make sure to ask follow-up questions if the interviewees left an important characteristic of the case out. The interviews primarily gain qualitative and quantitative information about the impact (e.g. if they could locate the case site on a map or describe land-use changes in the area) and less about the opinions of the interviewees. Afterwards, reports for every case summarise the interviews, which serve as basic information for the data analyses.

3.4. Field investigations

A field assessment with or without the interview partners follows the interviews to map the processes and locations described in the interview. Important landscape features as well as buildings and infrastructure, if they are suspected to have an influence on the area, are noted and marked on the map.

To document the process and record the findings the case location and area are photographed. As the processes described are either long-term processes or extreme events in the past few years, no on-site climatic or weather data was gathered.

3.5. Attribution Case Studies

The attribution assessment described in 3. Methods is applied to four local case studies in the following chapters. The chapters 4. Rhone Glacier 5. Flüelen fish farm, 6. Sittlisalp hydro-power plant, 7. Haggenegg examine the case studies separately and 8. Discussion gatheres the findings and relates them back to the research questions.

Each of the case studies describes the observed impact and the local study area in detail. Additionally, the theoretical background and existing research on the impact are reviewed. After this introduction, the case assessment leads through each of the five steps to attribution. Subsequently, the cases are classified according to the classification scheme (see 3.2 Classification scheme). Finally discussion of the case limitations is provided and a conclusion for each case drawn. The statistical analyses were conducted with the open-source software environment R (R Core Team, 2015).

4. Rhone Glacier

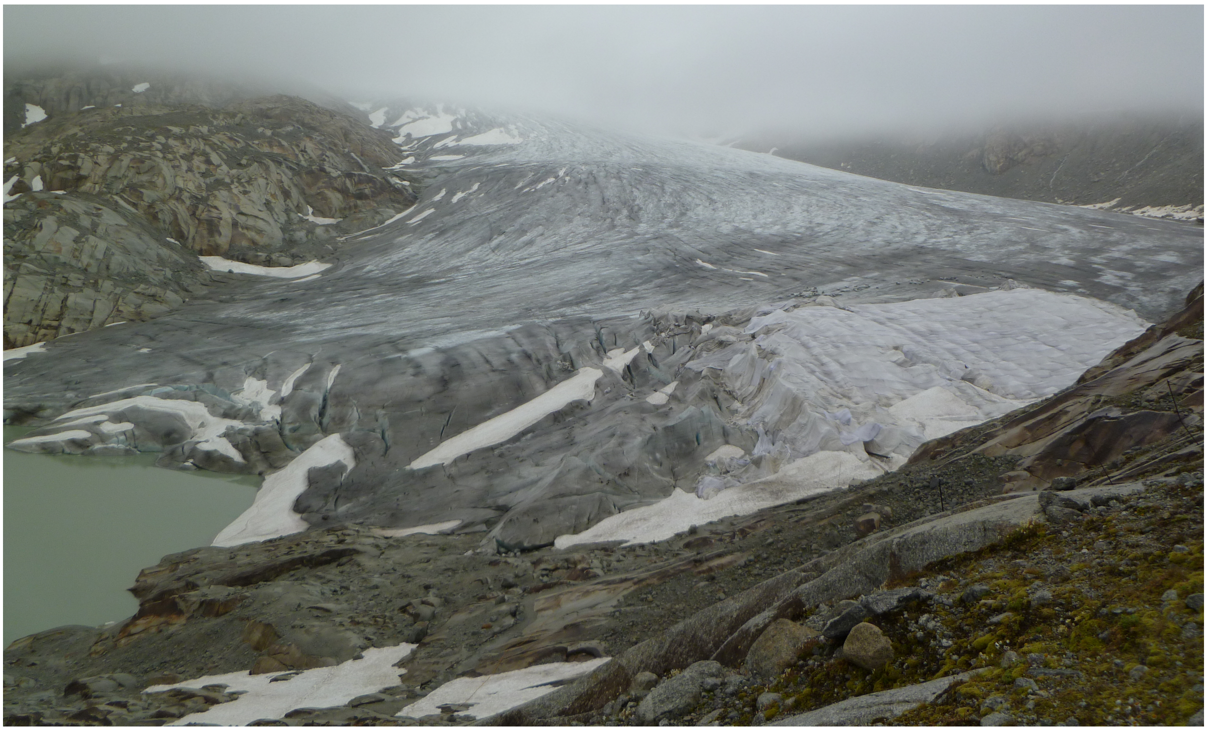


Fig. 7: Rhone Glacier in July 2016.

Rhone Glacier tongue in July 2016 with the terminal lake on the left and the sheet-covered ice cave site on the right side (Photo by Christine Schärer, 2016).

4.1. Study area

The case is located at the Rhone Glacier (see Fig. 8) in the uppermost part of the Rhone Valley and is part of the Central Alps in the Swiss Canton of Valais. The valley glacier is situated in a north-south facing valley with the Dammastock (3630m a.s.l.) in the north, the Galenstock (3583m) to the east and the Tierälplistock (3383m) and the Garstenhörner (3189m) to the west. The Furkapass leading into the Canton of Uri and the Grimselpass leading into the Canton of Berne are located to the east and to the west of the current glacial terminus (Swisstopo, 2017). The glacier spans from about 2210m a.s.l. to 3600m with the ELA (Equilibrium Line Altitude) at 2855m in 2013. As of 2016 the temperate Rhone Glacier covers an area of 15.8 km^2 and its melt water is the main input to the upper catchment of the Rhone River (Bauder et al., 2016).

Local climate

Extremes coincide climatically in the Canton of Valais; in the high-alpine regions of the mountain peaks there is up to 3000mm of precipitation per year, because of orographic precipitation. In comparison, the Rhone trough valley is very dry with only 590mm precipitation in Sion, as it is sheltered from precipitation through the depletion of water from the air masses north and south of the valley (Burri, 2012). The Rhone Glacier is situated in the main chain of the Central Alps and is surrounded with high peaks, which leads to a wet alpine climate.

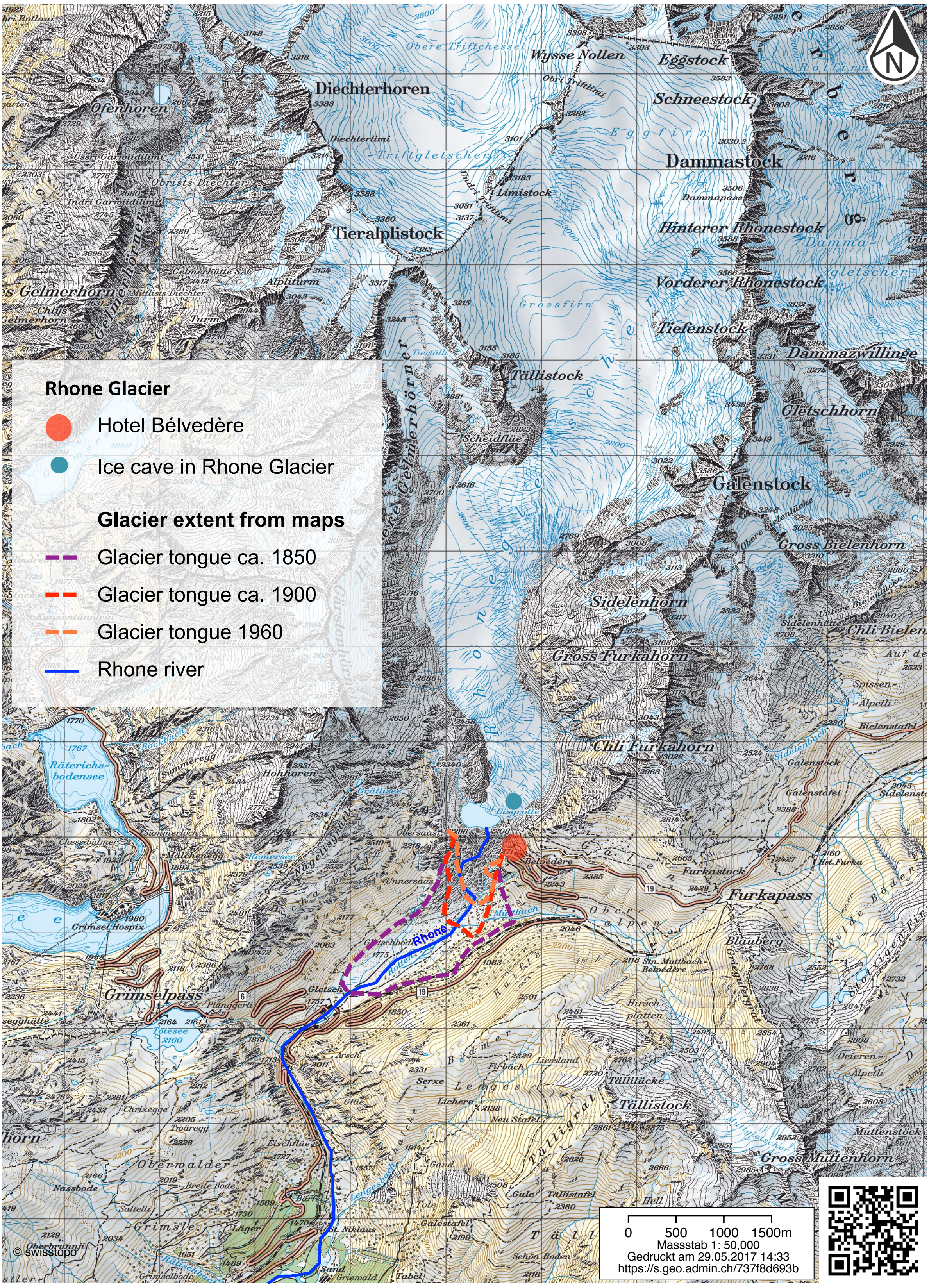


Fig. 8: Map of Rhone Glacier case site.

Rhone Glacier with historic glacier tongue extent reconstructed from old maps from Swisstopo (2017), ice cave site in 2016 and site of the Hotel Bélvedère.

Population

The high alpine environment is very sparsely populated. Oberwald, VS is the closest settlement inhabited all year round and is located about 6 km from the glacier terminus in the Rhone Valley (Swisstopo, 2017, Obergoms Tourismus, 2017). Due to its accessibility, the Rhone Glacier is quite well known as a tourist attraction located directly at the Furka Pass highway (Gletscher.ch, 2016). The pass street is used quite frequently in the summer months as it provides a link from the Rhone Valley to the Gotthard Pass (IG Alpenpässe, 2017).

Regional context

As this is a local case study, it concentrates solely on the Rhone Glacier and its surroundings. The region is, however, quite glaciated due to its high elevation. In a radius of 10 km we can find the Trift Glacier, Tiefen Glacier, Stein Glacier and the Damma Glacier amongst several smaller glaciers (Swisstopo, 2017). Regional glacier changes show a general trend of retreat since the late 19th century with the largest loss in the 1940s and 2000s and advance periods in the 1910s and 1970s (Pellicciotti et al., 2014).

4.2. Observed impact

The first case evolves around the ice loss at the Rhone Glacier. It has more or less constantly lost mass since 1879, which most notably resulted in a length change of 1421m or around 15% of its length, respectively.

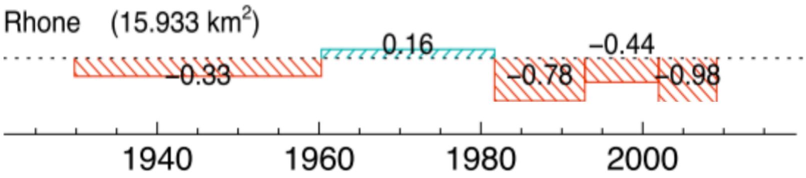


Fig. 9: Mean annual thickness change (m) on the Rhone Glacier.

(Bauder et al. 2016)

This has also been observed by the owners of the Hotel-Restaurant Belvédère located at the Furka Pass street, who build an ice cave into the glacier every year since around 1870 (Gletscher.ch, 2016). The tourist attraction was always located in the glacier tongue above a rock overhang close to the hotel. Due to the melt in recent years a lake formed in 2007 at the former cave site; thus, the cave had to be moved up the glacier every year since. To preserve at least a part of the cave for the following year and to assure that the ice cave can still be accessed well from Belvédère, the builders laid white sheets over the glacier in the area above the cave (Hamberger and Zängl, 2016). This temporary measure to delay ice melt was therefore a direct reaction to the increased ice melt in recent years. Fig. 7 depicts the glacier terminus with the lake and the covered ice cave site in July 2016. If the ice continues to retreat it will not be worthwhile to build a cave, as it cannot be accessed easily.

These changes were observed by different measurement campaigns as well. Fig. 9 illustrates the annual mean thickness change on the Rhone Glacier since 1929, given in metres. Except for the time period between 1959 and 1980 all phases recorded an annual mean thickness loss between 0.33m and 0.98m, with the larger melt rates in more recent years. This resulted in an overall volume change of -454.397 x 10^6m^3 of ice over these 78 years. The mean thickness change and the overall volumetric change indicate an increasing and significant ice melt rate (Bauder et al., 2016).

Apart from the direct consequences of the ice melt for the local business, it also introduces significant changes to the alpine environment. Furthermore, there is now a growing lake at the glacier terminus, which poses risk to travellers on the pass street and inhabitants of the Rhone Valley below through potential hazards e.g. outburst floods. The changed hydrological regime could also have a significant influence on the downstream ecosystem due to different seasonal water availability (Gletscher.ch, 2016, Bolch et al., 2008). It is therefore important to know the drivers of the change, to be able to foresee future impacts and adapt to these new circumstances.

4.3. Glacial melt

The theoretical basics for the assessment of glacial ice changes are summarised in this chapter. There are several factors influencing glacial ice melt. The main influences on overall glacier melt, which affect glacial mass balance, are reviewed. Also influences on melt at the glacier terminus are illustrated here. The melt at the glacier terminus is of particular interest as many glacial long-term measurement series consist of length change data. The longest consistent measurement series on the Rhone Glacier observes yearly length changes since 1879 (GLAMOS, 2015).

Many empirical glaciological studies have established, that air temperature and precipitation are the main climatic drivers for glacial mass balance changes, specifically surface melt (Braithwaite and Zhang, 2000, Cuffey and Paterson, 2010, Farinotti, 2013). Apart from surface melt, glaciers can also loose mass at the base, but mostly at a lower and more constant rate. Precipitation in winter months and air temperatures in the summer months influence surface ice changes. If accumulation in winter is low, through low winter precipitation and ablation is increased through high summer air temperatures, ice loss occurs. If these climate signals differ continuously from the long-term average of the climate signal, while other factors are constant, it leads to glacier retreat and mass loss in the long run (Bauder et al., 2016). Clearly, this is a simplification of the processes happening on the glacier surfaces.

As a basic principle, melt is driven by the energy influx, which can be described through sensible heat input, net radiation and latent heat input. The latter for instance cannot really be approximated by air temperature, which is one of the most commonly measured climate variables. However, empirical studies have shown that latent heat fluxes on a mid-latitude valley glacier are quite balanced. Consequently they have a minimal influence on glacier melt compared to the other energy fluxes (Hooke, 2005). These influences also differ depending on the location on the glacier. On temperate glaciers, energy influx decreases with higher elevation, so the main ablation occurs in the lower elevation tongue areas of the glacier (Cuffey and Paterson, 2010). The net radiation gradient may vary strongly, depending on the exposed surface. On snow cover the radiation influence is quite low, but as soon as ice is exposed, the albedo is lowered and its influence heightened. Thus, the impact of the radiation is greatly dependent on the state of the glacier surface and can vary strongly across its area (Hooke, 2005).

There are several drivers of glacial ice loss that are not primarily climatic. This involves bottom melt and calving among others. Here, melt processes important for glacial length changes as well as overall mass changes are clarified. They are important factors to understand the processes influencing the length data used.

A factor influencing net radiation, which has been observed on the Swiss glacier Vadret da Morteratsch for instance, is increased melt due to dust covering the ice. Dust and debris falling from exposed side moraines and, to a lesser degree, from mountainsides land on the exposed ice and increase the albedo of the surface. This process can lead to higher melt rates in the summer, particularly on the more affected front of the glacier tongue. The effect declines at higher elevations, as there is less dust input (Oerlemans et al., 2009).

The opposing effect was found in studies on valley glaciers in the Himalaya region, where debris-covered and bare-ice glacier behaviour was compared. Clean glaciers were in clear retreat while debris-covered glaciers were shrinking at lesser rates (Shukla and Qadir, 2016). To assess if the effect of the debris on the melt is positive or negative, the thickness of the debris cover is critical. A higher debris cover insulates the ice beneath and lowers the melt rate, while thin debris cover such as dust, increases the melt rate due to the heightened albedo (Benn et al., 2012, Pellicciotti et al., 2014).

The melt at the glacier tongue is also influenced by lake formation. Glaciers terminating in water generally show larger retreating or advancing rates than land-terminating glaciers. Through heat exchange of the water and the ice and different flow dynamics through floating tongues, the melt rates can change significantly. As many alpine valley glaciers including the Rhone Glacier have formed overdeepenings or high terminal moraines, lake formation at the glacier terminus during a retreat is very common. The reactions of different water-terminating glaciers to changes in climatic signals are less predictable than land-terminating glaciers (Truffer and Motyka, 2016). Generally over 50% of ice loss in water-terminating glaciers is through calving with the calving rate being the highest in October due to the high water temperature (Cuffey and Paterson, 2010).

Bedrock topography also influences ice loss at the tongue directly. Melt on the glacier surface can lead to very thin ice over rock overhangs or at the edge of an overdeepening of the bedrock. If this surface melt is strong, it can lead to separation of a lower part of the glacier tongue. The separated ice is then considered dead ice. Through this process the glacial length can lose hundreds of metres per year. Retreat of a glacier through an overdeepening is then additionally sped up as the basin fills with water and forms a lake (Cook and Swift, 2012). Hence, uneven bedrock topography is often responsible for large annual to decadal variability of length change rates.

4.4. Rhone Glacier research

The existing glacier research on the Rhone Glacier is reviewed next. The glaciers location close to the pass street makes it easily accessible and therefore its development has been surveyed for quite a long time. Due to these long measurement series, it was the object of a reasonable amount of research. First long-term changes on the glacier were evaluated in the 1910s (Mercanton, 1916, Mougin, 1917).

Goehring et al. (2012) reconstructed the glacial changes throughout the Holocene using cosmogenic nuclide samples from pro-glacial bedrock and numerical modelling of the ice flow. The reconstruction was completed with a study on the influence of insolation on the glacial dynamics during this timeframe. They conclude that the Rhone Glacier reacts to insolation changes superimposed with short-lived climate events.

Boscarello et al. (2014) included the melt of the Valais glaciers in a hydrological model to account for the large impact it has on the hydrological balance of the Rhone valley. Similarly, the Rhone Glacier specifically was also included in a review on hydrological impacts of glacial changes in the Swiss Alps, where a mass balance model was applied for the glacier and compared with others to predict changes to the glacio-hydrological system (Pellicciotti et al., 2014). Both concur that modelling of the glacier is important for the hydrological system, as changes in the glacier impacts runoff regimes significantly.

The newest glaciological report on Swiss glaciers gives a comprehensive account of length, mass and volume changes of the Rhone Glacier since begin of measurement. These are based on glacier observation data as well as calculations from airborne imaging. The data gathered in this report serve as a basis for a large part of the trend analysis in this thesis (Bauder et al., 2016).

Additionally, changes in the glacier since the 1870s have been modelled through numerical simulations by Jouvet et al. (2009) using mass balance data as input. They modelled different glacier state scenarios up to 2100 based on this model and climate predictions. The most realistic scenario, based on state of the art climate scenarios, expects a near total disappearance of the glacier until 2100.

4.5. Attribution assessment

Now that the observed impact and the theoretical background are established, potential attribution of the impact to climate change is assessed. There are two main prerequisites for the attribution framework to be applied, according to the research goals: Firstly, the observed impact has to have a relation to climate change. An influence of the climate signals to glacier mass change has been observed in literature (see *Glacial melt*). Although this relationship still has to be established in the case study. Secondly, the case has to be of local extent. As only one glacier is concerned in this study this prerequisite is also given. Since the conditions for the assessment are met, the five steps of the attribution framework can subsequently be applied to the Rhone Glacier case.

4.5.1. Step 1: Hypothesis

Based on the research presented above, the following hypotheses were formulated for the observed impact. As it would be too complex for this local study, it does not differentiate between-climate changes driven naturally and anthropogenically.

H_0: Recent changes in Rhone Glacier length and mass occurred independently of natural and anthropogenic climate change.

H_1: Recent changes in Rhone Glacier length and mass occurred due to a trend in the local climate signals of air temperature and precipitation (in line with regional climate change).

4.5.2. Step 2: Trend analysis

First the impact analysis brings the observed impact of glacier mass loss into relation to the local climate signals. After establishing this relationship, a trend analysis evaluates trends in both precipitation and temperature. Finally, it is confirmed whether the behaviour of the climate signals models the observed impact adequately. It is very important to approach this step diligently and to describe the data input and methods for the trend analysis, before trend analysis.

Data for trend analysis

A range of data was gathered on the Rhone Glacier starting in the late 19th century. Tab. 1 details the data source, time frame and resolution of the data used in the trend analysis.

The first recorded glacier mass balance measurement in the world was conducted in 1874 on the Rhone Glacier with stakes (Bauder et al., 2016). In this glaciological measurement method, the winter balance approximates the accumulation of snow during the winter months, while summer balance measures the snow and ice melt in the summer months and is therefore negative. The sum of these two quantities in water equivalent is the mass balance. The assumption in this method, that accumulation occurs mainly in winter and melt in summer, is fitting for the temperate alpine valley glaciers such as the Rhone Glacier, but may be inadequate for some arctic or tropical glaciers. Usually these measurements are conducted once or twice yearly through stakes drilled into the ice, measuring surface height relative to the last year. If mass balance measurement is conducted diligently and yearly, it provides the most suitable data for surface

Data for statistics	Source	Time frame and resolution
Glacier length	GLAMOS, Glacier Monitoring in Switzerland (GLAMOS, 2015)	1879-2015 yearly in m
Geodetic mass balance	Glacier report Nr 133/134 (Bauder et al., 2016)	1929-2007 multi-decadal resolution in m/a Water Equivalent (W.E.)
Glaciological mass balance	(Chen and Funk, 1990)	1884-1909 yearly resolution in mm/a W.E.
Glaciological mass balance	(Chen and Funk, 1990)	1980-1982 yearly resolution in mm/a W.E.
Glaciological mass balance	Glacier report Nr. 131-134 (Bauder et al., 2014, Bauder et al., 2015, Bauder et al., 2016)	2007-2013 yearly resolution in mm/a W.E.
Air temperature	MeteoSwiss station Andermatt (MeteoSchweiz, 2016)	1863-2016 with intermission mean daily temperature in °C
Precipitation	MeteoSwiss station Andermatt (MeteoSchweiz, 2016)	1863-2016 with intermission daily precipitation sum in mm

Tab. 1: Data used in trend analysis for Rhone Glacier case.

melt up to now (Hooke, 2005). Today, these measurements are also supplemented with snow pit investigations and snow probing (Bauder et al., 2016). However, continuous glaciological mass balance observations (mm/a W.E., recalculated to m/a W.E. to be comparable to the geodetic mass balance) were only recently taken up again, with many missing years in between the 1885-1909, 1980-1982 and the current campaign started in 2007 (Chen and Funk, 1990, Bauder et al., 2016). For the 1885-1909 campaign the measurement dates were less consistent than in the later campaigns with up to a month delay. This results in a higher uncertainty for the measurements of this early campaign (Chen and Funk, 1990).

Through repeated aerial photographs of the topography, a photogrammetric analysis of several states of the glacier between 1929 and 2007 was used to reconstruct ice melt. Digital Elevation Models (DEM) were derived from these photographs, from which multi-decadal volumetric change data could be computed, approximating the mass balance change over the given time frame. Using the volumetric change and the area, the mean thickness change (m/a) and the mean annual mass balance (m/a W.E.) could also be calculated (Bauder et al., 2016). It has to be kept in mind that the dates the aerial photographs were taken dictate the time frames, over which the geodetic changes were recorded, so the time frames are not process-related.

Additionally to the mass balance data, the glacier length change is documented yearly with very few missing years since 1879. As the temporal resolution of the length change is much better, it is more suitable for statistical analysis than the mass balance data (GLAMOS, 2015). However, many non-climatic melting processes affect short-term glacier length changes (see 4.3 Glacial melt), so the distinction between climatic and non-climatic drivers might be more challenging.

A very long running and reasonably close MeteoSwiss station in Andermatt provides both air temperature and precipitation information. The station is located at an elevation of 1348m above sea level, which is about 1000m lower than the glacier tongue (Swisstopo, 2017). But as it has the longest air temperature time series in the region, running intermittently from 1863 to 2016, it is used to approximate the climate signal trends. The station data is also more suitable for statistical analysis than interpolated gridded data, which is available for a much shorter time frame (MeteoSchweiz, 2016). To compare it with the two glacial measurements, the signals are analysed from 1879 onwards. This range of data measured on or near the glacier provides a well-observed system for the impact attribution assessment.

Methods

For the analysis of the observed impact, it is important to both take a look at mass balance changes and length changes of the glacier. For most glaciers, and the Rhone Glacier is no exception, glacier length changes are taken with a higher frequency and accuracy than mass balances. The volumetric change (and its implications for mass balance) in contrast is more relevant to actual ice melt, as the length alone does not give information on ice thickness. Both signals together, however, should give a more complete picture of the ice melt situation.

Linear regression analyses using both data types established that the relation of the climate variables 'summer temperature' and 'winter precipitation' with glacial melt applies in this local case as well. Both the mass balance changes and the length changes were tested separately against the two independent variables. This approach requires that the relationship between the variables is linear and the data is quantitative (Backhaus et al., 2011). The variable winter precipitation is defined as the mean daily precipitation over the months October to March while the summer temperature describes the mean air temperature between April and September. As the glaciological year starts in October the winter precipitation is summed up over the winter months of October to March and the mean April to September temperatures are taken for the summer temperatures. In particular the early summer months determine how fast the snow melts on the glacier, which leaves the ice bare in the later summer months for ice melt (Bauder et al. 2016). In general, the significance level of 0.05 is chosen, so results are statistically significant if the p-values is below this level.

For the climate variables, daily data from MeteoSwiss is available from 1871/1881 onwards, with only single years early on, where the data is insufficient. These climatic datasets were adjusted to be comparable with the length and mass changes respectively. The relation of the glacial datasets to the climate variables is analysed for all datasets individually (the different mass balance datasets and the length change) and additionally the mass balance data is analysed jointly.

A positive degree-day model is another common method to estimate ice melts using temperature data. It estimates the melt rate according to the number of days with temperatures above 0°C. However, there are no consistent temperature measurements on the Rhone Glacier. And as there is a specific threshold involved in this method, using temperature data from a station at a lower elevation like Andermatt is not a valid approach (Cuffey and Paterson, 2010).

4.5.2.1. Impact assessment

Firstly, the mass balance data is assessed (Bauder et al. 2016). Since there are different data sources and measurement techniques applied to the Rhone Glacier, the geodetic and glaciological mass balance datasets are first assessed separately in a linear regression model, then analysed as a combined data set. For the climatic variables the mean over the timespan in question is calculated to be comparable to the mass balance data. Hence the mean daily air temperature is averaged over the summer months (April to September) of one year for the yearly measurements. For the multi-decadal geodetic data regression these summer temperatures (ST) are averaged over the longer timespan. The same is done with the daily precipitation sum, which is aggregated to mean daily winter (October to March) precipitation (WP) per year or decade. Tab. 2 outlines the model parameters and results.

Model diagnostics

A multiple linear regression model was chosen as it is used to estimate if the behaviour of a dependent variable is related to the behaviour of multiple independent variables (Backhaus et al., 2011). In the models, ice melt is the dependent variable while climatic measurements constitute independent variables.

Evaluating the model diagnostics helps assessing if the model is appropriate. Through examination of the plot diagnostics, each of the models is tested for linear relationship, normal distribution of residuals, homoscedasticity and particularly influential cases. For the models with very few data points (i.e. geodetic mass balance and combined mass balance models) it was noted, that the model requirements can be seen as given, but that the addition or removal of one data point can skew the diagnostics significantly. Influential cases were detected within this dataset, but due to the small number of observations these are not removed.

For the models with more observations (i.e. glaciological mass balance and length change models) these plot diagnostics are more indicative. In the case of the glaciological mass balance measurements the normality and homoscedasticity seem to be given and there are no particularly influential cases. Still some points fall out of line and care has to be taken. In particular this applies to the points of the early measurement campaign, where measurement inaccuracies have to be expected. As they are only very few points, which are otherwise unsuspicious, no data points are excluded for this model.

A similar situation is present with the length change data. However, there are four outlying points out of the around 135 measurements, which are also particularly influential cases. The model presented here excludes these four points. If these points are excluded, the model diagnostics indicate a much better fitting model. These points are most likely a result of short-term influences on the glacier tongue e.g. mass loss through local bedrock topography and not particularly important for the long-term impact.

Length change data

A first linear regression model is constructed using the glacier length change data and the independent variables summer temperature (ST) and winter precipitation (WP). As the length change is influenced by many more factors than just climatic variables, the coefficient of determination R^2 is expected to be lower than with the mass balance data.

The results in Tab. 2 show a low determination coefficient (adjusted-R^2) of 0.133, which indicates that only 13% of the length change variability can be explained with the independent variables. However, due to the low p-value of <0.001, R^2 is statistically significant and the null-hypothesis, that the model would have a better fit without the predictor values can be rejected. Changes in ST are negatively related to length gain and is a meaningful addition to the model (significant at p-value <0.001) and changes in WP are positively related (p-value <0.01).

Geodetic mass balance (1929-2007)

A first linear regression model explains geodetic measurements by their corresponding mean summer temperature and winter precipitation. The timespans of the geodetic mass balance are irregular as the time steps between photographs range between 7 and 30 years, affecting the linear regression. Not surprisingly, the linear model is not robust. As there are only five irregular data points, this results in a linear regression that is not significant.

The summer temperature suggests a negative relationship with the mass balance, so melt occurs when the temperature is higher. And the winter precipitation also suggests a negative relationship with mass balance; suggesting growth is observed when less precipitation is present, which contradicts the findings in literature. However, both of these independent variables are not able to predict the independent variable and the model results have to be dismissed.

Glaciological mass balance (1884-1909, 1980-1982, 2007-2013)

The three timeframes of glaciological mass balance measurements are joined as the dependent variable in a linear regression model, with the corresponding yearly mean summer temperature and mean daily winter precipitation as independent variables.

For the glaciological model Tab. 2 show a determination coefficient (adjusted-R^2) of 0.36, which indicates that 36% of the mass balance variability can be explained with the independent variables. Here, the low p-value of <0.001, R^2 is statistically significant and the null-hypothesis, that the model would have a better fit without the predictor values can be rejected. Again, changes in ST are negatively related to length gain and is a meaningful addition to the model (significant at p-value <0.001) and changes in WP are positively related, however only at a p-value of 0.06.

If the apparently erroneous measurements of the 1884-1909 campaign are taken out, the model is able to explain about 70% of the variability with the independent variables with a p-value of 0.05, WP is not a valuable predictor (p-value >0.1), however.

Combined mass balance

To complete the analysis, a combined model with data from both datasets is designed for comparison. Both mass balance datasets are calculated to m/a W.E. (height of the water equivalent of ice gain or melt in meters per year) to be comparable. Here the glaciological data is aggregated over timespans of similar lengths as the geodetic data to lessen the influence of a single year compared with a timespan. The length of the measurement campaigns dictates these constructed timespans: 1884-1896, 1897-1909, 1980-1982 and 2007-2013. Especially the timespan of 1980-1982 is shorter than the rest, so a single year might have a higher influence on the model. It also produces the only overlap in measurement with the geodetic reconstruction period of 1980-1991. As the glaciological measurement is deemed more exact than the photographic reconstruction for this time, the 1980-1982 period is used and the 1980-1991 measurement is excluded from the model.

Even though this leaves the model with only eight data points, the independent variables can explain 93% of the variability. With a p-value of <0.001, R^2 is statistically significant and again the null-hypothesis, that the model would have a better fit without the predictor values can be rejected. The independent variables show a negative relationship for air temperature (p-value <0.001) and a positive relationship for precipitation with mass balance (p-value <0.01).

Linear regression	**Model with glacier length change**	**Model with glaciological mass balance**	**Model with combined mass balance dataset**
Dataset	GLAMOS (2015)	Chen and Funk (1990) Bauder et al. (2014), (2015, 2016)	Chen and Funk (1990) Bauder et al. (2014), (2015, 2016)
Measurement method	Glacier length change	Glaciological mass balance	Geodetic and glaciological mass balance
Timeframe	1881-2015, yearly (some missing years)	1884-1909, 1980-1982, 2006-2013	1884-2013 intermittently
Data points used	130 data points, yearly	34 data points, yearly	8 data points, aggregated to decadal
Explained variance	Adjusted R^2: 0.13 13% of variability explained through independent variables	Adjusted R^2: 0.37 About 38% of variability explained through independent variables	Adjusted R^2: 0.93 About 93% of variability explained through independent variables
	p-value: 0.00005 Significant at p-level 0.001	p-value: 0.0003 Significant at p-level 0.001	p-value: 0.0006 Significant at p-level 0.001
Summer temperature (ST)	Estimate: -4.90 If ST rises by 1 °C in a year, the glacier length changes -4.90 m W.E.	Estimate: -0.50 If ST rises by 1 °C in a year, mass balance changes -0.50 m W.E.	Estimate: -0.66 If ST rises by 1 °C in a year, mass balance changes -0.66 m W.E.
	p-value: 0.0005 Not significant at significance level 0.001	p-value: 0.0001 Significant at significance level 0.001	p-value: 0.0005 Significant at significance level 0.001
Winter precipitation (WP)	Estimate: 3.11 If WP rises by 1 mm daily, the glacial length changes 3.11 m W.E.	Estimate: 0.15 If WP rises by 1 mm daily, mass balance changes 0.15 m W.E.	Estimate: 0.46 If WP rises by 1 mm daily, mass balance changes 0. 46 m W.E.
	p-value: 0.007 Significant at p-level 0.01	p-value: 0.06 Significant at p-level 0.1	p-value: 0.004 Significant at p-level 0.01

Tab. 2: Model comparison with length change and glacier mass balance datasets.

Model discussion

Apart from the model using geodetic mass balance only, all models show a relationship between ice melt and the climatic variables. The geodetic model will not be looked at further, as its results are not robust. A significant influence of the investigated variables on the ice change could be detected across all other models, even though the estimated magnitude of this influence varies strongly. All models have their weaknesses and strengths: The glaciological mass balance model consists of three measurement campaigns with large timespans in between. Also, the early campaign of 1884-1909 harbours measurement uncertainties. On the other hand, the glaciological measurements have a high temporal resolution and are more precise than the geodetic mass balance.

The temporal resolution of the geodetic mass balance is coarse, the longest timespan covering 30 years. This constitutes a challenge for the combined model, as there is an inherent imbalance between the geodetic data points and the constructed timespans with the glaciological mass balance data. On the positive side, through calculating the mean over a longer timespan, the measurement uncertainties in the 19th century campaign are smoothed out. Still, it cannot be ascertained if the geodetic and glaciological mass balance series really are comparable. To test for comparability, a common timespan is needed, where mass balance was measured by both methods (Zemp et al., 2013). As the two do not cover a common timespan, this test cannot be used, and the model results have to be interpreted cautiously.

Lastly, as established in the theoretical background (see *Glacial melt*) the length change measured at the tongue is influenced by many non-climatic influences and feedback processes. These influences cannot be accounted for statistically. Yet, the length change data has been measured since 1874 and with a yearly resolution, which provides the most consistent data.

Overall it can be said that the summer air temperature and the winter precipitation predict a significant part of the glacial variability. All models suggest a similar dependency between the variables, temperature rise leading to ice melt and precipitation rise leading to ice gain. The ability to predict glacial changes by variables ranges from minor (for the length change model) to major (for the glaciological and combined models). Therefore, since climate is established as a potentially major driver for the observed impact, we can take a look at the recent behaviour of the climate as an indicator for the impact behaviour.

4.5.2.2. Climatic trends

Finally, the climatic trend in summer air temperature and winter precipitation are analysed to represent the change in local climate. For this the MeteoSwiss temperatures from Andermatt, UR are analysed. The climatic variables at the Rhone Glacier at an about 1000m higher elevation can be expected to have changed with a parallel trend, if a little colder and wetter. A highly significant trend of summer air temperature can be detected for the station between 1882 and 2015. This particular timespan was used to be comparable to the glacier data. The mean temperature from April to September changed on average 0.0086 °C per year, which over the whole 135 years is an increase of 1.145°C. This trend fits the regional trend for Central Switzerland where an average annual increase of 0.1°C per decade since the mid 19th century was detected (MeteoSchweiz, 2013). If we only consider the trend of the past 50 years in Andermatt (from 1960 onwards) a faster increase of 0.5°C per decade is detectable (see Fig.10). This trend also fits in with the regional development as well as the global trend (MeteoSchweiz, 2013, IPCC, 2014b).

Over the 135 years there is also a significant trend to more precipitation detectable for winter precipitation. The daily mean precipitation from October through March increased by 0.0064 mm per year, which over 135 years would indicate an increase of 0.864 mm (compare trend line in Fig. 10). If inspected more closely it is clear that this trend to increasing precipitation is prevalent in the early years (before 1960) with up to +0.1mm per decade. However, if the recent development since 1960 is looked at, the trend tends to a decrease rather than an increase in precipitation, though this decreasing trend is not deemed significant. Therefore, it must be stated that in the current climate, no clear precipitation trend in either direction can be detected. This also falls in line with the observations in the regional climate, where no clear trend can be detected (MeteoSchweiz, 2013). Another factor to keep in mind is that if the temperature is warmer, more of the precipitation falls as rain and runs off instead of falling in solid form and accumulating on the glacier. To get a clear image of the trend of solid precipitation, more local information, preferably determined on the glacier, would be beneficial.

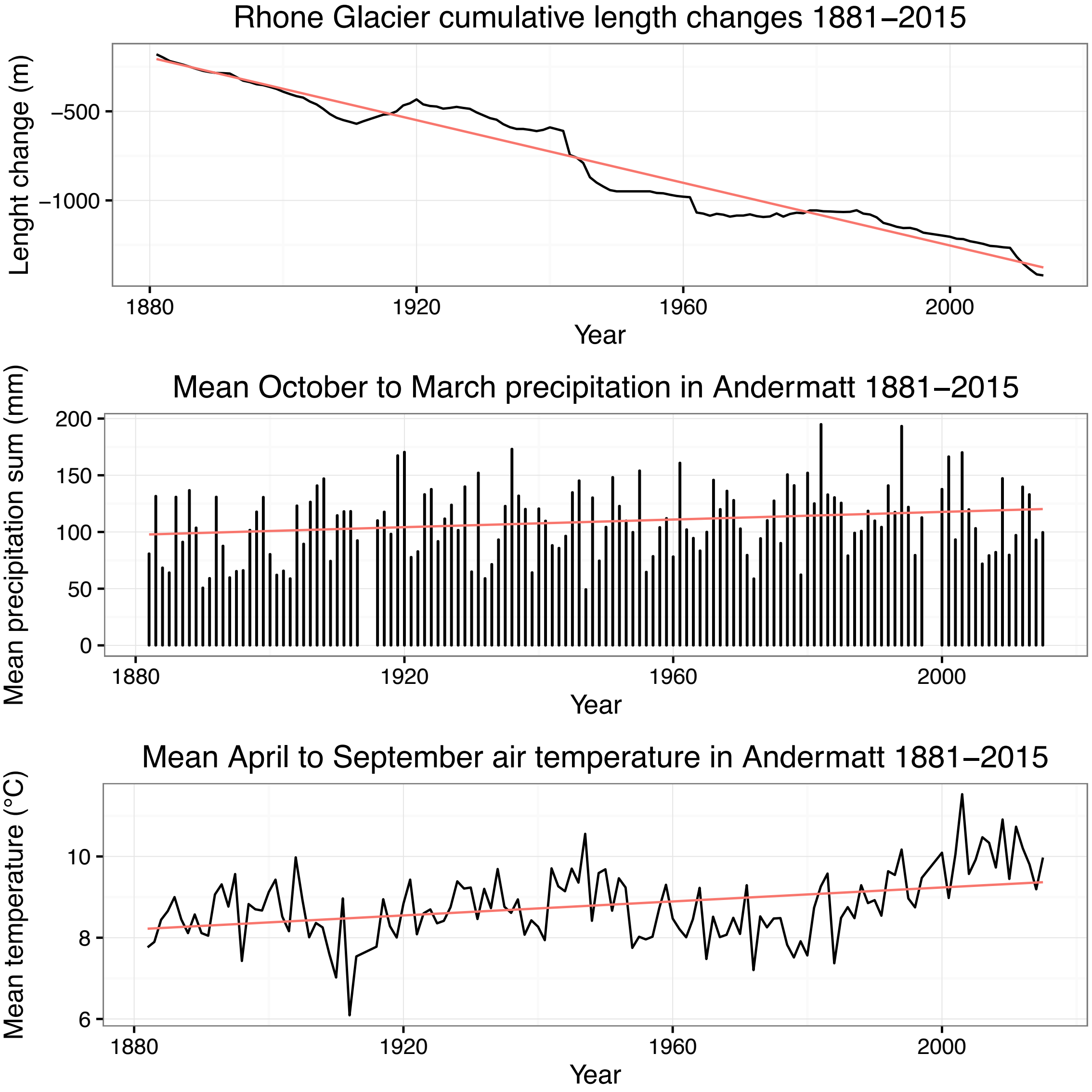


Fig. 10: Glacier length change, precipitation and air temperature in Andermatt.

Glacier length change trend and development of winter precipitation and air temperature since the late 19th century (graphs developed for this thesis, data (GLAMOS, 2015, MeteoSchweiz, 2016).

If we look at the whole timespan, both of these trends can be expected to have an influence on the ice mass change, as established in the models. An increase in temperature would mean ice loss while a decrease in temperature would mean ice gain. To quantify the influence of each of the two variables, the estimates calculated in the models can be multiplied with the calculated 135-year changes of the variables. Both the glaciological mass balance as well as the combined model indicates that the influence of the temperature change surpasses the precipitation increase. The glaciological mass balance model indicates a mean of -0.44 m/a W.E. and the combined model a mean of -0.34 m/a W.E. Knowing that precipitation changed mostly in the early measurement period, before 1960 and temperature changed more in recent years, ice loss is expected to be moderate in early years and large in recent years. This expectation coincides with the geodetic mass balance measurements depicted in Fig. 9. The only slightly positive mass balance was recorded for the slightly colder and wetter period between 1960 and 1980. The measurements of the winter precipitation and summer air temperature compared with the cumulative length changes of the Rhone Glacier are depicted in Fig. 10.

In conclusion, the observation on the Rhone Glacier shows a distinct ice loss in the last 150 years. This impact can be observed through mass balance estimations based on geodetic and glaciological observations, which were negative except for a period between 1960-1980. The corresponding glacial length changes were also predominately negative with an overall length loss of nearly 1500m. These changes could be linked through multivariate linear regression models to the two climatic variables of summer air temperature and winter precipitation. The significant trend to an increase in air temperature dominates the climatic influence on the glacier over the last 135 years and especially in recent years. While increasing precipitation most likely had an influence on the glacier up to the early 20th century, after 1960 precipitation changes play an insignificant role, as there is no detectable trend.

4.5.3. Step 3: Baseline behaviour

As the climatic drivers have now been examined, the next step is the evaluation of the baseline behaviour. The baseline behaviour defines the progression of the observation, if the climate was in a stable state. The stable state of the climate is hypothetical, as it cannot be observed in the real world (Hansen et al., 2015). On a global level, General Circulation Models (GCM see 2.2 Climate change impact detection and attribution) can help simulate such a baseline. On this local level, computing a model is not practical, as the system is much more complex. Instead, the behaviour of the signal before the impact could be observed and its drivers can be evaluated. Of course a stable climate cannot be assumed in historical behaviour either, however, the climate has been quite steady in the last centuries compared with the changes in the 20th century. Finding the influences, which may change the behaviour today, compared with the historical influences, allows an estimation of the baseline behaviour.

Glacier fluctuations in the Swiss Alps during the Holocene have been reconstructed in many different ways, through exposure or 14C and ^{10}Be dating, with pollen sampling and geomorphological moraine reconstructions among many others.

Since the last glacial maximum (LGM) in the last ice age over 21’000 years ago, the alpine glaciers have retreated during the Holocene interglacial. During the LGM the Rhone Glacier was the largest piedmont glacier apart from the Rhine glacier in the Swiss Alps and covered a large part of the Swiss midlands and western Alps and pre-Alps. It retreated to a valley glacier of the Rhone Valley relatively rapidly as the other piedmont glaciers and ice shields did, no later than 19’000 years ago. Large piedmont glaciers show, however, more fluctuations than valley glaciers so their collapse was pretty fast after the first warming impulse (Ivy-Ochs et al. 2004).

This means that as the Rhone Glacier terminated ca. 12 km down the valley in the Younger Dryas 12'000 years ago a mean loss of 1m/a in length can be assumed. This applies given a constant melt scenario and ignoring topography (Goering et al. 2012). Even though we cannot assume a constant melt scenario, this is a rather low melt rate compared with the average 10m/a loss in the last 150 years.

Through modelling of the glacier Equilibrium Line Altitude (ELA) and matching to the reconstructions, Goering et al. (2012) tried to explain the main drivers of glacier dynamics. The Rhone Glacier has retreated farther than the current position during the warming period in the mid-Holocene and re-advanced during the Little Ice Age up until the 19th century; see Fig. 11.

Through modelling of the insolation variations, the retreat and advance of the glacier could be reasonably explained and matched up with glacier extent records until the Little Ice Age. Solar insolation is the major driver of glacial changes up to this point. Since the mid 20th century, the insolation does not model glacier changes accurately and must now be assumed to be a minor driver only. This behaviour on Rhone Glacier fits general regional glacier behaviour (Goering et al. 2012).

The long-term baseline behaviour before our observation period was therefore slow glacial advance to the largest glacial extent since the very early Holocene. Short-term glacial changes were mainly driven by insolation changes. Following the insolation changes, the glacier should be advancing for the last 60 years, after a short retreating period from the late 19th to the early 20th century.

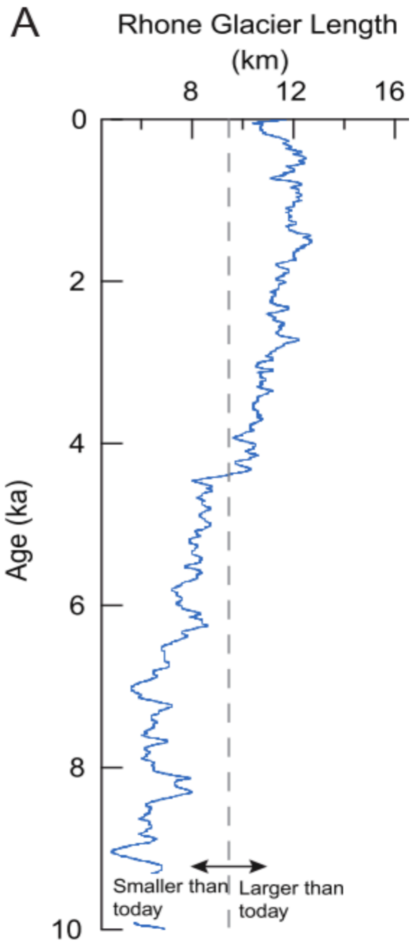


Fig. 11: Rhone Glacier length change during Holocene.

Glacial changes at Rhone Glacier before present (ka BP) (Goering et al. 2012).

Context analysis

To account for other outside influences that could have changed, other environmental changes are examined in the context analysis.

As the glacier is quite high up in the Alps and encompasses rough and ever changing terrain, the direct manipulation of the glacier through human activity was likely minimal. Apart from the ice cave at Belvédère and the Furka pass road, human influence is marginal. There is also no commercial skiing on the glacier, only some hiking activity (Valais/Wallis Promotion, 2016).

The Rhone Glacier is a mostly bare-iced glacier with little dust cover on the lower tongue. It can be considered a clean ice glacier, which receives no insulation through thick debris cover and only marginally increased melt through heightened albedo by dust cover. A small pro-glacial lake has developed in 2007 and expanded ever since (Alean and Hambrey, 2008). It is possible that the ice melt rates have since changed due to the ice water heat exchange. This is, however, a very recent development and should not impair the findings of the correlation analyses. According to the context analysis, there are most likely no outside influences, which should be considered as major drivers for ice mass changes.

4.5.4. Step 4: Impact detection

Impact detection is the next step in the attribution assessment. Here the influence of the climatic trend is compared with the baseline behaviour. If there is a significant difference, an impact can be detected.

The baseline behaviour of the Rhone Glacier and glaciers in the region suggest that the glacier length changes in the Holocene follow insolation changes up to the Little Ice Age glacial maximum in the 19th century. Modern insolation rates suggest low insolation, which should result in glacial advance or maintenance of location especially since the mid-20th century (Goering et al. 2012). The observation of glacial volumetric changes as well as length changes show increased ice loss of the Rhone Glacier in the last 150 years. This is related to the local warming trend in air temperatures of approximately 1.14 °C since 1882 in Andermatt. Insolation is most likely not the cause of this air temperature change so the climate forcing must be influenced another way.

Due to this comparison of modern day climatic data and glacier records to reconstructed glacier records from literature an impact can be detected. So the null hypothesis that the glacier changes occurred independently from climatic trends can be rejected. Instead the alternate hypothesis that recent changes in Rhone Glacier length and mass occurred due to a trend in the local climate signals of air temperature and precipitation can be accepted with a higher fit.

4.5.5. Step 5: Attribution

As an impact could be detected an attribution analysis can be done as a last step according to Hansen et al. (2016). The attribution analysis evaluates how much the detected impact was influenced by climate change and how much other variables contributed to the impact. In this analysis it is only possible to do this qualitatively not quantitatively.

Glaciers are reported to be very susceptible to a changing climate, particularly summer air temperature changes. Also they are mostly undisturbed by direct human activity, due to their isolated, highly mountainous position. As elaborated in the trend analysis, the climatic variables partly explain the glacier trends and there is a significant trend in increasing air temperatures. Overall it can be said that air temperature changes are a major driver for this local detected impact. This local climatic change also falls in line with the regional and global air temperature changes, so attribution of the impact to climate change is feasible.

4.6. Limitations

Both the glacier length change and climate data have very long observation periods, with about 150 years each. The mass balance data is available for a long time period as well, even though not as consistently measured. This makes it a well-observed system and provides a good basis for the attribution assessments. Still assumptions had to made, as not all of the factors influencing the system can be taken into account. While glacier length change is a result of glacial ice melt, glacier mass balance data is a better measurement of the ice lost or gained. The glacier mass balance data available is measured quite irregularly and through different methods, so each of the linear regression models has its weaknesses. Glacier length change gives only information about melt at the glacier terminus and not over the whole area. Bedrock topography, debris cover and lake formation also influence the melt at the glacier terminus. But information on how it influenced the data at hand is difficult to attain. Another assumption is the parallel trends between the climate signals in Andermatt and at the Rhone Glacier. As local trends in a region can differ, this assumption weakens the attribution to a certain degree.

4.7. Case Classification

Following the classification scheme introduced in 3.2 Classification scheme, the Rhone Glacier case is now classed into one of the five attribution classes. From the assessment it is clear that the climatic driver, in particular summer air temperature, is significant and contributes largely to the impact. The data used was suitable for the case and the system is well-observed system through a range of measurements. Even though there are some uncertainties in the early glaciological mass balance data, the majority of the data can be considered reliable. Some assumptions had to be made regarding the construction of the linear models, for instance, that the glaciological and the geodetic mass balance are comparable. With these challenges in mind, the attribution assessment still concludes that local climate change is the most important driver for the observed impact. The detected impact at the Rhone Glacier can therefore be classed into *Class 1: likely directly related to climate change*. Due to the limitations on the data and the assumptions made, the confidence in this classification is medium to high.

4.8. Adaptation

One of the aims of this assessment is taking a look at adaptation to the impact. The adaptation strategy of the Hotel Bélvedère is to lie out sheets over the site of their ice cave. This slows down the ice melt in that area of the glacier a bit, but has a limited effect on the larger ice melt process. For now this is a strategy, which brings results. The climate estimates in this thesis in line with other research finds that in the near future, the glacier will have retreated so far that this not sustainable anymore. Seeking an alternative touristic attraction is probably the best way to adapt for the locals. Above the Trift Glacier and its lake at the Susten pass there is a long suspension bridge, which provides a fantastic view. Even though the Trift Glacier has retreated a lot, it still attracts a lot of tourist attention (IG Alpenpässe, 2017). Another probably less costly possibility is to focus more on the experience of the alpine environment. For instance, a special theme hiking trail using the remnants (the lake, moraines, the Rhone river) of the glacier as inspiration. At the Zugspitze Glacier in Germany an interactive trail introduces the basics of glaciers (zugspitze.de, 2017). Apart from the direct repercussions on the Hotel owners, the downstream valley of the Rhone might also be affected through decreased summer runoff and higher risk through lake outbreak for instance. New policies and close observation of the glacier-lake system are imperative to adapt to these risks. Glacier melt, however, can only be stopped by stopping its driver, climate change itself. Unless the temperature increased is contained to a minimum, the Rhone Glacier will be largely gone by 2100 (Jouvet et al., 2009).

4.9. Conclusion

The attribution assessment can be used reasonably well for the Rhone Glacier case. A generally well-observed impact and local climate provide a good base for the attribution framework. Regional air temperature change appears to be a major driver of Rhone Glacier ice mass loss. Therefore, attribution of the detected impact to climate change is feasible. Subsequently, this case is classified as *likely directly related to climate change*. However, some constraints in the data and the analysis limit the confidence in attribution.

5. Flüelen fish farm

Fig. 12: Flüelen fish farm at Vierwaldstättersee.

The municipality of Flüelen from above (large picture) with the fish farm marked in an orange circle on the left (Gemeinde Flüelen, 2017) and inside pools of the fish farm, where hatched fish are reared (Kanton Uri, 2017a).

5.1. Study area

The second case is located at the eastern board of the Urnersee in the municipality of Flüelen in the Canton of Uri (see Fig. 12 and Fig. 13). The major contributor of the upper Urnersee is the Reuss joining about 2km from the site at the southern tip of the lake. The Urnersee fills a glacially formed north-south running trough valley and is the most upstream part of the Vierwaldstättersee. It lies on the eastern side of the valley at an elevation of 436m a.s.l. on an alluvial fan of the Gruonbach. The Gruonbach is a smaller stream joining the Urnersee north of the fish farm (Swisstopo, 2017).

Tertiary alpine orogenesis produced the original limestone in the area. In the early Quaternary glaciers reformed this bedrock and left moraine deposits. More recently, the water bodies dominated landscape genesis by leaving alluvial deposits like the Gruonbach alluvial fan (Swisstopo, 2017).

Local climate

The northern flank of the Alpine mountain range is mainly influenced by mild and wet winds coming from the Atlantic. These winds provide more regular precipitation in all seasons and milder temperatures compared to continental climates. The winters are colder than on the southern flank and wetter than in some inner-alpine valleys like the Valais. Especially, the higher elevated regions are mostly very cold and wet (MeteoSchweiz, 2013).

The low elevation in a larger valley provides warmer than average temperatures and lower precipitation than the rest of the region. Both temperatures and precipitation amounts are comparable to lowland measurements. The site at the lake-board has an estimated yearly temperature of 9-10°C and 1200-1300mm of precipitation, with the highest precipitation amounts falling in summer. The precipitation is lower than average in the region partly because of shielding effects of the large mountain ranges and partly because of warm winds (MeteoSchweiz, 2013).

Uncharacteristically warm and dry days occur regularly because of warm falling winds from the south. The low elevation in an alpine north-south running valley means there is a regular occurrence of Föhn at the site, especially so in the months April and May (MeteoSchweiz, 2013).

Population

Flüelen was first mentioned in historical records in the 13th and 14th century. The fish farm lies on the outskirts of the village Flüelen next to a camping ground. The municipality including the Gruon valley counts about 2000 people, just about 10% more than 1970. The lake is an important part of daily life and source of pride for the locals (Gemeinde Flüelen, 2017). Fishery was once an important trade in the area, now it is a revered hobby. Due to national and international competition and decreasing fish grounds only one professional fisher is licenced to fish the Urnersee today.

Lake ecosystems

Many of the fish species affected by the impact are endemic to the Urnersee. The Swiss lakes harbour many such species – most of them are endangered. Some of the species living in the lake 100 years ago cannot be found anymore. To blame are overfishing and lake pollution from agricultural input amongst other factors (Kottelat and Freyhof, 2007, Rösemeier-Buhmann, 2017). Some of the fish species repopulate due to restrictions on recreational fishing and breeding efforts. However, fish grounds shrank due to construction on lake- and riverbeds and are too small to sustain fish populations (Tierwelt, 2016).

5.2. Observed impact

This case investigates groundwater warming at a fish farm in Flüelen, in the Canton of Uri (see Fig. 12). The fish inspectors tending to the site reported a rise in temperature of about 1-2°C over the last 30 years. As the groundwater is used for fish egg hatching, which is very temperature-sensitive, this temperature change has serious consequences. The local information for this case stems from interviews with local experts

Local observation

The case is centred around a fish farm, located in Flüelen on the eastern waterfront of the Urnersee (Lake Uri). The Urnersee is the upstream part of the Vierwaldstättersee (Lake Lucerne) with its main contributor the Reuss river flowing into it in Flüelen (Swisstopo, 2017). The pur-

Fig. 13: Fish farm case site, measurement stations and significant influences.

Fish farm site, data measurement stations (Kanton Uri, 2017b, MeteoSchweiz, 2017), perimeter of Reuss delta restoration (reussdelta.ch, 2017) and groundwater protection areas (restriction on construction and activities endangering groundwater quality: increasing regulations S1, S2 to S3 (Swisstopo, 2017)).

pose of fish farming in Uri is to support the native fish population in the area, which gets reduced through recreational and professional fishing and building activities.

The fish farm system helps to conserve the species in an environment under stress and increases the fishing stock. The system consists of three farms around Altdorf, UR. In Flüelen, the fish eggs hatch in autumn and the fish grow until summer when they are transported to one of the outdoor farms. There they stay until the age of a year before being set free or kept in the farm for breeding purposes. The grown fish are then released into streams, lakes and reservoirs in the Canton of Uri (Jaun, 2017).

In Flüelen the focus lies on the hatching and early development stages of the fish. This early development stage is the most critical and sensitive to disturbances. To ensure optimal conditions, the water used should be free of germs and parasites. Therefore, groundwater from directly under the site is used instead of lake water. The fish farm breeds a range of fish species, including: *Coregonus zugensis* (Balchen) and *Coregonus suidteri* (Albeli), *Salmo trutta* lacustrine and riverine forms (Lake and river trout) amongst others (Jaun, 2017, Kottelat and Freyhof, 2007). These species lie in the focus of this study as they are all cold-water spawners, laying their eggs in October-December (Kottelat and Freyhof, 2007).

The fish farm in Flüelen does not use the lake as a farming ground but indoor tanks and containers fed with groundwater from underneath the site. However, the temperature of this water determines early fish development. The higher the temperature of the water, the faster the fish development. A too fast development results in high fish mortality. In the Urnersee the ideal temperature for hatching is around 5-6°C. The optimal temperature for fast growth, but reasonably low mortality and malformation in the fish farm is around 8°C (for the fish from the Urnersee). This was the temperature of the groundwater around 1985 when the groundwater pump was installed. Water temperature should not surpass the critical threshold of 10°C. This general rule is applied on the fish farm for the hatching of the more sensitive *Coregoni* and *Salmo trutta* species.

Because fish development is easily disturbed by temperature changes, the water temperature is closely monitored on the farm during the fish egg hatching in October to November. If the water temperature rises to 10°C it is cooled down using colder water pumped up from a low layer of the lake. The water-cooling system does not mix in lake water with the groundwater, because the germs in the lake can lead to higher fish mortality. Since the 1980s and especially in the last 10 years the water increasingly rose above the threshold and has to be cooled down nearly every day now. Hence, a steady increase in groundwater temperature was observed.

Repercussions and adaptation measures

The fish farm is directly impacted by this development, as there is an added effort to cool down the water. This is especially taxing as they report that the lake temperatures in autumn also increased and this makes the cooling process less efficient. Also their workflow needs to speed up along with the rapid fish development. The fish farm could only marginally adapt to this development, as they put a larger part of their budget toward electricity expense. A large scale renovation installing new equipment with higher cooling efficiency is not planned, as it is not clear how long the fish farm will remain at this site.

Apart from the fish farm this also has significant implications for the Urnersee fish ecosystems. If increasing lake temperatures causes the groundwater temperature increase, lake temperatures will also instigate serious disturbances in the ecosystems. Higher autumn and winter temperatures cause the fish to hatch early, when the lake is too cold and there is a lack of nutrients for the hatchlings to develop. To counteract this, fish have to look for more suitable spawning and living grounds. The lake is deep and layered, so if water temperature is increased at the surface, fish have to move further down and disturb the species living at this level. Also fish that spawn in shallow water cannot easily move to lower levels because of water temperature. Other

factors that change at a lower lake level, like oxygen levels and lake floor vegetation, are also important for the spawning and hatching process. So increasing groundwater temperature could be an indication of changing lake conditions that impact water ecosystems severely. This impact observation stresses the need for research of the situation but also that the support the fish farm gives local fish ecosystems has become crucial for the survival of the endemic species.

5.3. Fish and water temperature

A basic understanding of the processes linking the local fish ecosystem with water temperature is important. Even though the impact here was observed in a man-made system, the same impacts arise in natural systems if temperatures in water bodies rise. This chapter discusses the basic connection of fish development to water temperature.

It is notable that fish nomenclature is often not correctly applied in the context of the fish industry and also in research literature. Here, the nomenclature of the Handbook of European Freshwater Fishes by Kottelat and Freyhof (2007) is used, which provides a comprehensive taxonomy for freshwater fishes.

The pre-hatch and hatchling development of these fish is dependent on water temperature and therefore susceptible to temperature changes. There are studies about thermal water stress during incubation on Coregonus clupeaformis a north American species with the common name lake whitefish (Brooke, 1975, Lee et al., 2016, Stefanovic et al., 2016) and on European whitefish (taxonomically incorrectly labelled as Coregonus lavaretus, which does not refer to a single species, but multiple undefined species in central and northern Europe) (Cingi et al., 2010, Karjalainen et al., 2014).

Incubation experiments under controlled environments help assess how fish development is affected. Brooke conducted experiments as early as 1979 with a focus on incubation temperatures. According to this study the healthy range of incubation temperatures where Coregonus clupeaformis can develop is around 3.2 to 8°C. A temperature of 2°C or 10°C resulted in lower hatching rates (6-28%, with the optimal being 70-73% at 4°C). A 10°C hatching temperature also resulted in abnormal development of 86% of the fry. Higher incubation temperatures therefore speed up the development to a point, where hatching is starkly reduced and malformation of the fish prevalent (Brooke, 1975). The incubation studies (Brooke, 1975, Karjalainen et al., 2014, Lee et al., 2016) all show results that lead to the conclusion that development is accelerated in higher water temperatures. The temperature therefore needs to lie in a certain range depending on the temperature the species is adapted to.

While constant changes of the water temperature affect the fish development, short-term heat fluctuations do not impact the development significantly. In the wild this means that the fish can cope with short-term (e.g. industrial) thermal influences but long-term warming or cooling is problematic (Lee et al., 2016). This raises concerns about the conservation of fish species in different climate change scenarios (Karjalainen et al., 2014). A long-term warming could therefore seriously disturb local systems and threaten the survival of the wildlife.

The conditions of Coregonus clupeaformis are comparable to the less distributed and researched coregonid species endemic to Vierwaldstättersee (Kottelat and Freyhof, 2007). While the temperature range and their specific mortality rates vary from location and species, the developmental reaction to temperature is the same. So these local species would also be seriously affected in their early development if water temperatures rise long-term.

5.4. Groundwater temperature

The impact primarily observed is groundwater temperature change. This chapter introduces the different factors influencing groundwater temperature. The focus lies on shallow groundwater flow and temperature, in areas close to infiltrating water bodies.

Knowing how water flows in the ground provides information on water mixing and storage length. Classifying the case site into the correct aquifer type helps to estimate in which direction and how fast groundwater flows. The velocity and direction of the transport also gives an indication of the time lag between infiltration and sampling. In Switzerland all three aquifer types are present: Karst-aquifers, fractured rock aquifers and unconsolidated rock aquifers. For a site on alluvial deposit, the most likely aquifer is the unconsolidated rock aquifer, where groundwater flow is the fastest and possible in any direction (Hölting and Coldewey, 2013).

Groundwater temperature is based on the temperature of the water infiltrating the ground. The temperature of infiltrating water changes through mixing with older groundwater and through ground temperatures. A large part of infiltration is stream water, especially so, if the groundwater site is close to a water body. So stream temperatures are a major driver of groundwater temperatures. At the source, stream water has the mean yearly ambient air temperature. Downstream, glacial or snowmelt waters join in and atmospheric exchange of sensible and latent heat occurs. The fluctuations of these atmospheric influences constantly affect the stream temperature. Further downstream, the water progressively warms up because of these atmospheric influences until the temperature is at balance with the surrounding system. In the mountain this state is never reached, as the mean temperature steadily increases with lower elevation. Mean stream water temperatures are therefore lower than mean air temperatures (BAFU, 2012b).

Climatic variables like air temperature are major drivers of river water temperature changes. However, there is a time lag between the forcing of air temperature and the river temperature because of the different heat capacity of air and river temperatures. A certain amount of energy induced in water will produce less of a temperature change than the same energy induced in air. So a trend observed in air temperature is less steep in a water body. Eventually the lagging water temperature will rise a similar amount as the air temperature and the system will reach a new equilibrium (BAFU, 2012b).

In the upper zone of the ground up to a depth of 10m, the temperature of the water shows seasonal changes. The closer the groundwater is sampled to its recharge source and to the surface the more seasonal fluctuation it undergoes. Farther down in the ground the yearly amplitude in temperature gets smaller until fluctuations only represent larger multi-year trends. Moreover, the closer the sampling site is to the source, the faster seasonal fluctuation can be observed. So the depth of the sampling site and how fast water travels through the aquifer determines the extent of variability. This means water in the very shallow ground next to an infiltrating water body would show large seasonal fluctuations with a slight time lag to the recharging water body (Parsons, 1970, Figura, 2013). Due to the time lag between surface water and groundwater the highest temperature peak in the ground is later in the year and the amplitude of the fluctuations is smaller. So temperature of air and infiltrating water bodies is reflected in groundwater temperature measurements (Figura, 2013).

Moreover, human activity influences both ground and surface water temperatures, especially in systems where human-system interaction is substantial. One of these influences is thermal exchange through ground heat exchangers used in heating or cooling systems in houses. Ground heat exchangers draw heat or cold from the groundwater and subsequently change the temperature of the ground. This is an effective and increasingly used method as the thermal capacity of water is large (Figura, 2013).

Climate change influence

Climate change is expected to have a significant influence on groundwater in Switzerland, predominantly because of air temperature and subsequent river temperature rise. Groundwater temperatures will likely rise most drastically, where river water feeds it. How large these temperature changes will be, depends largely on the modelling scenarios, which also harbour many uncertainties. Up to the year 2085 the modelled temperature for Swiss aquifers ranges from 0°C to +7°C. Apart from the influence the rising temperature has on the fish ecosystem, the rising temperature also affects water quality. Groundwater provides 80% of the drinking water in Switzerland today. Rising temperatures lead to higher groundwater pollution through chemical and organic substances. Of course such a big temperature and water quality change would have devastating effects on both natural and human systems (CH2014, 2014).

5.5. Research in the region

The BAFU (2009) observed and reported groundwater situations and changes all over Switzerland through the National groundwater observation network NAQUA. However, their report focuses on groundwater levels and not temperature analysis. The national research program "Sustainable Water Use" NFP61 (2017) launched a project to observe groundwater temperature changes in Switzerland and analysed them in connection with climate change. Consequently, multiple sub-projects investigated recent groundwater temperature changes in Switzerland (Figura et al., 2011, Figura, 2013, Figura et al., 2015).

Figura et al. (2015) investigated historical groundwater change in alluvial valley aquifers in Switzerland to assess how temperatures might change in the future. They suggest that local groundwater temperatures, fed by river water infiltration, will increase between 1.1 and 3.8°C by 2100. Increase in temperature in certain perialpine lakes is already attributed to climate change. Lepori and Roberts (2015) found that the temperature in Lago di Lugano (Lake Lugano), which is a comparable pre-alpine lake, changed to a large part due to climate forcing and will continue to change until the end of century between 1-2°C and 4-5°C depending on scenario. This is comparable to the projected groundwater temperature changes.

Locally, the Canton of Uri publishes a hydrographical yearbook since 2011 including yearly analysis-tables of ground and river temperatures and levels. They do not provide any analyses about long-term changes, however. For the fish farm site specifically, there are no analyses of groundwater temperature changes up to now (Kanton Uri, 2017b).

Groundwater at study site

Even though no particular research in the proximity of the site exists yet, mapping of the site is extensive and allows setting the site into context. The national map portal Swisstopo (2017) and the Cantonal geographic database of Uri Geo.ur.ch (2017) provide a range of maps on geographic information. This includes the important circumstances for groundwater generation at the fish farm location.

Located on an alluvial fan, the main aquifer type is an unconsolidated rock aquifer. The high permeability of this aquifer allows for movement of water in any direction. So infiltration is possible through stream water, lake water and precipitation (Hölting and Coldewey, 2013, Swisstopo, 2017).

The fish farm is on the board of the Urnersee just about 1m above the lake level (Portmann, 1985), where the water saturated zone lays only 1-2 metres below the surface (Swisstopo, 2017). Consequently, there is a large interaction between the groundwater and water from the lake. The water collection site is at a distance of about 15m from the lakefront and over 30m from the Gruonbach delta. Additional to the lake, the Gruonbach is a potential infiltration source. As it is a much smaller body of water and a larger distance away, the contribution of water is likely less large and the time lag of fluctuations longer compared with the lake water (Geo.ur.ch, 2017). The relative contribution of the two sources will also vary based on water levels and stream runoff (Hölting and Coldewey, 2013).

The current groundwater pump collects at a depth of around 7m below the surface, more than 5m below the groundwater level. It was built in February 1985, while the fish farm itself opened in June 1973 (Portmann, 1985, Gisler-Jauch, 2015). Because the collector is quite close to infiltrating water bodies and not lower than 10m below the surface, the water temperature should show seasonal fluctuations (Figura, 2013). The temperature at the site results from a combination of lake, stream, ground and air temperature amongst other minor drivers.

5.6. Attribution assessment

The five steps of the attribution assessment now evaluate the observed impact, based on the information gathered in the introductory chapters. The assessment only applies, however, if the two main prerequisites for the research questions are met. First the observed impact needs to have a connection to the climate. Generally, groundwater temperature is influenced by climatic variables and changes in temperature principally come from infiltrating water body temperatures, which are mainly influenced by air temperature (see 5.4 Groundwater temperature). Step two of the assessment estimates if this is the case on the local scale. In addition, the observed impact has to have a small spatial extent. As the groundwater observed stems from a single groundwater pump, the local extent is given. The case therefore fulfils the prerequisites and the five steps of assessment can be applied to the Flüelen fish farm case.

5.6.1. Step 1: Hypothesis

The attribution assessment evaluates the following hypotheses, based on the research and context analysis presented above. For the observed impact, the air temperature is the most influential climate variable, indirectly through surface water and ground temperatures (Figura, 2013). According to this underlying process, the hypotheses are formulated. As it would be too complex for this local study, it does not differentiate between climate changes driven naturally and anthropogenically.

H_0: The groundwater warming is due to factors other than climate change.

H_1: The groundwater warming is most likely caused through air and surface water temperature changes connected to climate change.

5.6.2. Step 2: Trend analysis

The trend analysis consists of two consecutive steps. First is observed impact analysis to see if the connection of the groundwater to the climate variables is present in the local case as well. Secondly the trends in the impact and climate signals are identified. This chapter discusses the data and methods used in both steps, before the trend analysis commences.

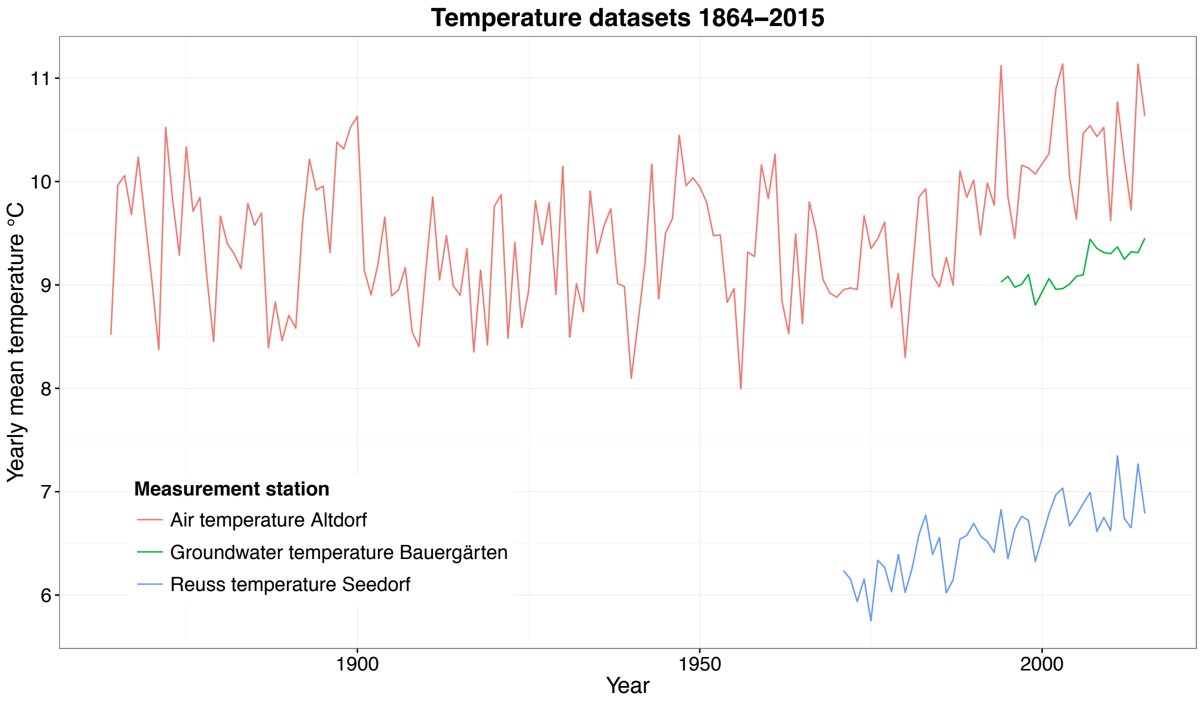


Fig. 14: Mean yearly air, groundwater and Reuss water temperature data used for Flüelen fish farm case.

Mean yearly air temperatures at the station in Altdorf, mean yearly Reuss water temperatures at the Seedorf station and mean yearly groundwater temperatures at Bauergärten (MeteoSchweiz, 2016, Kanton Uri, 2017b).

Data for statistics	Source	Time frame and resolution	Location
Reuss river temperature	Kanton Uri (2017b)	1971-2016 Hourly in °C	Reuss delta
Groundwater temperature	Kanton Uri (2017b)	Nov 1993- 2016 Hourly in °C	Bauergärten, Seedorf
Air temperature	MeteoSwiss station (MeteoSchweiz, 2016)	1864-2016 mean daily temperature in °C	Altdorf

Tab. 3: Data used in trend analysis for Flüelen fish farm.

Data for the trend analysis

Three main datasets provide a base for the observed impact and trend analysis (see Fig. 14 and Tab. 3). Unfortunately, while the fish farm monitored the groundwater temperatures, no records of the temperatures exist. These would be beneficial, but as they are not available the observation is based on the recollection of the fish farm employees.

Neither lake temperatures in the upper part of the Urnersee nor the Gruonbach have been monitored. There are no archived measurements of lake water temperatures anywhere in the lake, only temperatures of the inflowing rivers like the Reuss or Muota (BAFU, 2017a). However, the Canton of Uri measures the Reuss river temperatures just before its entry into the Urnersee about 2.5km from the fish farm since 1971. The Reuss temperature largely influences the upper Urnersee temperatures, as it is its major contributor. About 40m from the river, close to the river temperature measurement station, the Canton also measures groundwater temperatures in a depth of about 5m since late 1993 (Kanton Uri, 2017b). The station is comparable to the fish farm site in elevation, proximity to the infiltrating water body and sampling depth. The saturated zone also lies only 1-2m below the surface, with recharge from Reuss (Geo.ur.ch, 2017). Unlike the fish farm site, it lies on a largely undisturbed pasture not in an urban area. Both river and groundwater stations are part of the Cantonal water observation campaign including five river and 15 groundwater measurement stations (Kanton Uri, 2017b).

Together the two measurements are the most similar to the lake – stream – groundwater system at the fish farm. The rivers temperature is likely similar to the Urnersee temperature at the site of the fish farm as it is reasonably close. Therefore these datasets are proxies for the fish farm groundwater and Urnersee temperature changes.

The air temperature at the Altdorf station serves as the closest related climate variable. The station is located at the same elevation as the fish farm in Altdorf, about 1 km from the river and groundwater measurement stations and 3km from the fish farm. The measured air temperatures therefore are more or less equal to the temperatures at the fish farm and the water measurement stations. The time frame of the air temperature data spans over 150 years from 1864 onwards. This long time series is optimal for such climate observations.

The year 2000 was excluded for all datasets, as the summer months were not measured at the groundwater site.

Methods

The methods rely primarily on both Spearman's correlation coefficient to link the observed impact to climatic variables and simple linear regression models to identify trends. The advantages of linear regression models are that they assess how a dependent variable reacts to a change in an independent variable. This is useful as a trend in a temperature dataset can be quantified if time is used as an independent variable. The significance level is again 0.05.

Air temperature influences the river water and also the ground temperature, so it should have a relation to the groundwater temperatures (Figura, 2013). Empirical research found this link at other sites and such an impact analysis assesses if local climate trends development concur with groundwater temperature at this local site. However, linear regression with groundwater temperature as the dependent variable and air temperature as an independent variable are not appropriate. The plot diagnostics for such a model show, that the residuals do not fit a normal distribution and the model is also vulnerable to influential cases due to the small number of observations. Instead a non-parametric rank-based correlation test by Spearman is used to establish the link between both the air and groundwater temperature and the river and groundwater temperature. As similar trends in both datasets could overestimate the correlation between the datasets, they were stripped of the trends before applying Spearman's test with the air temperature data (Backhaus et al., 2011).

The temperatures used are mean monthly and yearly temperatures. This aggregation smoothens out seasonal variability and is therefore useful for long-term trends. Furthermore, the monthly temperatures are used to identify seasonal variability. Through identification of the yearly peak temperature in each dataset, the time lag between the temperatures can be determined. Correction of this time lag is crucial to be able to compare the air and river temperature influencing the groundwater.

Time lag correction

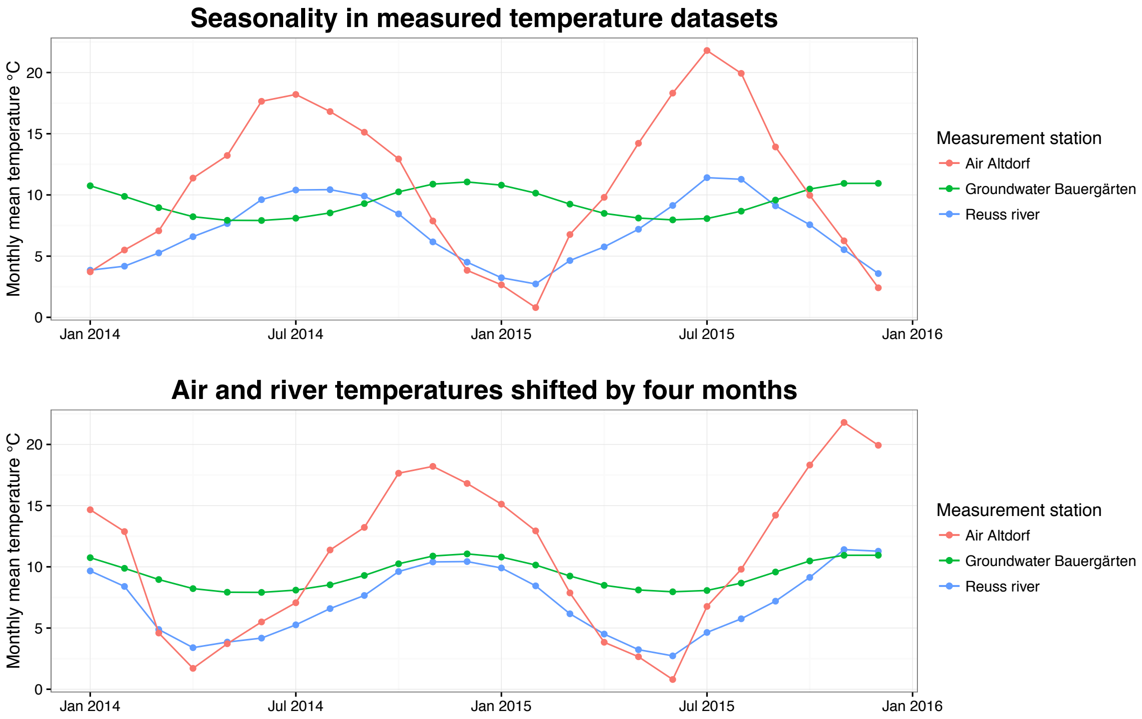
Fig. 15 shows a two-year extract of the temperature datasets. The upper plot graphs the temperature datasets. While the air temperature peaks in June to August, and the river temperatures in July to August, the groundwater temperatures are highest in November to December.

Consequently the time lag between air/river and ground temperature is about four months. This is an approximation as the time lag is not identical in all years, but actually varies between 3.5 and 4.5 months for air and ground temperatures. The lower plot depicts the same groundwater temperatures with air and river temperatures from four months before, getting rid of the time lag between air temperature and groundwater temperature. The models presented here always compare the monthly groundwater temperatures to their corresponding shifted air and river temperatures. The other major difference between the temperature curves is the amplitude of the seasonal fluctuations. The time lag and the low amplitude illustrate how the temperature fluctuations are dampened in the ground through ground temperatures and water mixing.

Secondly, linear regression assesses the trends found in the three datasets. The groundwater temperature trend is a proxy for the groundwater trend at the fish farm. The climatic trend is mainly assessed by air temperature. Air temperature serves as an independent climate variable, as it influences groundwater but the influence of groundwater on the air temperature is likely minor. The air temperature does not influence groundwater temperatures directly but indirectly through influence on ground and water body temperatures (BAFU, 2012b). Hence, trend analysis of the Reuss temperatures complements the assessment.

5.6.2.1. Impact assessment

The trend analysis first links the observed impact to the larger climate context. Tab. 4 lists the result of Spearman's correlation test of both river and groundwater temperatures to air temperatures. The analysis aggregates monthly data to yearly data over the available timeframe. To


Seasonality in measured temperature datasets

Air and river temperatures shifted by four months

Fig. 15: Seasonality of groundwater temperatures compared with river and air temperature.

Upper: The mean monthly temperatures (°C) for the three datasets: Groundwater temperatures at Bauergärten, Air temperature in Altdorf and Reuss river temperatures in Seedorf 2014-2015. Lower: Same datasets with air and river temperatures shifted to four months before groundwater temperature.

Spearman's rank correlation	**Reuss river temperature at *Seedorf***	**Groundwater temperature at *Bauergärten***
Timeframe	Jan 1971- Dec 2015, yearly	Jan 1994- Dec 2015, yearly
Shift in months	No shift	GWT shifted four months
Trend	Stripped before testing	Stripped before testing

Mean monthly Temperatures (°C)	Rho: 0.60	Rho: 0.42
	p-value: 0.00002	p-value: 0.057

Tab. 4: Spearman's rank correlation of river and groundwater temperature to air temperature.

Using the Spearman's correlation coefficient rho, the river water temperature at Seedorf is compared to the air temperature in Altdorf on the left. On the right the groundwater temperature at Bauergärten is compared with the air temperature. All temperature series were stripped from trends before testing.

account for the time lag of groundwater temperature, the two datasets were shifted by four months. For instance, the Spearman's correlation coefficient compares the Jan 1994 - Jan 1995 groundwater temperature with Sept 1993 - Sept 1994 air and river temperatures.

The river temperatures show a very strong positive correlation (rho 0.60) with a very low p-value (p-value < 0.001) with the air temperatures. The groundwater temperature shows a similar positive correlation of rho 0.41 and p-value 0.057. So the null hypothesis that there is no association between the two variables can be rejected for both tests. So both variables linked to the impact have a correlation with the air temperature. While the relationship is strong between both temperature series and the air temperature, the correlation between groundwater temperature and air temperature could improve if additional factors were considered. Ground temperature and water already in the system are such additional factors. However, water mixing is a factor that is difficult to assess, because mixing water is of an unknown temperature. Hence, the groundwater temperature reacts rather sluggishly to changes, and the variability is smoothed out (Figura, 2013). If the exact time lag and the average age of the water already in the ground were known, the model would probably also improve. This can also be seen in Fig. 16 where the yearly temperature of all datasets between 1995 and 2015 is plotted. Visually, especially the peaks in especially warm or cold years seem to coincide in all datasets, while the groundwater otherwise shows little variability.

For the purposes of this project it is sufficient to say that there is a significant link at this local site between climate variable and impact observations. The air temperature should therefore reflect a trend in groundwater or river temperature development.

Observed impact

The trend in the observed groundwater temperature at Bauergärten gives a temperature change over the last 22 years. This analysis provides an estimate of yearly change that can be extrapolated for the timeframe since the current pump was installed (1985 onwards). The linear change indicates if the magnitude of the impact observation is realistic. Thr trends over all datasets are illustrated in Fig. 16.

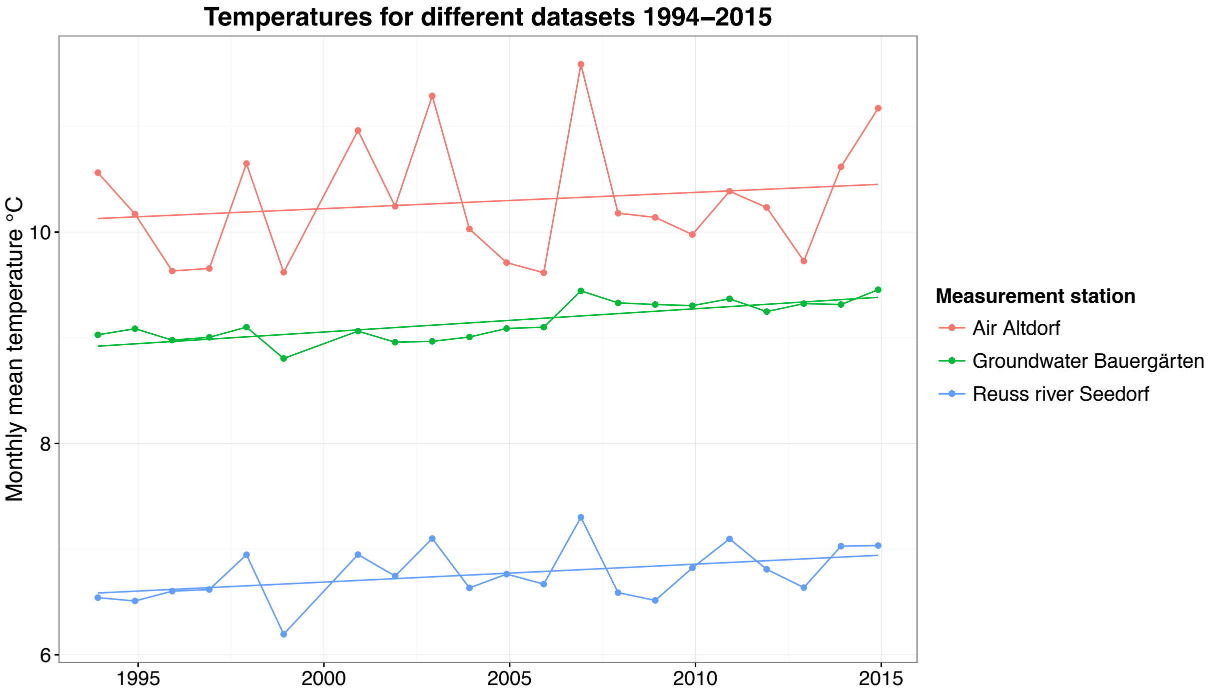


Fig. 16: Temperatures of air, river and groundwater used for Flüelen fish farm with trend line 1994-2015.

Plot of the air temperature measured in Altdorf, river temperature measured at Seedorf and groundwater temperature measured at Bauergärten. The linear regression lines over the timeframe measured (1994-2015) are added.

Even though the observation was only measured for 22 years, yearly mean temperatures show a significant increase (see Tab. 5). The trend in groundwater temperature is highly significant at a p-level of <0.001 and increases at 0.019°C per year. Extrapolated over the timeframe 1985 to 2016 this is equivalent to an increase of 0.62°C. The projected temperature ranges between 0.33°C to 0.92°C (2.5% to 97.5% confidence interval). This is a slightly smaller impact than the reported 1-2°C of the fish farm. Temperatures in October-November, when the groundwater is extracted at the fish farm, show a slightly higher increase of 0.68°C since 1985. As the report of impact was not clear on when exactly the observation started, the temperature change could also refer to the opening of the fish farm instead of the installation of the current pump. In summary, there is a definite increase in groundwater temperatures of about 0.7°C since 1985, with a maximal increase of 0.92°C (at the upper limit of the 95% confidence interval), which is close to the observed impact of 1-2°C.

5.6.2.2. Climatic trend

The second step in the trend analysis, after the impact is linked to the climate, and the development in the observed impact is assessed, is the evaluation of the climatic trend. The air temperature and river temperature trend is assessed from 1971 to 2016 as both datasets cover this time period using linear regression.

Firstly, the significant trend in mean yearly river temperature is very similar to the groundwater temperature with an increase of 0.68°C since 1985 (groundwater: 0.62°C per year). This similarity falls in line with the expectations that the infiltrating water body shows a very closely related trend. Secondly, the significant trend for mean air temperature since 1985 shows a faster increase. With 1.23°C since 1985 the increase rate is doubled. This is to be expected as the water and air temperature did not have enough time to achieve a new balanced state, so the water temperature rise lags behind (BAFU, 2012b). In summary, the air temperature representing the climate variable, the river temperature and the observed impact all show a comparable trend (see Fig. 16 and Tab. 5). Thus, a significant climate trend related to the observed impact is present in the data.

Model diagnostics

For each of the analyses, the suitability of a linear regression model for the datasets is tested. Plot diagnostics test for normal distribution, homoscedasticity and influential cases. The diagnostics found no irregularities or influential cases for any of the models. Therefore, the models are suitable for the analysis and no adaptation was needed.

Linear regression	**Groundwater temperature *Bauergärten***	**Reuss river temperature *Seedorf***	**Air temperature Altdorf**
Temporal resolution	1994-2016, mean yearly	1971-2016, mean yearly	1971-2016, mean yearly
Temperature trend over timeframe	Estimate: 0.019	Estimate: 0.021	Estimate: 0.038
	Yearly change: 0.019°C Cal. change since 1985: 0.62°C	Yearly change: 0.021°C Cal. change since 1985: 0.68°C	Yearly change: 0.038°C Cal. change since 1985: 1.23°C
	Significant at level 0.001	Significant at level 0.01	Significant at level 0.001

Tab. 5: Linear trends in temperature datasets calculated for different timeframes.

5.6.3. Step 3: Baseline behaviour

As a third step in the attribution assessment the baseline behaviour of the system if no climate change was present, is identified. If this baseline behaviour is different from the trend behaviour modelled in step two, an impact can be detected. The magnitude of the influence non-climatic drivers have on the observed impact is weighed up against the contribution of the climatic influence. Therefore, it is important to assess non-climatic drivers diligently.

There is no research of how the groundwater temperature in the area would develop without climate change influence. On a larger scale, climate models such as Global Circulation Models (GCM) could be used to model behaviour of a system with natural and anthropogenic forcing (see 2.2 Climate change impact detection and attribution). As it is a local case, climate models are not a viable option because they need a range of quantitative data and local influences on climate are complex to model. Therefore, a context analysis of the case is used to assess baseline behaviour. If the circumstances of the impact changed, it is likely that the impact was influenced in some manner.

Influential changes on the observed impact could stem from a range of factors. Especially in urban areas groundwater temperatures can be severely affected by the rapidly changing circumstances (Epting and Huggenberger, 2013). The changing circumstances included here are infrastructural and land-use changes in the area, changes in groundwater use on the farm and its circumference and influences on the infiltrating water bodies.

Firstly the infrastructural changes in the circumference are assessed. Particularly influential are water-cooling systems using groundwater and heated buildings, which reach into the aquifer. Water-cooling systems use cold groundwater in a water exchanger for air-conditioning. The water given back to the system after this process is warmer than before (Epting and Huggenberger, 2013). There are no heat exchangers registered in a radius of 250m from the fish farm collecting site. Outside of this perimeter there are five earth probes in the upper part of the aquifer, which could potentially influence the water at the site. Whether they are used for heating or cooling and when they were installed, is not open for public inspection. As these are quite far away and mostly not directly in the path, groundwater would take according to the isohypses, it is not likely that this influence is large (Geo.ur.ch, 2017).

Heated buildings reaching into the aquifer can also raise groundwater temperatures. In the proximity of the site and closer upstream part of the aquifer, no new buildings were built after 1985. The campsite next to the fish farm opened at the same time as the pump was installed in 1985. So additional buildings likely had no effect on the groundwater temperature. Most of the surrounding area is used as a campsite, without basements reaching into the aquifer. The other already existing buildings could have changed their heating system or the locals could have used the heating installed more often. However, as the main influence on October-November groundwater temperature is in the summer month this should have a small influence on the months the water is gathered. Of course it could still have an influence if the yearly mean temperature was increased due to larger heating. As the habits of the locals are not known, this possible influence cannot be assessed (Swisstopo, 2017). Information on other influences on the aquifer like installing of hot water pipes or warm waster deposition was gathered, but no additional suspicious influences were detected (Geo.ur.ch, 2017).

Influences on the water bodies include changes in the Gruonbach catchment, the Urnersee and precipitation. As there was no real change in infrastructure since 1985, thus precipitation infiltration amounts have likely not changed. A groundwater protection area protects the middle part of the Gruonbach catchment since 2008, which ends 700m upstream from the delta. The fish farm also lies within the perimeter of the surface water protection zone for both the Urnersee and the Gruonbach (Swisstopo, 2017).

The Urnersee itself and particularly the Reuss delta leading into the Urnerseee underwent major construction in 2003-2007. While building the NEAT basis tunnel through the Gotthard massif, a large amount of debris from the drilling was used for revitalisation of the Reuss river delta. Ecological studies researched beforehand suggested, that in the long-term the systems profit much more from the revitalisation than is being destroyed by the debris. However, whether the water temperature could be affected somehow is not mentioned (Schilter and Gemperli, 2002). The Reuss temperature measurement station is located a few hundred metres upstream of the delta and should therefore be unaffected by the revitalisation. Other distinct influences suggesting river temperature change could not be detected.

In summary, baseline behaviour is difficult to distinguish for the fish farm, as there are many possible factors influencing groundwater in an urban area. No single factor seems likely to have caused such a slow but steady increase of temperatures. Due to the fact that since 1985 the closer proximity of the fish farm has largely stayed the same for the above-mentioned factors, there is no clear indication that the temperature would rise at such a rate as the observed impact suggests. A slight increase or decrease of temperature or no change, all lie in the range of possibility for baseline behaviour. The combination of heating behaviour changes, lake temperature changes due to construction and water cooling systems amongst others could all sum up to make a significant impact on the groundwater temperature, however. Assessing the magnitude of this influence and even if the influence has an increasing or decreasing effect on temperature is very taxing and outside of the scope of this thesis. As there is no clear indication, however, that the baseline temperature increased, the assumption is made here that this influence would also not explain such a drastic increase as reported by the fish farm.

5.6.4. Step 4: Impact detection

Impact detection compares the influence of the climatic trend found in step two with the baseline behaviour. If there is a significant difference between the two, an impact can be detected.

On the one hand, air temperature and river temperature suggest a significant increase which coincides with the trend of the measured groundwater temperature of around 0.7°C up to 0.92°C. The trend detected at the neighbouring, comparable, but less disturbed site suggests such a trend would also emerge at the fish farm site. The temperature increase in the groundwater measurements extrapolated over the years explains most but not all of the temperature increase reported for the fish farm. On the other hand, the baseline behaviour cannot be identified with certainty, as some influences with the potential to change the temperature have to be estimated.

Relating these findings back to the hypotheses, both the null and the alternate hypothesis cannot be accepted or rejected. Instead a new hypothesis could be suggested that the full impact of 1-2°C temperature increase at the site is a combination of both climatic and non-climatic drivers. To test this hypothesis and qualify the contribution, even more in-depth data for the baseline behaviour is needed, which surpasses the extent of this case study. However, alternate hypothesis that groundwater warming is most likely caused through air and surface water temperatures is at least partly applicable. An impact of climate change can therefore be detected, possibly augmented by non-climatic drivers.

5.6.5. Step 5: Attribution

Detection of an impact of climate change is possible so attribution analysis is done as a last step according to Hansen et al. (2016). This fifth step assesses qualitatively how large the contribution of climate change was compared to other, non-climatic contributors.

As step four established, there is a significant trend of the climate on the impact but it is likely that other factors amplified the impact trend. Climate change through temperature and river temperature change explain about half of the warming trend. The augmentation of this trend could be an effect of a combination of non-climatic factors. Other possible contributors to the impact are climatically influenced variables affecting the system, which are neglected here. For instance ground temperatures could have both increased in summer through higher infrared influx and decreased because of less insulation through shorter snow cover.

Another possibility is that the groundwater temperature increase was perceived and reported stronger than it actually was. In this case, the climate could be the sole forcing for the increase.

In any case, climate change through air temperature increase is a major contributor to the impact along with non-climatic drivers of the urban setting. As this assessment bases on an estimation of the baseline behaviour, confidence in this attribution is low to medium.

5.7. Limitations

The main limitation was the urban setting of the case. Even though the area is rural and the settlement of Flüelen is rather small, the fish farm does lie adjacent to a residential area. Due to the varying influences such residential areas have on the ground, the baseline behaviour estimation is quite vague. Both a better understanding of how urban areas affect groundwater parameters on a local level and more precise local information would be needed to identify this baseline.

Another restriction is the short measurement period (23 years) of the groundwater temperatures in Bauergärten. A longer, climatically relevant time period could have given more clear indication about groundwater temperature behaviour. Additionally, temperatures from the Urnersee or the groundwater on site would have been very informative. The magnitude of the impact on site is reported quite vaguely, which on site measurements over the same time could have clarified.

5.8. Case Classification

The fish farm case is now classified into one of the five cases using the classification scheme from section 3.2 Classification scheme. The climatic driver air temperature has a significant relationship with the groundwater temperatures. Step five of the assessment discusses, that while the climatic drivers explain a major part of the ground temperature change, other contributors are very likely. It can be said, that the climatic drivers contribute the same as or more than the non-climatic drivers. Nevertheless, this attribution is based on assumed baseline behaviour, so it is classed in *Class 3: Suspected climate influence.*

5.9. Adaptation

Direct adaptation of the fish farm to climate change is difficult. Installing a new, more efficient water cooling system or taking water from a different site and transporting it to the farm require funding. The farm needs a system to control water temperatures are not too high and at a more or less constant temperature for hatching.

Of course the site could be moved, but if so, the groundwater used at this site should have a lower temperature of about 5-6°C. This is the optimum for these fish species to hatch and if the temperature rises between 1.1 and 3.8°C as projected (Figura et al., 2015), temperature should not surpass the 10°C mark. However, in all sites where groundwater was measured in the Uri valley, the temperature in October - November lies at or above 10°C as of 2015 (Kanton Uri, 2017b). The only possibility to move to a site with colder groundwater is to move to a higher elevation, which is not practical as the farm needs to be close to the lake and easily accessible, as fish transportation between the farms needs to be fast.

Another possibility is to collect water further down in the ground at the fish farm site. As the yearly mean groundwater temperature is lower than the October- November temperatures, the water about 10m below the surface should be around 9.5°C (if the temperature is slightly higher than measured at the Bauergärten site). However, if the mean temperature rises any farther, which is likely, the water again becomes too warm for the fish eggs. So deepening the borehole would just postpone the problem for another few years.

The aquaculture farm planned at the Gotthard tunnel entrance also uses groundwater for commercial fish production. The groundwater at the site has a temperature of 12-14°C, which is even higher than the Flüelen fish farm. Because the focus in the basis57 fish farm lies on food production with fish thriving in warmer water it does not pose a problem (basis57, 2016). This site is therefore not a viable alternative.

Apart from the farm, the warming of the lake could be critical for the wild fish as well. Lake temperatures in the spawning season do not yet surpass the threshold temperature for high mortality. But any increase in temperature will speed up fish development and if the fish hatch too early, the lake is too cold and barren to let them survive until the next summer. Additionally, thermal stress through high temperatures in summer months is often a problem in fish adapted to relatively low lake temperatures. Genetic and habitual adaptation of fish is more difficult if they live at their thermal limit (Somero, 2010). Self-adaptation of these species is therefore doubly difficult, on the one hand because of disturbed early development, on the other because of thermal stress on the adults. Hence, it is important to provide an optimal environment for the fish to adapt to and not add further stresses on the system. Such an environment for the fish living along the lake bank could be improved with digging small pools where creeks join the lake. The cold water from the creek stays in the pool and gives the fish a refuge during particularly warm summer days. Such a system was successful on the banks of the Rhine (Hofmann, 2006). Such pools could also be useful during spawning season.

5.10. Conclusion

The attribution assessment is applicable to this case to a certain extent. Attribution of the impact to climate change is possible based on assumptions on the baseline behaviour. Even thought the system is well observed and there are representative measurement stations, the location of the case site in a rather urban environment is challenging. Still climate change is identified as a major driver of the detected impact with low-medium confidence. Because of the restraints in baseline behaviour identification the case is categorised as *Class 3: Suspected climate change influence*.

6. Sittlisalp hydro-power plant

Fig. 17: Sittlisalp cheese factory.

Part of the settlement on the Sittlisalp with the alpine cheese factory in the background (Melanie Graf, September 2016).

6.1. Study area

Topography and geomorphology

The case study is located on the Sittlisalp in the Urner Alps in the Canton of Uri (see Fig. 18). The alp is situated on the western board of the Brunnital, a north-south running side valley of the Schächental. It sits on the eastern flank mountain of a mountain range, that consists of the Sittliser, the Blinzi and the Grossspitzen, which all stand around 2400m a.s.l.. The alp itself spans an elevation of 1600-1900m a.s.l (Swisstopo, 2017).

Geologically, the alp is part of the Aarmassif, which was formed in the orogenesis of the Alps in the Tertiary. During the Quaternary the region was transformed through glacial and peri-glacial processes. There is no glacier present today, but glacial remnants, e.g. moraine walls are still prominent features of the alp. Today, hillslope processes are predominant in the higher elevated part of the alp, which is noticeable through the talus deposits on the eastern flanks of the Blinzi and Sittliser. At lower elevations, fluvial processes dominate through the two streams Winterbach and Grossbach (Swisstopo, 2012). This all indicates that the ground consists of mainly loose material over sedimentary rock (SGTK, 2016). Alpine pastures with some smaller shrubs and wetland vegetation dominate the vegetation (BFS, 2016). Soil formation at the site is most likely comparatively shallow due to the slope and the limited vegetation at high elevations.

Local Climate

The northern flank of the Alpine mountain range is mainly influenced by mild and wet winds coming from the Atlantic. These winds provide more regular precipitation in all seasons and milder temperatures compared to continental climates. The winters are colder than on the southern flank and wetter than in some inner-alpine valleys like the Valais. Especially, the higher elevated regions are mostly very cold and wet. An exception to this cold-wet climate is the recurrence of warm falling winds called *Föhn,* which provide uncharacteristically warm and dry days mainly in spring in the alpine valleys (MeteoSchweiz, 2013).

In this regional climate the Sittlisalp climate shows characteristics comparable to other areas at the same elevation. The location on a quite high elevation leaves the alp wetter than the valleys with around 1700 mm precipitation per year (norm period 1981-2010). Also the mean yearly temperature is about 2°C, which is not quite high alpine, but significantly colder than the 10°C average in the valley (MeteoSchweiz, 2013).

Population

From June through September, the various alpine farms and the cheese factory are occupied. The inhabitants work in suckler cow husbandry, producing milk and other dairy products at the alpine cheese factory. There are also some hiking trails leading across the alp, hence some touristic businesses such as a small bar and overnight accommodations have been established in recent years. Still, the main land-use is cow grazing in these summer months (Seilbahn + Alpkäserei Sittlisalp, 2016). The alp is in a remote area only accessible by a small cable car or over a narrow, restricted access street. Alpine farming has a long tradition and the alp has probably been in use for some centuries, nevertheless, human influence on the area is comparatively small (Swisstopo, 2017). Occasionally, there are some vacation guests in winter in holiday houses (which are self-sustained with electricity), but otherwise the alp is uninhabited from October to April.

Regional hydrology

The Sittlisalp is part of the upper catchment area of the river Reuss, which flows into the Rhine in the Swiss midlands. On the alp there are several small springs at 1850-1900m a.s.l., which develop into little streams, fed additionally by surface runoff. At around 1650m a.s.l. they join to either the Grossbach or Winterbach which both join the Schächen lower in the valley (Swisstopo, 2017). The hydrological regime in the higher Alps today is mostly driven by glacial and snow melt. The local regime for the Winterbach on the Sittlisalp is classified as *nivo-glaciaire,* which means stream flow peaks drastically in Mai-June and is low in the winter months. This peak is caused by snowmelt primarily and glacial melt secondarily (HADES, 2015). The moderately high runoff in the later summer months is due to orogenic rainfall (MeteoSchweiz, 2013).

6.2. Observed impact

This third case study is centred around water shortage on the Sittlisalp in the Canton of Uri. During two summer seasons, low water levels were observed in the small alpine streams of the alp. The two years 2003 and 2015 were both considered exceptionally warm and quite dry years in all of Switzerland. Especially the hot and dry summer months led to the two warmest summers in measurement history, with 2003 supposedly being the warmest in over 500 years. This heat and lack of precipitation led to dry spells in Switzerland and all over Europe (BAFU, 2016).

On the alp, waters were especially low in the late summer months in mid August to early September 2003 and end of July to mid August 2015. Over a three weeks period each, the run-off water resources were unusually low, which affected the local inhabitants. The local information in this chapter was gained through interviews.

Local observation

The local residents observed the low water periods most clearly through low productivity phases of a small hydroelectric plant fed by the streams (layout of the plant see Fig. 18). As the alp is in a remote area and only seasonally used, it is not supplied by the commercial power. In 1991, the inhabitants built a private hydroelectric plant with maximally 27 kW/h productivity, using water from several small streams. Before building the plant, runoff measurements were taken over the summer months to make sure that it is an appropriate site for such a plant. It provides an effective and cost-efficient alternative to the previously used wood fires and heating oil. It supplies the 29 alpine farms and businesses and the cheese factory (depicted in Fig. 17) with electricity and warm water. Over the span of the last 25 years there were several years, where the plant fully sustained the alpine businesses with electricity. In most years, the plant had to be occasionally supported by wood fire, however, only over a few days at a time, excluding the two years in question. These observations were only taken over the summer months of May to September, as the alp is uninhabited in winter.

Repercussions

The extra effort and expense for the inhabitants were the main observable and somewhat measurable repercussions of the dry periods. In both dry years, especially in 2015, the operators of the plant had a loss of thousands of franks, as they had to support the hydroelectric plant with heating oil and wood firing. If these dry periods were a regular occurrence in the future due to climatic changes, it could result in the hydroelectric plant not being cost-effective over several years. This would imply that the plant could not be maintained anymore. This would affect the alpine community significantly, as they could loose an integral part of their self-sustenance. There is no record of the dry periods affecting the ecosystem of the alp. The streams are at a high elevation and too small to sustain any wildlife, thus there is little disruption of the stream ecosystem. However, it is possible that the lack of precipitation on the alp influenced downstream systems and if such a summer happened repeatedly, the alpine systems could also have more difficulty to adapt. In summary, it is important to assess the situation on the alp to gain information on future developments and also adapt appropriately to the impact on hand.

6.3. Water resources

Water shortage describes a situation where water resources are not sufficient for a system. Insight into water resources can best be gained by understanding the different parts of the hydrological cycle. The cycle explains transportation and storage of water from the ocean to the atmosphere, and back over the land to the ocean (Hiscock and Bense, 2014). If the study area can be located in the water cycle, it helps assessing why water resources are lacking.

The vast majority of the water on land is locked in storage in either ice, lakes or in the ground. The groundwater is a major source of drinking water as it is purified from germs and mineral-enriched through filtration. The major transportation processes between these storage mediums are evaporation and precipitation. Through this change of state and atmospheric vapour transport it is possible to move large quantities of water from land or ocean to the air and vice versa. More minor transportation processes include overland flow and groundwater flow. These transportation processes move liquid water between different storage media. Surface flow, like streams and rivers, is especially important for human use.

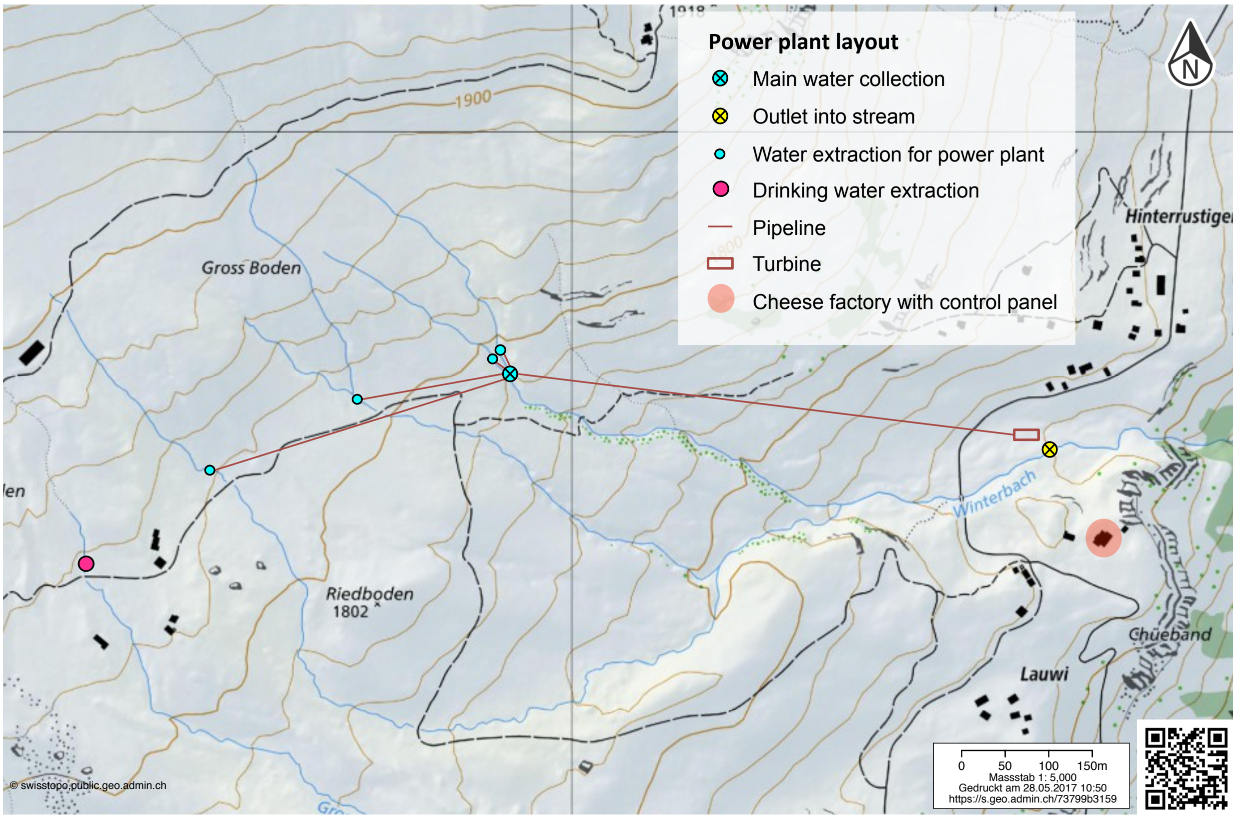


Fig. 18: Layout of the power plant on Sittlisalp.

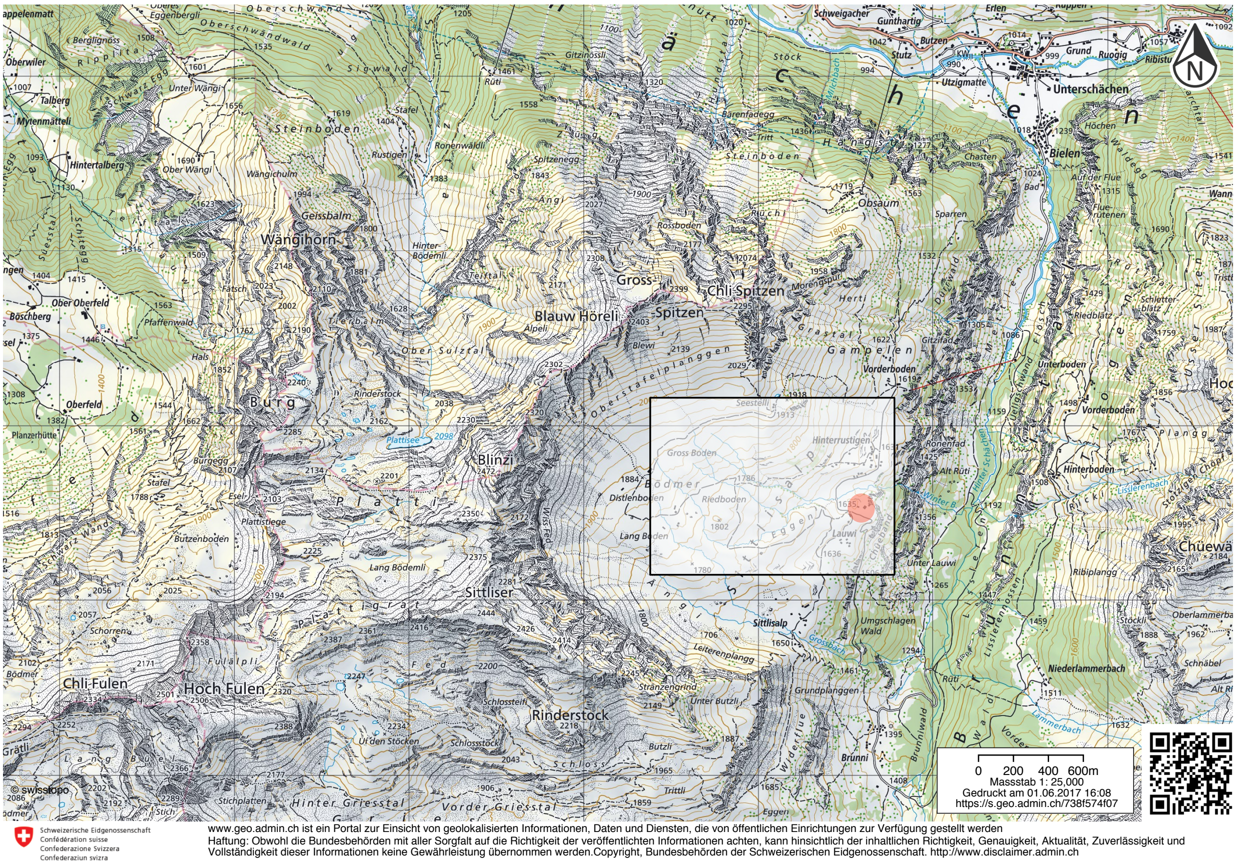


Fig. 19: Overview map of the Sittlisalp within the Brunni-valley.

Rectangle marks the location of the layout plan and the red circle marks the cheese factory, see Fig. 18.

Transportation of goods and people on ships, fishing and hydroelectric power production all make use of surface waters. Streams are fed through direct precipitation, surface runoff or groundwater exfiltration. Concurrently, stream water evaporates and infiltrates into the ground. Which processes are dominant is changing throughout the year as it depends on the amount of precipitation, air temperature and solar radiation (Hiscock and Bense, 2014). The water balance in the Alps suggests that (mean elevation 1664 m a.s.l.) a quarter of the mean precipitation of 1600 mm/a evaporates, while about 1200mm/a runs off directly or after storage. Compared with lowland water balance, the precipitation and runoff are much higher and the evaporation lower (Weingartner et al., 2007).

By understanding the underlying processes, the contribution of the water sources to locally available water can be evaluated. The location of a study area in a high-mountain region indicates that the main water sources are precipitation, glacial melt and groundwater storage exfiltration. The runoff in smaller streams in the glacier-free alpine zone is essentially fed by precipitation and minor groundwater exfiltration (Hiscock and Bense, 2014). Additionally, the characteristics of the catchment are important when considering the influences on stream runoff rate. The time water spends in storage before exfiltration to a stream provides an estimate on the response time of stream flow to precipitation events. Both catchment size and topography are important to assess how long water is stored in a catchment. For small catchments topographic attributes like the flow path gradient influence the residence time considerably (McGuire et al., 2005). Asano et al. (2002) support the argument, that residence time of the water in groundwater storage in small steep catchments can be estimated either by the depth of the soil or the area upslope contributing area. Shallow soil or small contributing areas lead to shorter residence time (Asano et al., 2002). Streams in a catchment that is both very small and has shallow soil depth therefore react quite fast to higher or lower precipitation rates.

Another tool to assess mountain hydrology is the hydrological regime classification. Through measurement of the monthly runoff rates, streams can be classed into different runoff regimes. This classification classes streams according to their major contributing source. These major contributors are rainfall, snowmelt and glacial melt or any combination of those. A shift in regime often means that runoff amounts change in the seasons (HADES, 2015).

A basis for a local climate change assessment is thorough knowledge of the local system. Characterising the local context of the water shortage case therefore provides beneficial information. Furthermore, understanding of mountain hydrology is important not only for the alpine region but also for the downstream systems, as mountainous areas contribute majorly to lowland freshwater resources (Weingartner et al., 2007).

Water shortage

When the water sources are assessed, the water shortage can be evaluated. Water shortage for a prolonged timeframe can lead to a drought. There are several types of droughts, but all types stem from lower than average precipitation possibly coupled with higher than average evaporation and other factors. The water shortage is always relative to the climate of the observed region. Hence, the same amount of precipitation in a dryer area might not lead to a drought. Droughts can vary in severity and length, which are both difficult to estimate, especially in real-time drought observation. Therefore, droughts are classed according to the systems they impact (Wilhite and Glantz, 1985).

Wilhite and Glantz (1985) defined four basic types of drought. The most common type is the *Meteorological drought,* which evaluates the situation based on climatic parameters only. It occurs if water resources are lower than average over an extended time period. This is primarily a product of low precipitation compared to the local climate conditions. However, it can also be caused by other climate variables like increased air temperature. A range of drought indices provides tools to estimate meteorological drought (Wilhite and Glantz, 1985). The indices primarily use precipitation data gathered over a long timeframe and additional parameters such as air temperatures. Drought indices that estimate evaporation are often preferred for climate change estimations, as they account for changing air temperature additionally to precipitation patterns (WMO and GWP, 2016). Meteorological drought is the base of the other drought types, though it can be intensified by non-climatic factors.

The *Agricultural drought* type defines a drought with agricultural definitions additionally. The biological needs of the plants in the ecosystem are considered and if the water resources do not meet these needs an agricultural drought is present. There are also indices to assess the severity of this drought type, for instance the Crop Moisture Index (CMI).

If the hydrological system in the area is impacted, it is considered a *Hydrological drought.* Practically this means the surface and subsurface hydrology is affected by dry spells. As it is concerned with lack of water in surface runoff and storage instead of lack in precipitation, it lags behind the meteorological and agricultural drought and its impacts arise later on. The Surface Water Supply Index (SWSI) for example introduces storage capacity and runoff rates to the drought assessment.

The last type is the *Socio-economic drought*. This term comes into use if social and economic needs cannot be met due to water shortage. Agricultural droughts can have such an impact on economic productivity but unlike the agricultural drought the socio-economic drought is defined through the impact on the human-made system instead of the plant need. Land-use practices can even produce such a drought situation due to excessive demands of the system (Wilhite and Glantz, 1985). An example of a drought reinforced by human behaviour is the US dust bowl period in the 1930s. In this incidence, misguided land-management processes led to dust and erosion amplifying drought conditions impacting land and people majorly (National Academies, 2016). So socio-economic drought introduces an additional driver of drought to the climatic drivers (Wilhite and Glantz, 1985). Most important in all these drought assessments is to evaluate it in the context of the system. Each local system reacts to the water shortage in an individual way and therefore drought thresholds cannot be defined universally.

Meteorological droughts leading to water shortage are categorised as impacts of extreme weather, flooding, for instance, is an impact of intense precipitation events. If the variability of the climate changes, the frequency of all extreme events can increase. Therefore, an increase in intense precipitation and low precipitation periods can coincide in the same area. Additionally, drought frequency can rise if the mean precipitation decreases. Internationally, both of these phenomena have been observed locally, potentially linked to climate change (Easterling et al., 2000).

Attribution of local hydrological impacts has been researched to some extent. Ryu et al. (2011) and Luo et al. (2016) assessed attribution of basin scale hydrological impacts in local cases. Luo et al. (2016) discovered that the main driver of hydrological impacts in recent years was evaporation change and claims that the contribution of climate driver compared to other drivers rose drastically. However, attribution of hydrological impacts especially on a local level has not been used extensively yet.

6.4. Sittlisalp research

The Schächen valley is not the site of a lot of research. That the region is not particularly appealing to researchers is probably due to a range of factors. An important factor to consider is the remoteness of the region and the absence of well-researched landscape features like glaciers or rock glaciers (Swisstopo, 2017). There are no established or planned nature parks in the region, for which investigations would have been necessary or interesting (Netzwerk Schweizer

Pärke, 2017). Also winter and summer sports are very minor as the aim of the locals is to encourage gentle tourism (Unterschächen, 2017). Economically motivated research is therefore not a priority. The region is hardly ever mentioned in research publications most likely due to these factors.

Similarly, long measurement series and regional analyses of precipitation and temperature patterns and similar variables have been conducted in the alpine valleys (Altdorf, Andermatt) but not in higher elevation sites. They are included in the MeteoSchweiz gridded interpolation datasets, which spans the whole area of Switzerland (MeteoSchweiz, 2017).

Although there is no research on water resources in the Schächental region or even specifically on the Sittlisalp, the region has been considered in nation-wide water resource evaluations. This allows putting the study area into the water cycle context. The Swiss Federal Office for the Environment has reported on the regions groundwater situation (BAFU, 2009) and the hydrological regime of the Winterbach was assessed for the Hydrological Atlas of Switzerland (HADES, 2015). Additional ground condition information can be gained on the Swisstopo map portal (Swisstopo, 2012).

According to these sources the cumulated stream catchment size above the water extraction site is less than 1km^2, which is very small. Most of the catchment has a slope angle of over 25%, which indicates a strong slope. The soil depth is classified as shallow with a low to moderate water storage capacity (Swisstopo, 2017). On these reported characteristics the assumption can be made that the stream flow on the alp is closely linked to the precipitation and the residence time of water in the ground is short (see 6.3 Water resources). This means water shortage on the alp would arise soon after a precipitation deficit.

Water shortage and climate change

Water shortage is not a usual occurrence in Switzerland as usually water resources are abundant. Some water intense agricultural practices for fruit and vegetable cultivation developed water management strategies hundreds of years ago. Also irrigation in agriculture is widespread today (DROUGHT R&SPI, 2015). For alps, however, such shortages are rarely reported as agriculture other than animal grazing usually is not feasible anyway. With the introduction of new technologies new water needs arose in recent years.

According to the (BAFU, 2009) report, the groundwater levels were at an absolute minimum in many regions of Switzerland in 2003 and at a very low level between 2003 and 2005 due to below average precipitation quantities. Whether these extraordinary groundwater conditions were connected to climate change was not researched. However, groundwater level changes connected to climatic changes were not observed as of 2009 (BAFU, 2009).

Climatically, air temperature increased with a mean of 0.1°C per decade since beginning of measurements in the mid 20th century in all of Central Switzerland. The spring and summer months show this increasing trend most clearly, especially since 1980. Precipitation trends, however, are either not detectable or differ across the area (MeteoSchweiz, 2013). Regional climate scenarios expect an increase in dry conditions with a moderate confidence level for Central Switzerland. Precipitation is suspected to decrease by an average of 20% in the summer months by 2085 (compared to the norm period of 1981-2010), however; the projections differ largely depending on the scenario they are based on. For temperature projections, an increase of more than 1°C in summer is certain, with an increase of over 3°C by 2085 more likely (MeteoSchweiz, 2013). The combination of these scenarios suggests an increase in dry spells specifically in summer.

Changes in the runoff rates in Switzerland are mainly expected to arise due to a shift from regimes dominated by glacier- and snowmelt to more rain dominated regimes. The Sittlisalp region is no exception and projections for 2085 indicate a shift from the current *nivo-glaciaire* to a *nivo-pluvial méridional* regime. Instead of glacial melt, the second largest influence on stream flow is now rainfall. This regime shift would result in reduced summer stream flow especially in late summer (BAFU, 2012b).

6.5. Attribution assessment

Based on the report on the water shortage on the Sittlisalp the attribution can be assessed next. Again, there are two main prerequisites for the attribution framework to be applied according to the research goals: Firstly, the observed impact has to have a relation to climate change. Water shortage is largely based on precipitation deficits and influenced by other climate variables like air temperature (see 6.3 Water resources). Secondly, the case has to be of local extent. The impact was observed on a single alp for a very small catchment, so the local extent is given. The prerequisites for the assessment are met, thus next the five steps of the attribution framework are applied to the Sittlisalp water shortage case.

6.5.1. Step 1: Hypothesis

The first step of the assessment is to formulate hypotheses for the attribution of the water shortage. According to the literature review (see 6.3 Water resources) and hydrological context of the case, the major influence on stream flow is precipitation. Due to the high elevation and small catchment size it can be assumed that the response time to precipitation events is quite fast. As a secondary influence, air temperatures should be assessed. Based on these processes the following hypotheses have been formulated.

H_0: Water shortage events at Sittlisalp occurred independently from natural and anthropogenic climate change.

H_1: Water shortage events at Sittlisalp are due to an increasing frequency of drought conditions, which were most likely a result of climate change.

6.5.2. Step 2: Trend analysis

In a second step the observed water shortage impact is analysed and brought into relation to the local climate signals. Again it has to be seen if there is a trend detectable in the precipitation and temperature and if the behaviour of the climate signals models the observed impact adequately.

Data for the trend analysis

The primary data used stems from a MeteoSchweiz measurement site in Altdorf see Tab. 6 and Fig. 20. The site in Altdorf measures air temperature and precipitation since 1865 with few missing measurements. Additionally, many other parameters are measured since 1980 (MeteoSchweiz, 2017). For climate trend purposes, long measurement series are preferable, hence, daily precipitation sums (mm) and daily mean air temperatures (°C) from 1865-2015 are used to analyse the climate trend. From these daily measurements, data is aggregated to timescales more suitable for the process. Even though the water resources on the alp are closely linked to precipitation deficits (see 6.3 Water resources), water shortage is not an instant reaction to low precipitation. Rather, water resources decline when a prolonged period of low precipitation occurs. Therefore, the data is aggregated either over a month or a three-month period to get the average condition over the desired timeframe.

Data from the longest standing and closest measurement station is used, however, the station is located at a much lower elevation than the Sittlisalp in the Reuss valley. It can be expected that the Sittlisalp has consistently lower temperatures due to the elevation difference, and also some diverging precipitation amounts. It would of course be preferable to use data measured on site, however, like for all these local cases, such measurements are rarely attainable. Long-term trends of mean temperatures or precipitation can be expected to follow a similar course in both stations. Before using indices though, the principles behind the calculations have to be assessed, to see if the elevation difference has a major influence on the output.

Because of measurement inconsistency, some years had to be excluded from the analysis. Records for May in both precipitation and air temperatures are missing for 1875, so the data for that year had to be excluded. Also the Altdorf measurement site had to be moved in 1920 as surrounding trees started to shield the site from precipitation. Due to the trees the 1919 and 1920 precipitation amounts are much too low and had to be removed from analysis (MeteoSchweiz, 2013).

To estimate magnitude of the impact, runoff data of the streams would also have been interesting to analyse. However, the closest runoff station is located low in the Schächen valley, shortly before the Schächen joins the Reuss (HADES, 2015). As there are many contributing streams apart from the Grossbach and Winterbach, this measurement is not particularly useful.

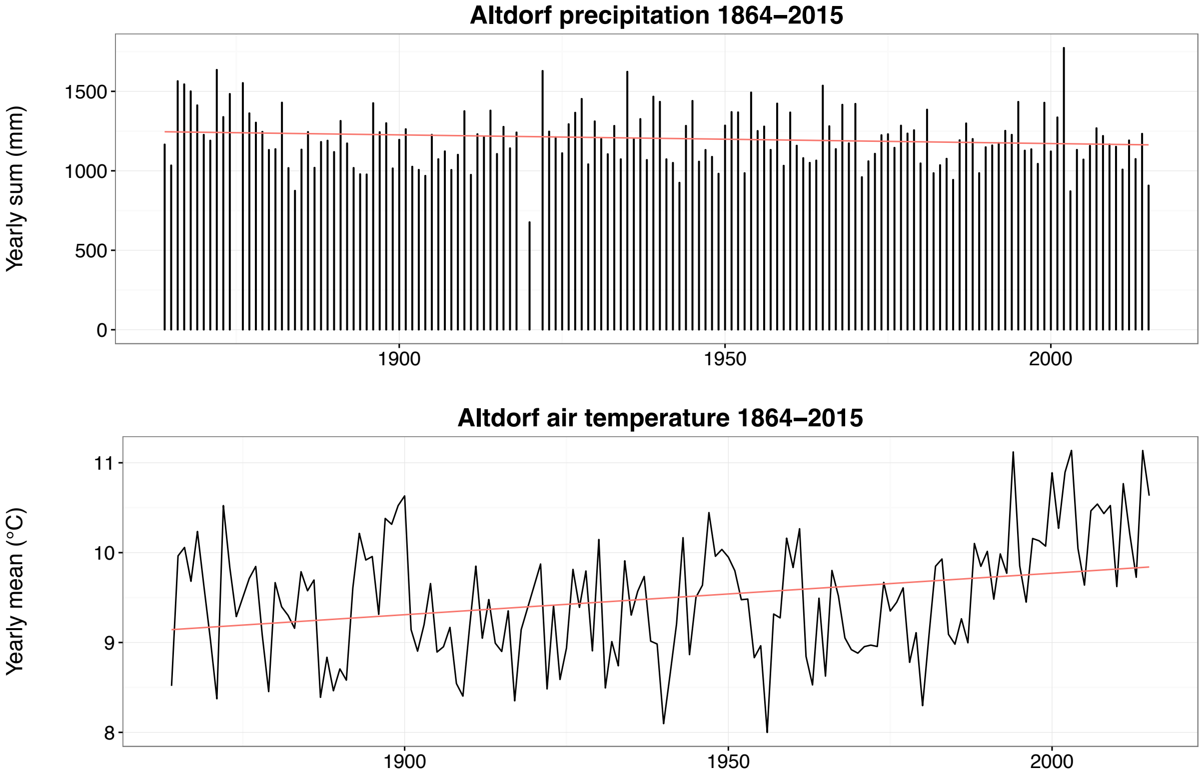


Fig. 20: Precipitation and air temperature data in Altdorf used for Sittlisalp hydro-power plant case.

Yearly precipitation sum and yearly mean air temperature from 1864-2015 in Altdorf. Red lines represent the linear regression lines for each data set.

Data	Source	Time frame and resolution
Air temperature	MeteoSwiss station Altdorf (MeteoSchweiz, 2016)	1864-2016 with intermission daily in °C
Precipitation	MeteoSwiss station Altdorf (MeteoSchweiz, 2016)	1864-2016 with intermission daily in mm

Tab. 6: Data used for Step 2: Trend analysis in the Sittlisalp case.

Methods

The observed impact can be categorised as a hydrological drought with socio-economic implications. The runoff rate is primarily impacted, while agricultural stress has not been observed. It also does not fall strictly in line with a socio-economic drought. Hydrological drought conditions in streams are usually assessed through comparison of the measured runoff with the seasonal climate statistics (Drought.ch, 2011). For small streams where no such measurement data for a climatically significant timeframe is provided, these thresholds cannot be applied. Instead the underlying meteorological drought is assessed through precipitation analysis. This is a suitable proxy as the runoff in this system is so closely linked to precipitation and therefore a meteorological drought would most likely lead to a hydrological drought within a short time.

To link the observed impact to climatic influence, the three-month precipitation average is used to calculate the Standardized Precipitation Index (SPI). The SPI evaluates drought-like conditions in the area compared with the available timeframe. The World Meteorological Organisation (WMO) suggests the SPI as the prime index for drought assessments. The key advantage of this method is that it gives a measure of unusual dryness or unusual wetness, using only precipitation data as input. For the precipitation data a fitting timeframe can be chosen to compare, for instance three months. The chosen three-month period e.g. January to March is then compared to all January to March periods in the dataset. Through fitting of the long-term record to a probability distribution and transforming to a normal distribution, the local data is standardised and thus the SPI is comparable across climate zones. The three-month SPI is chosen as it returns short- to medium term processes. The process length for the local hydrology to reflect a precipitation deficit is monthly to seasonal, so a three-month period fits best (WMO, 2012).

It could be beneficial to use the Standardized Precipitation-Evapotranspiration Index (SPEI), which additionally includes the influence of temperature on the system. While precipitation models the water availability, potential evapotranspiration models the atmospheric water demand. This water demand has to be deducted from the water availability, to model the water resources accurately. It allows direct assessment of climatic changes of the system. The SPEI estimates evapotranspiration based solely on air temperature (WMO and GWP, 2016). However, this is a stark simplification as evapotranspiration is dependent on a range of factors such as wind speed and atmospheric humidity. Additionally, for evapotranspiration to be assessed correctly, local temperatures are needed. These temperatures should at least be measured at the same elevation and aspect if not on site, otherwise too high temperatures could overestimate evaporation grossly (Hölting and Coldewey, 2013). As information on these factors is only available for a short time period and measured at a location not comparable for evapotranspiration, the SPI is used for drought assessment instead of SPEI. Similar considerations hinder the use of other drought indices such as Palmer Drought Severity Index (PDSI) where additional data is needed, for example available water capacity of the soil (WMO and GWP, 2016), which is missing for this case.

Still, it is important to include air temperature trends in the analysis of the process, as they do have an influence on the water resources on the alp as well. Hence, the SPI and the temperature development are assessed separately. As a consequence of this separate assessment, the relative contribution to the observed impact of the precipitation deficit against the temperature is not quantified anymore. The influences of the different drivers are therefore assessed qualitatively.

The *Mahalanobis distance* is a standardised distance measurement for multiple variables. The greater the distance, the less likely it is that a value belongs to a group. Here it is used to estimate if the concurrence of values of two climate variables is extraordinary (Backhaus et al., 2011). Specifically, it is used to estimate if the coincidence of precipitation amount and air temperature for a given year is typical compared to the whole timeframe.After the relation of the impact to the climate is established, it is assessed if there is a trend in the influential climatic factors. The trend analysis for long-term air temperature and SPI changes are used. For this, both seasonal Mann-Kendall test and simple linear regression tests were used. Seasonal Mann-Kendall test is a non-parametric test to detect monotonic trends in seasonal data. To achieve an overall trend, the trends in monthly data are aggregated (Helsel and Hirsch, 2002).

In summary, the methods need to address both, an assessment of the observed impact through drought assessment to link the impact to the climate, and trend analysis for the climatic variables.

Impact analysis

The first analysis is concerned with the observed impact and how it is connected to the climate. The impact was reported only by qualitative observation and no consistent measurements were conducted on the alp. So the dryness conditions over time are modelled to see if the observed impact can be reconstructed with precipitation data. Fig. 21 shows the three-month Standardised Precipitation Index (SPI) using the daily precipitation sum at the Altdorf station since 1980. Here, the three-month period is named for the month it ends, but it refers to the whole period, e.g. March on the graphs refers to January to March period.

The value assigned gives an indication how the drought situation is compared to the long-term average. When precipitation falls below the standardised mean for the period, a negative value is assigned. Wetter than average conditions are assigned positive values. A drought starts at the time, where SPI falls into the negative as long as it reaches -1 (red) at some point before getting positive again. The drought continues until the SPI is positive (light grey) again (WMO, 2012). In the years 2003 and 2015 such drought conditions can be detected on the graph.

When calculating the SPI over the whole time series since 1864 the drought onset and end for the two years can be seen. Fig. 22 shows the development of the SPI over the course of the two years in question. In 2003, the SPI fell to -1.2 in the January-March period already and was slightly negative all through 2003. The SPI only became positive again in April-June 2004. In 2015, the SPI first fell below -1 for the December 2014 –February 2015 period, but rose slightly above 0 in March-May 2015 again. In June-August the second drought period begins with its low point in October-December ending in February to April. As the SPI is strongly negative in spring and only barely positive in early summer, it is possible that the system was also not able to regenerate fully between the two drought periods.

Overall, both incidences show below average conditions for most of the year and half of the following year. The evolution of the SPI runs a similar course with the drought starting early in the year, in summer SPI is slightly higher, before decreasing in autumn and winter. In 2015 the onset is a month earlier, and the general deficit is less severe. This is comparable with the observed impact, which was earlier in 2015. For the locals the 2015 impact was more severe, but this is due to decreased electricity needs in September, when the inhabitants start to leave the alp for winter hiatus. In summary, the impacts can be reconstructed using precipitation data. The causal relationship between precipitation and the observed impact, reported in literature, can be assumed in this local case as well.

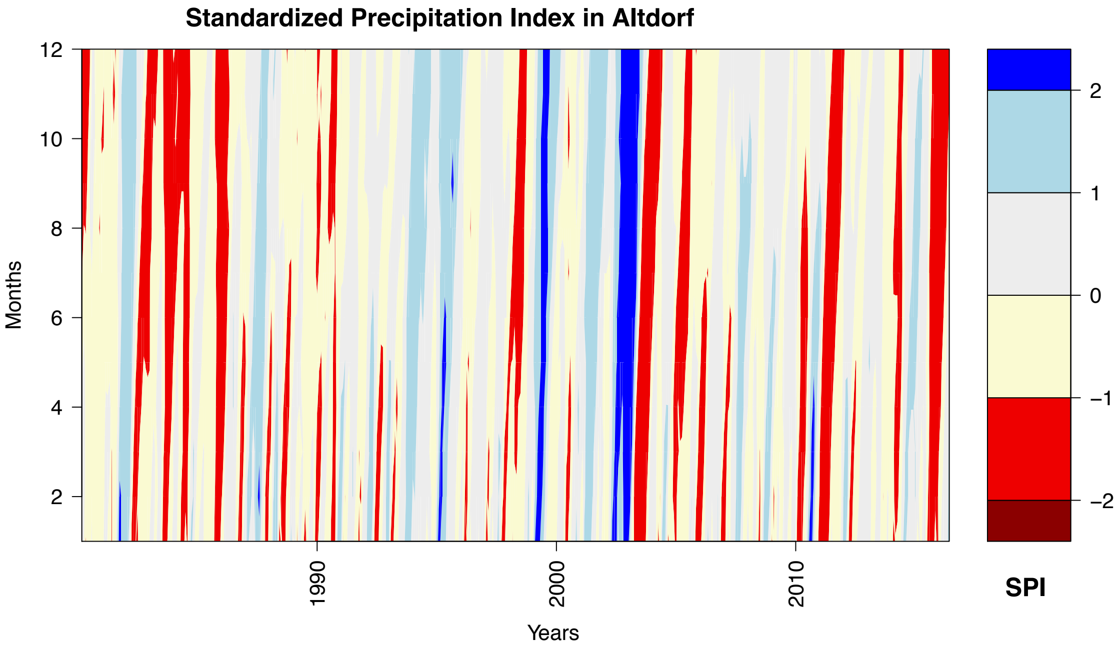


Fig. 21: Standardized Precipitation Index Altdorf 1980-2016.

Three-month Standardized Precipitation Index (SPI) for the Altdorf station January 1980 to June 2016. On the x-axis the timeframe in years and months is plotted against the months on the y-axis. The plotting represents single years in slightly slanted bands. The red bands mark dry periods.

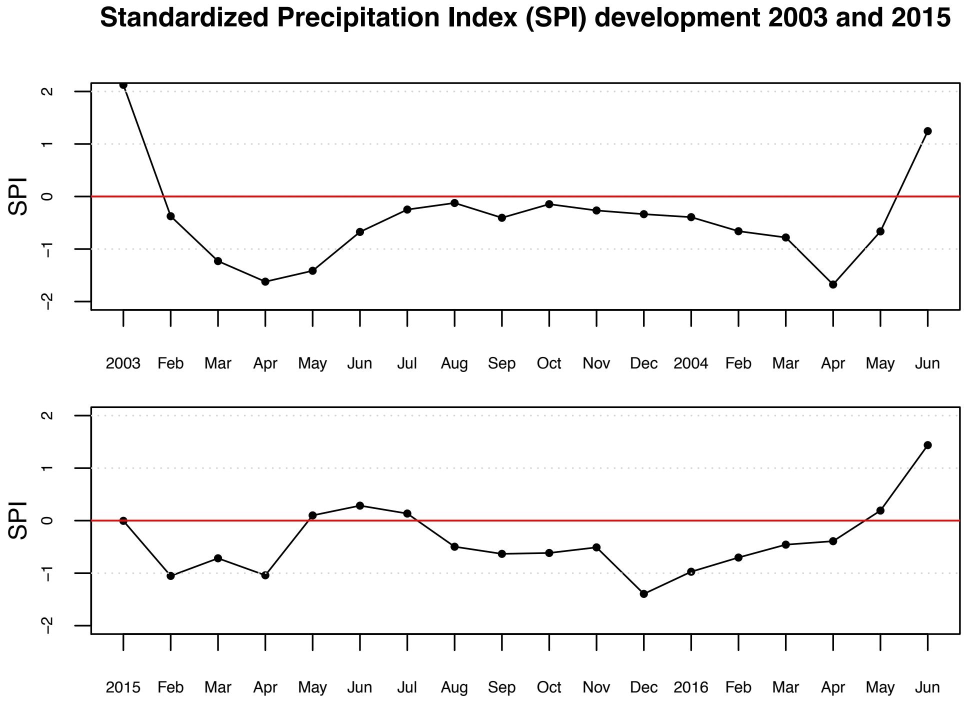


Fig. 22: Yearly SPI profiles in 2003 and 2005, Altdorf.

Three-month Standardized Precipitation Index (SPI) for the Altdorf station in 2003-2004 and 2015- 2016. Again the March SPI represents the Jan-Mar period for instance.

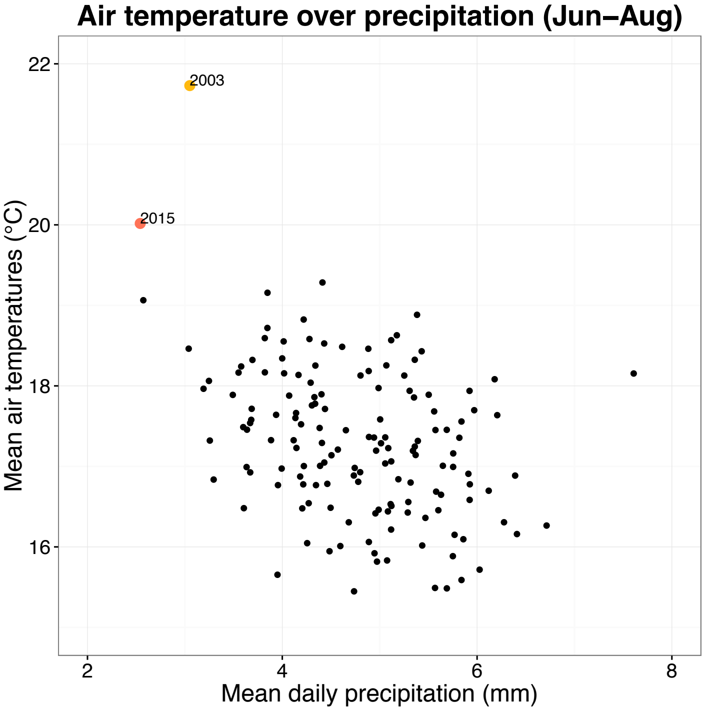


Fig. 23: Scatter plot of the June-August air temperature and precipitation from 1864 to 2015.

Another climate variable, which can influence water shortage, is air temperature. Since higher air temperature amongst other factors increases evapotranspiration, years with the same amount of precipitation but higher temperatures are more likely to produce water shortage. Because the data on hand would not fit the estimation method, evapotranspiration cannot be calculated. However, an estimation of how high the temperatures were relative to other years is possible using the air temperature data from Altdorf. The temperature is aggregated over the same three-month timeframe. The June to August temperature, which is critical in both cases, can be compared with the rest of the observed years. With 21.73°C in 2003 and 20.02°C in 2015, both considerable above the mean 17.32°C, these are the two hottest years in observation in Altdorf. Knowing that air temperature in both years was very high, it is plausible, that higher than average evapotranspiration occurred. Therefore the drought conditions modelled were most likely more severe than the SPI alone suggests.

If the average precipitation for the June-August period is plotted against the June-August average temperature (see Fig. 23), it is obvious, that there was an extraordinary coincidence of high temperature and low precipitation in these years. By calculating the Mahalonobis distance (for all data points 1864-2016) over the two variables, the visual analysis can be confirmed. Both years are extreme outliers of the group, especially for dry and hot conditions.

6.5.2.1. Climate trends

To assess if these local drought conditions were a result of changing climate, trends in the climate variables are investigated.

First the three-month SPI calculated above are tested for trends to see if there is a change in low precipitation extremes connected to drought. For the three-month SPI no trends can be found for the timeframe from 1864-2015. Only the August to October period shows a significant decreasing trend. If the timeframe is reduced to 1960-2015, however, this trend disappears. It is most likely that the trend appeared due to a greater variability in SPI in the very early years. Since in this research no trend occurred for the recent years, it is disregarded here.

Additionally, the Seasonal Mann-Kendall test tests the precipitation data was for a monotonic seasonally trend. Linear regression tests yearly precipitation sum and the three-month precipitation of June-August for trends. Both yearly and three-month tests rendered no trends for either the 1864-2015 period or the more short-term periods of 1960/1980-2015. Next, the Seasonal Mann-Kendall test is used on monthly precipitation data, which analyses if there is a monotonic trend in deseasonalised precipitation. Again no significant trend is detectable since 1864. Only, for the period 1980-2016 a weak negative trend is detectable (tau = -0.102, p-value <0.01).

While there is no clear trend detectable in the average precipitation data or SPI, a trend is detectable in the summer (June – August) air temperature (see Tab. 7). A significant rise in temperature is detectable for all timeframes tested. The rate at which temperature rises over the whole dataset is much slower at 0.043°C per decade, than over the shorter timeframes. The 1960/1980 to 2016 change rates are similar with around 0.4°C air temperature rise per decade. These findings concur with regional trends detected, which propose a rise of 0.1°C per decade for 1864-2012 and 0.5° per decade for 1961-2012 in summer air temperatures.

Now if these findings are looked at in a hydrological context, it can be said that water availability supplied by precipitation has not changed significantly. Increased evapotranspiration, driven by air temperature, could increase water demand however. The water balance could therefore be changed because of evapotranspiration. If other factors influencing evapotranspiration did not change, rising air temperatures should cause an increase in evapotranspiration. However, there is no way to assess how these other factors changed. Hence, evapotranspiration changes cannot be assumed. Moreover, though a contribution of air temperature cannot be ruled out, these two instances are unique compared with recent years as well. If more similar impacts were observed, coinciding with high temperatures through climate change, trend detection would be more plausible. Therefore an increase of evapotranspiration through climate change, leading to more severe water shortage situations, is a hypothesis that cannot be supported yet.

6.5.3. Step 3: Baseline behaviour

Following the trend analysis, the baseline behaviour is assessed. Thus the behaviour of the system is identified, if any climatic changes were excluded. If this baseline behaviour suggests the system should behave differently from the observation, an impact can still be detected, even though climate is an unlikely driver. Dry spells in the alps are rare compared with the dry spells in the Swiss midlands, because there are higher precipitation rates overall in the mountainous areas (Schorer, 2012). As there is no research on the subject, which applies to such remote alpine areas or to the Sittlisalp specifically, context analysis assesses the baseline. Therefore all factors influencing the local conditions other than climate are gathered.

Here, a change in baseline could occur if the landscape around the extraction sites changed, through changing operation of the power plant or through changed water use on the alp.

Linear regression	Mean Jun-Aug air temperature °C	Mean Jun-Aug air temperature °C	Mean Jun-Aug air temperature °C
Timeframe	1864-2016	1960-2016	1980-2016
P-value	0.0143	6.05e-07	0.0036
Significant at level	0.05	<0.001	0.01
Trend estimate	0.0043	0.0389	0.0446
Calculated temperature change (total)	0.65 °C	2.18 °C	1.61 °C
per decade	0.043 °C	0.39 °C	0.45°C

Tab. 7: Linear regression model results for Altdorf air temperature over different time periods.

In the years since the plant was built and our frame of reference for this case, very few infrastructural changes were made on the alp. Only two alpine compounds are within the larger catchment area of the streams above the extraction sites. Since 1978 there was no infrastructural change recorded at all (Swisstopo, 2017). Also the upper part of the alp is and always was exclusively used for grazing animals. There is no reason to suspect the landscape has been changed by human influence. Moreover, there is no indication of significant changes through erosion or geomorphologic processes (Swisstopo, 2017). Actually, over all of the 20th century barely any such changes were recorded. Because of the remoteness it is likely, that the area above the extraction site especially, has been changed by human activity only minimally in the last 150 years.

Inhabitants of the alp stated that there was no change in operation of the power plant and that it was kept in prime condition through regular maintenance. There were incidences of lightning strike into the turbine room. However, this did not happen in the years in question and in the other years the damage never rendered the plant unusable for long.

Increased electricity consumption would also not have influenced the observation, because the impact was observed by the amount of energy produced. On both occasions the power plant could only run at less than half of its full capacity. Also, water shortage through increased use of drinking water would also not reduce the energy production, because drinking water is not collected from the same streams joining into Winterbach. Instead the drinking water is taken from Grossbach on the far side of the alp. So if there was increased drinking water consumption it should not have influenced the water availability for power production. There are a few small wells for animal troughs, which are not serviced by the drinking water collected. Nearly all of them are below the extraction points, and the amount of water used is minimal compared to the overall availability.

In conclusion, all these factors suggest that the baseline behaviour on the alp was not changed by any natural or human influences. This certainly applies for the period since the power plant was built and it seems as if barely any circumstances changed over the last century as well.

6.5.4. Step 4: Impact detection

The next step in the attribution assessment entails impact detection. For detection, the influence of the climate is compared with the baseline behaviour. If there is a difference between the climatic trend and the baseline, an impact can be detected.

The context analysis insinuates that the baseline behaviour did not change while the impacts were observed. There was no change in human or natural non-climatic drivers detected.

While the observed impact could be linked to climate, it could not be linked to a significant climatic trend. The connected variable of precipitation did not show a detectable trend in the average or in the variability. It is probable that the trend to higher temperatures amplified the severity of the observed impacts modelled by the precipitation. But there is no causal relationship discernible between the increasing temperatures and observed drought conditions, beyond what could be coincidence. Although an influence of the air temperature on water shortage cannot be dismissed, there is no change in climate, which the observed impact can definitively be assigned to.

As there is no change detectable in both baseline behaviour and climate, there is no impact detection. The null hypothesis that water shortage events at Sittlisalp occurred independently from climate change can subsequently not be rejected. Due to the absence of a detected impact, Step five: Attribution of the assessment is omitted. Because no climatic drivers were identified, it is impossible to assess the magnitude of their contribution to the impact.

6.6. Case Classification

Following the classification scheme introduced in the methods, the Sittlisalp case is now classed into one of the five attribution classes. Even though the last step of the attribution assessment had to be omitted, a classification is still possible. As there was no impact detection, contribution of climatic drivers was not larger than of non-climatic driver. Also there is no suspicion that the non-climatic drivers were caused by climate change drivers. An influence on the impact through increasing air temperature is still suspected, thus a contribution of climate change to the impact should not be dismissed. *Class 3: Suspected climate influence* best applies to this case. While this is not an attribution to climate change as of now, the case could be revisited at a later time when more data is available.

6.7. Limitations

For this case the major limitation was data availability. The process in question is dependent on local data. While the station is close in distance, the situation in a valley at a 1000m lower elevation is quite different to the situation on the alp. Trends observed at the lower level are probably similar to the local trend. But for estimations of local evapotranspiration the data was insufficient.

Another limitation is that impact was only observed over a short timeframe. Before the building of the power plant, water shortages were not quantifiable and would most likely not have caused any impact on the local community.

6.8. Adaptation

On the Sittlisalp no measures are planned to adapt to potential reoccurring water shortages. In the case of such a shortage, alternative energy sources such as wood firing and heating oil are used. These are more expensive and inconvenient to purchase because of the remoteness of the area. To request a connection to the commercial power grid is not a viable option for the locals, as their power plant is convenient and efficient most of the time. Based on this assessment, adaptation because of climate change is not necessary yet. Based on the suspicion, that air temperatures could reinforce drought conditions in the future, additional renewable energy sources to supplement the power plant in case of such a water shortage could be useful. Some of the houses on the Sittlisalp already use solar panels for additional electricity generation. The alp is generally not well suited for solar panels, as the narrow valley limits sunlight hours. However, for especially warm and dry summers with a lot of sunshine, this could complement the low energy production through runoff.

6.9. Conclusion

In conclusion, there is no detection or attribution to climate change possible for the water shortage impact on the Sittlisalp. This is both due to the low frequency observation of the extreme events impact and because no climate trend could be linked to the impact. Still there is a possible climate influence, which cannot be dismissed, therefore, the case is classed as *Class3: Suspected climate influence*. The attribution framework and classification scheme can be applied to this case, however, attribution without more appropriate local data is too ambitions for such a local hydrological case. In the future, when local trends are better understood as more data is available, the attribution assessment could be revisited.

7. Haggenegg inn

Fig. 24: Haggenegg pass with inn.

The Haggenegg pass with the mountain inn "Haggenegg" in the background (1) and the its drinking water well on the left (2) (Melanie Graf, early October 2016).

7.1. Study area

Topography and geomorphology

The case study is located at the Haggenegg pass in the pre-alpine mountain range in the Canton of Schwyz (see Fig. 26). The pass lies between the Haggenspitz (1762m a.s.l) in the south, a subsidery summit of Klein Mythen (1811m a.s.l.) and the Nätschberg (1525m a.s.l) in the north. The inn is located on the northern side of the pass, on the south-western board of the Nätschberg, at 1414m a.s.l (Swisstopo, 2017). Nätschberg is largely free of trees, because it is used as a ski slope in winter and for animal grazing in summer (Haggenegg, 2017). The vegetation consists mainly of alpine pastures with small groups of trees. Soil depth is shallow with limited water holding capacity (BFS, 2016).

Geologically, the region consists mainly of sedimentary stone formed in the orogenesis of the Alps in the Tertiary. During the Quaternary the region was first transformed by glaciers and later on through hang sliding processes. Today fluvial processes dominate the landscape genesis (SGTK, 2016).

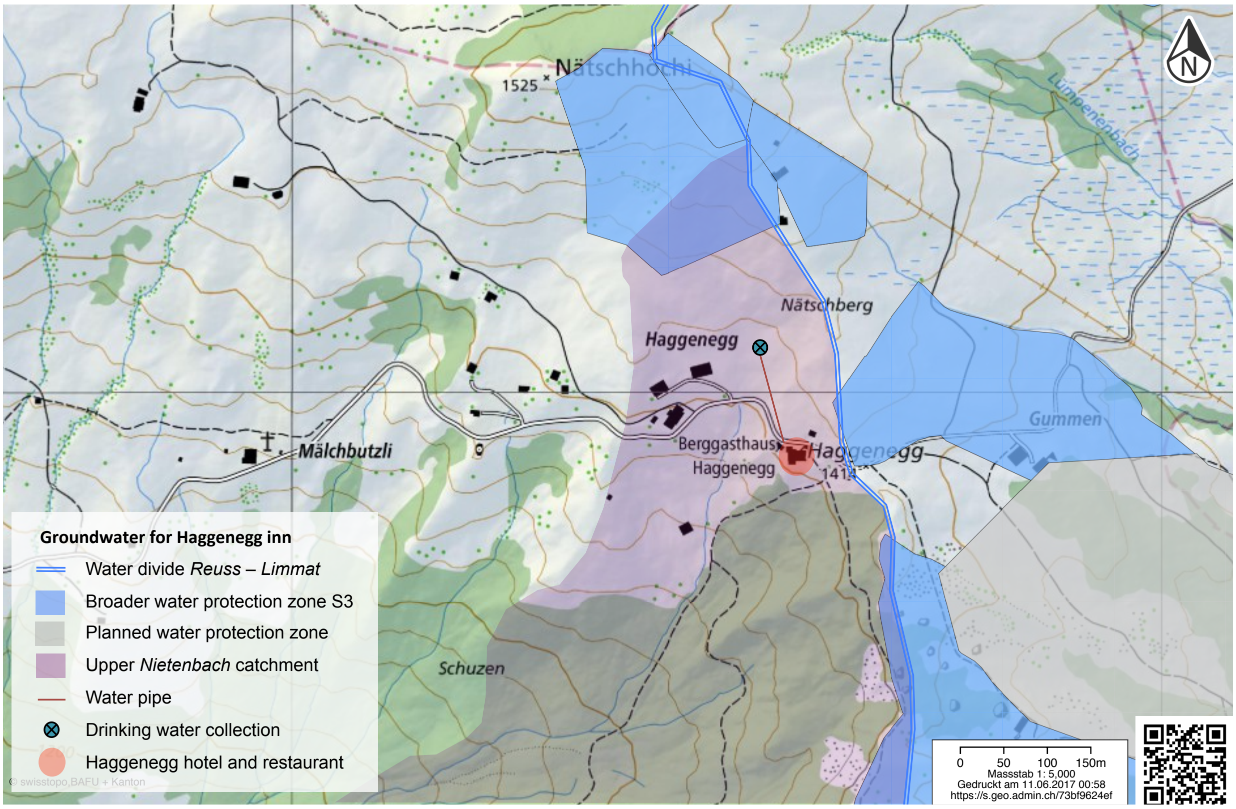


Fig. 25: Drinking water extraction and groundwater situation for Haggenegg inn.

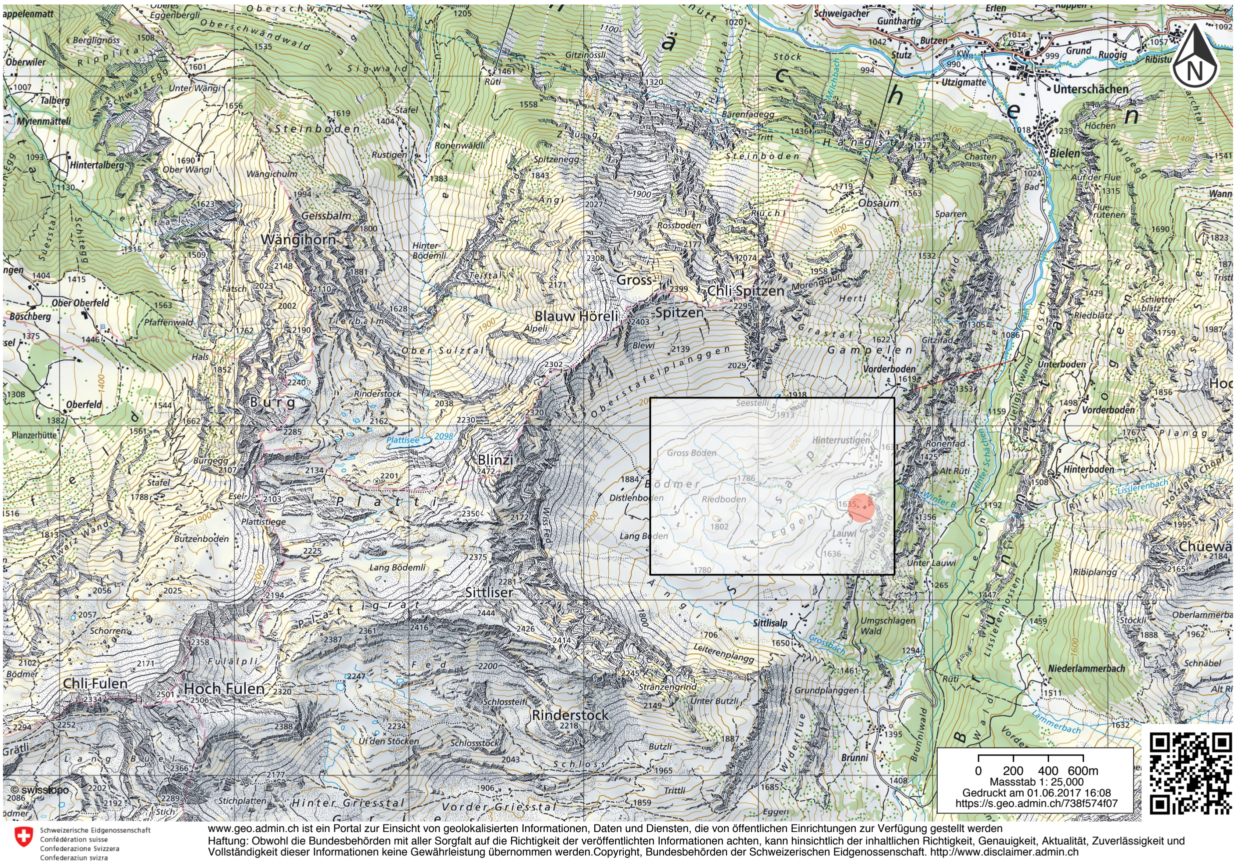


Fig. 26: Overview map of the Haggenegg and the stations Einsiedeln, Sattel-Aegeri and Erlenbach.

The white rectangle marks the location of the layout plan above and the red circle marks the cheese factory.

Local Climate

The study site lies in the region of the northern flank of the Alpine mountain range at about 1500m a.s.l. and profits from the same mild and wet climate as the Sittlisalp (MeteoSchweiz, 2013). The local climate on Haggenegg is warmer than other locations at the same elevation, probably because the Nätschbergs' southwest exposition guarantees a lot of sunshine. The mean yearly temperature is estimated at about 8°C, just about 2 °C colder than the mean temperature in the town Schwyz at 550m a.s.l. Precipitation rates are also higher at Haggenegg with around 1900mm per year. It lies at the outskirts of the Alpthal and Muotathal region, which is the wettest region of Switzerland, rivalled only by the Maggia-Verzasca region in Ticino. So while the temperature is comparable to low-land temperatures, the precipitation amount fits into the pre-alpine climate (MeteoSchweiz, 2013).

Population

A first record of an inn on the Haggenegg dates back to the 15th century, built to accommodate pilgrims on the Camino the Santiago trail. The modern-day inn was opened in 1984, including a hotel with 50 beds and a restaurant that can accommodate 150 people. Its customers are mainly hikers in summer and winter sport tourists (Haggenegg, 2017). The Haggenegg pass is quite remote, only reachable by a small pass street, even though it is just seven kilometres away from the cantonal main town Schwyz (Swisstopo, 2017).

In proximity to the inn there is a dairy farm and some holiday houses. The hotel at Haggenegg and the close by alpine dairy farms are occupied all year round, but most of the houses at the Nätschberg are holiday homes, which are only occasionally used. In winter, the Nätschhöchi can also be reached by ski lift as the ski slope down to Brunni starts there. The largest human influence on the alpine is likely through winter sports (Haggenegg, 2017, Swisstopo, 2017).

Regional hydrology

The Haggenegg pass falls on a major water divide line running north to south. Water flowing down the west side of the pass flows into the catchment of the river Reuss, while on the east it flows into the catchment of the Limmat (HADES, 2015). Just below the pass street several springs produce small streams joining at about 900m a.s.l. to form the Nietenbach, a contributor of the Muota, which flows into the Vierwaldstättersee (*Eng. Lake Lucerne*) (webGIS.sz, 2017).The hydrological regime is mainly driven by snowmelt and rainfall. This *nivo-pluvial préalpin* regime is characterised by a primary runoff peak in May-June from snow-melt and a secondary rainfall peak in late summer. This is a common regime in the pre-alpine region (HADES, 2015).

7.2. Observed impact

This last case study is concerned with water shortage incidences at the Haggenegg pass in the Canton of Schwyz. In the summer of 2015 and in winter 2003, the *Berggasthof Haggenegg* reported water shortages. As established in the Sittlisalp case (see 6. Sittlisalp hydro-power plant) both 2003 and 2015 were exceptionally warm and quite dry years in all of Switzerland leading to heat waves and water shortages (BAFU, 2016). As the impact observed here is very similar to the impact at Sittlisal and bases on the same processes, the case studies essentially use the same procedure. A large part of the theoretical background and the methods refers to 4.3. Sittlisalp. This chapter therefore only elaborates on locally specific information of the Haggenegg. Unreferenced information in this chapter was gathered by interview.

Local observation

The local inhabitants observed the low water periods directly as the well supplying the inn with drinking water ran unusually low in both of these years. In 2015 the water shortage became noticeable in the beginning of August and stopped on 22. August, after a large precipitation event. From December 2003 to January 2004, a comparable water shortage was observed. In both years water usage had to be rationed strictly, which usually is not necessary.

A shallow groundwater well supplies the inn with water all year round. It is located next to a small spring. The well fills a cistern with about 30 m^3 holding capacity. Usually the ground is well saturated and the cistern overspills, as there is more than enough groundwater flow to fill it. The well was built and taken into operation in 1984 together with the reopening of the inn. Since then only these two severe water shortages occurred. Both the inn and the site of the well are depicted in Fig. 24 and the layout of the groundwater extraction is mapped in Fig. 25.

Repercussions

The main observed repercussion was the effort of the owners and the implications for their business. In both years the hotel business had to be reduced and hotel guest were turned away. For a local business this is a grave restriction resulting in loss of revenue and image. A regular occurrence of such water shortage due to climatic changes would impact this local business strongly and additional water sources would have to be contemplated. Other repercussions were not reported, but as in the Sittlisalp (see 6. Sittlisalp hydro-power plant) case, it is possible that the dry spells impacted the alpine ecosystems. Sinking water resources in the mountainous regions could have an influence on the downstream hydrological systems and ecosystems. So in the interest of the local businesses as well as the ecosystem on the alp and downstream, it is important to research the drivers behind the impact observed and hence being able to estimate if water shortage is likely to occur more frequently in the future.

7.3. Groundwater resources

Chapter 7.3 Groundwater resources gives an overview over alpine water resources and shortages, where water cycle, hydrological regime and drought types important for the Haggenegg case are explained in detail. The impact observed on Haggenegg is also tied to the water cycle, but the primary impact is low groundwater storage, not runoff. This section explains the basic principles of groundwater flow and introduces important factors, which affect groundwater differently from runoff. The focus lies again on small mountainous catchments. Finally the importance of local groundwater research in combination with climate change is discussed.

To estimate how groundwater flows in a region, it is crucial to know the aquifer type. This basic type determines the typical flow dynamics in the aquifer. There are three main aquifer types, which can all be found in Switzerland: Karst-aquifers, fractured rock aquifers and unconsolidated rock aquifers. The aquifer in the larger region around the Haggenegg is a fractured rock aquifer. Water can infiltrate such an aquifer through fissures and fractures in the otherwise impermeable bedrock. Consequently, the water can only flow through the aquifer along such fractures. As a consequence it is difficult to estimate large-scale groundwater flow. Water can however flow rather unhindered in the soil above the aquifer (Hölting and Coldewey, 2013).

Another important factor for mountainous water resources to consider is the resident time of the water in the ground. To know how long it takes for precipitation to infiltrate and flow through the ground gives an idea of the response time of the groundwater levels to precipitation events. As elaborated in 4.3.3, in small steep catchments either soil depth or upslope catchment size mainly determine how long water resides in the ground. The shallower the soil and the smaller the catchment area, the shorter is the residence time (Asano et al., 2002). The distance to the water divide is another important factor influencing response time to precipitation. According to Stewart and McDonnell (1991) the closer a sampling site is to the divide, the shorter is the response to precipitation events.

7.4. Local water resources and research

This section assesses the local hydrological situation with the basic hydrological and specifically groundwater processes in mind and reviews existing local research.

There is no research specific to the pass or for the affected aquifer. Alpthal on the east side of the pass is a test region of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) with a focus on runoff and sediment transport. These topics are of special interest as the Alpthal receives an average of 2200mm precipitation a year. Groundwater is not a focus as the region, similar to the Haggenegg, has minimal groundwater resources because of the local geology. There are runoff measurements further down in the valley, but these are not of particular use for this case study. Not only is the Haggenegg not within the catchment, the Alpthal is also expected to have larger precipitation and runoff amounts. Moreover, the location of the Haggenegg very close to the water divide is unusual, and has little to do with the processes influencing runoff lower in the Alpthal valley. While the local research is not concerned with water shortages, the research area encompasses some stations in the area, which measure climate variables. The climate data from Erlenbach, about 2.5km from Haggenegg is used in this study (see 7.4 Local water resources and research) (WSL, 2015).

The groundwater situation on the Haggenegg can be summarised well from several maps on the Swisstopo (2017) and the webGIS.sz (2017) map portals. The general aquifer type in the area is fractured rock, which can imply irregular groundwater flow through fissures. The rest of the bedrock is impermeable to water. The impermeable bedrock is one of the reasons the Nätschberg and its surrounding area has very little to no groundwater resources. Direct precipitation is the only source of inflow in the area. Additionally, the soil is shallow and has low water holding capacity. So water flows above and through the soil but does not permeate the bedrock and does generally not stay in ground storage. The upper part of the Nätschberg above the Haggenegg encompasses a designated groundwater protection area, probably because groundwater is a fleeting resource there, but needs to supply a number of wells.

The slope of the catchment area is steep with an angle above 25°. The upslope catchment of the sample site is very small with an estimated 30’000-50’000m^2, as the well is close to the water divide and the Nätschhöchi. Together with the shallow soil depth and low water holding capacity this guarantees fast response time to precipitation events (Swisstopo, 2017). This assumption is supported by the observation that within a day of a single large precipitation event in August 2015 the water shortage was alleviated again. This observed fast response to high precipitation events also suggests the system reacts to sub-average precipitation amounts quickly. All these characteristics suggest that groundwater levels are dominated by precipitation variation and groundwater flow dynamics play a minor role. Monthly and three-monthly drought assessments periods should therefore reflect the water shortage situation well (WMO, 2012).

In winter, the Haggenegg is part of the skiing area Brunni-Alpthal skiing region. A ski lift up to the Nätschberg was built in the 1970s. The upper part of the skiing area, close to the Haggenegg lies usually not serviced with artificial snow generators (Brunni-Alpthal, 2017). So no influence through artificial precipitation in winter is expected.

Water shortage and climate change

Changes in water shortage and their connection to climate change in Central Switzerland are discussed at length in 4.3.4. Additionally, expected changes in groundwater levels in Switzerland are addressed here.

The hydrological regime in the area is expected to change from snow dominated with secondary rainfall influence to a predominant rainfall (*pluvial inférieur*) regime. This means there is no peak in runoff in May-June due to snowmelt. Rather the runoff is much more constant throughout the year (BAFU, 2012b). Groundwater is a major source for drinking water and water for irrigation, not just in mountainous areas but also in lowlands. If a large amount of groundwater is extracted for human use, it can lead to groundwater depletion, if groundwater levels cannot be recharged. In many areas of the world this is an increasing problem (Hiscock and Bense, 2014). In Switzerland, this is usually not a concern, as water is recharged quite easily through precipitation and groundwater flow (BAFU, 2009). Still, 80% of Switzerland's drinking water is extracted from the ground. If the amount or quality of the water declines it would affect not just local ecosystems but also the drinking water supply (CH2014, 2014).

But research on the influence of climate change on groundwater is rare. The main projected impact based on climate change scenarios is a decrease of groundwater quality through increase in water temperature. Pollutants and organisms accumulate and thrive in warmer water (BAFU, 2009, CH2014, 2014). The federal adaptation strategy therefore is focussed on ensuring groundwater quality (BAFU, 2015). There are no general trends of groundwater levels observed concurring with climate change yet, so groundwater levels are disregarded (BAFU, 2009). One can hypothesise that many of these impacts are very local and incidences will not be reported and this circumstance could also hinder such trend investigations. If water resource problems could be registered on a more local level, trend assessment could yield more information.

7.5. Attribution assessment

Based on the report on the water shortage on the Haggenegg the attribution can be assessed next. Again, there are two main prerequisites for the attribution framework to be applied according to the research goals: Firstly, the observed impact has to have a relation to climate change. Water shortage is largely based on precipitation deficits and influenced by other climate variables like air temperature (see 6.3 Water resources). Secondly, the case has to be of local extent. The impact is local, observed for a single well for a very small catchment. The prerequisites for the assessment are met, so next the five steps of the attribution framework are applied to the Haggenegg water shortage case.

7.5.1. Step 1: Hypothesis

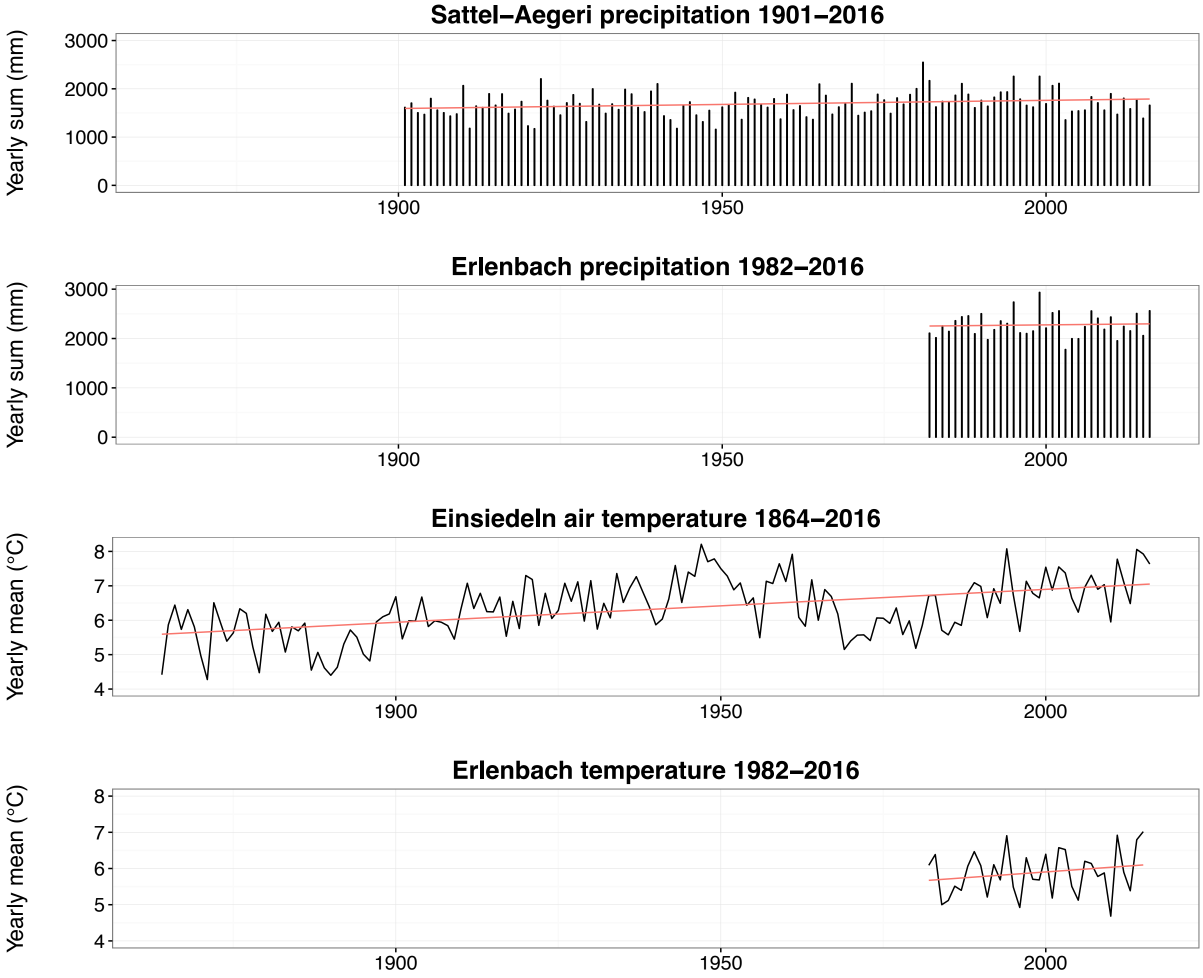
The first step of the assessment is to formulate hypotheses for the attribution of the water shortage. According to the literature review (see 6.3 Water resources and 7.3 Groundwater resources) and hydrological context of the case, the major driver of the hydrological regime is precipitation. Due to small catchment size and shallow soil depth in a region where almost no groundwater can be stored, it can be assumed that the response time to precipitation events is quite fast. Again as a secondary influence, air temperatures should be assessed. Based on these circumstances the following hypotheses are formulated.

H_0: Water shortage events at Haggenegg occurred independently from natural and anthropological climate change.

H_1: Water shortage events at Haggenegg are due to increasingly occurring drought conditions, which were most likely a result of climate change.

7.5.2. Step2: Trend analysis

As mentioned above, the same trend and context analyses as in the Sittlisalp case are used for this case. On the one hand, the observed impact is very similar and on the other hand the two cases and the approach taken can be compared afterward. So first the water shortage is investigated and brought into relation to local climate signals. Again it has to be seen if there is a trend detectable in the precipitation and temperature and if the behaviour of the climate signals models the observed impact adequately.


Sattel–Aegeri precipitation 1901–2016

Erlenbach precipitation 1982–2016

Einsiedeln air temperature 1864–2016

Erlenbach temperature 1982–2016

Fig. 27: Precipitation and air temperature data sets used for Haggenegg water shortage case.

Yearly precipitation sums in Sattel-Aegeri and Erlenbach and yearly mean temperatures in Einsiedeln and Erlenbach (WSL, 2015, MeteoSchweiz, 2016)

Data for the trend analysis

The data used for the Haggenegg case is precipitation data and temperature data from various meteorological measurement stations (see Fig. 27 and Tab. 8). Here more than one stations are used as the MeteoSchweiz (2017) stations in the proximity do not measure both temperatures and precipitation. The only station, where both is measured is the WSL (2015) station in Erlenbach in the upper Alpthal. The station is conveniently stationed less than 3km from the study site and just 200m lower at around 1200m a.s.l. However, measurements only started 1982. This is the same time span as the impact observation, as the Haggenegg inn was opened in 1984. Therefore, this data is suitable to reconstruct the observed impact with precipitation data. But to

Data	Source	Time frame and resolution
Air temperature	MeteoSwiss station Einsiedeln (MeteoSchweiz, 2016)	1931-2016 daily in °C
Precipitation	MeteoSwiss station Sattel-Aegeri (MeteoSchweiz, 2016)	1901-2016 daily in mm
Air temperature	WSL climate station Erlenbach (WSL, 2015)	1982-2015 daily in °C
Precipitation	WSL climate station Erlenbach (WSL, 2015)	1982-2016 daily in mm

Tab. 8: Data used for Step 2: Trend analysis in the Haggenegg case.

set the impact in a climate change context, longer timeframes are needed. Therefore, the precipitation data from Sattel-Aegeri, Canton of Schwyz, 790m a.s.l. (MeteoSchweiz, 2017) is used to cover a longer timespan, which provides continuous measurement since 1901. The long-term air temperature data used stems from Einsiedeln, Canton of Schwyz, 910 m a.s.l., where air temperature was measured monthly from 1864 to 2016. Even though the station is farther away than other stations, it is the closest that measured air temperature for over 30 years uninterruptedly and it lies at a higher elevation. The three measurement sites all have their own limitations. So one has to be careful when comparing the data directly. The data from Erlenbach are measured quite close to the site; so they are expected to fit best to Haggenegg, with maybe slightly lower temperatures and higher precipitation due to exposition.

The air temperature data is measured quite far away and at a 500m lower elevation (MeteoSchweiz, 2017). This means they are also not useful for indices calculation, as they would most likely give an estimation of evapotranspiration than deviates from real evapotranspiration on the Haggenegg (WMO and GWP, 2016).

The precipitation data used are daily precipitation sums (mm) and mean daily or monthly air temperatures (°C). From the daily and monthly measurements, data is aggregated to timescales more suitable for the process. Here three-month averages are used to assess both impact assessment and climate trends. This timescale fits the underlying process of the hydrological drought.

Runoff measurements of the Nietenbach, which has its source on the Haggenegg would be interesting to analyse, as the runoff rate would also give an indication on the groundwater levels. However, only water quality was observed for this stream lower in the valley (Kanton Schwyz, 2017).

Methods

As the impact is very similar to the Sittlisalp case as far as the underlying processes, the local context and the timing of the observation go, the same methods are applied to the cases. Slight adjustments are made to the timeframes for the trend analyses, accommodating the differences in the data. For the exact methods used refer to 6.5 Attribution assessment.

7.5.2.1. Impact analysis

First the observed impact is analysed. The connection of the observed water shortage to the local climate is investigated. Precipitation variation modelled with three-month Standardized Precipitation Index (SPI) should represent water shortages in the groundwater. Later, the trend analysis of the three-month precipitation is used to detect if there is a trend in precipitation patterns. So the SPI is calculated with precipitation data of both Erlenbach and Sattel-Aegeri. Fig. 28

depicts the three-month SPI for the Erlenbach station and Fig. 29 for Sattel-Aegeri, calculated using daily precipitation sums. While the Erlenbach data spans the same timeframe as the owners of the inn monitored the water situation, Sattel-Aegeri provides the long-term comparison.

The value assigned gives an indication of how the drought situation is compared to the long-term average. When precipitation falls below the standardised mean for the period, a negative value is assigned. Wetter than average conditions are assigned positive values. A drought for this specific climate is detected anytime the SPI reaches -1 (red). The starting date of the drought is where the SPI is first negative and continues on until the SPI is positive (light grey) again, as long as the SPI falls below -1 in between (WMO, 2012). As it is calculated for three-month periods, the month listed here always refers to the three-month period before; e.g. March refers to the January to March period.

Both 2003 and 2015 show such dry conditions in the graphs for Erlenbach and for Sattel-Aegeri. However, in Fig. 28 the situation seems to have been more severe in 2003 to 2005 with a minor dry spell in 2015. Fig. 29, which uses precipitation from 1901-2016 in Sattel-Aegeri as a reference, reveals that precipitation was much lower from 1980-2002 than before and after. It is possible that dry spells in the 2000s were therefore experienced as more severe. The most severe drought conditions seem to have occurred around 1947.

The SPI profile in Fig. 30 shows that there were definitively drought conditions in 2003 and 2015, however. Here the developments for Erlenbach are illustrated, as the precipitation amounts were probably closer to Haggenegg than in Sattel-Aegeri. So in 2003 there were two drought periods, one in February (Dec-Feb) to June (Apr-Jun) 2003 and the other in August (Jun-Aug) 2003 to May (Feb-May) 2004 with its minimum in Apr (Feb-Apr) 2004. The impact observed in Dec 2003 to Jan 2004 is therefore detectable through precipitation. In 2015 the drought starts in August (Jun-Aug) and ends in February (Dec-Feb) 2016. The Sattel-Aegeri SPI values show largely the same development, if a little more severe in 2015 and less in 2003.

In summary, the precipitation data shows a drought in both years where an impact was observed. Especially the precipitation in 2003 to mid-2004 is constantly below average. In 2015, all three-month periods including August precipitation (Aug, Sep, Oct SPI) indicate drought conditions for the impact observation period. Consequently the causal relationship between precipitation and the observed impact, reported on in literature, can be assumed in this local case as well. However, other factors inducing water shortages cannot yet be discounted.

The other primary climate variable, which influences water shortage, is air temperature. As higher air temperature amongst other factors increases evapotranspiration, years with the same amount of precipitation but higher temperatures are more likely to produce water shortage. As the data on hand would not fit the estimation method, evapotranspiration cannot be calculated. However, an estimation of how high the temperatures were relative to other years is possible using the air temperature data from Erlenbach and Einsiedeln. The temperature is aggregated over the same three-month timeframe as the precipitation data.

Only the August 2015 water shortage case was observed in summer. The groundwater levels in 2003 might have been affected by high temperatures as well because the groundwater recharge in summer and autumn months was lower than precipitation suggest and therefore storage quantities lowered. Temperatures in the winter months, however, are so low that slightly above average temperatures (as measured in 2003) would not have an effect.

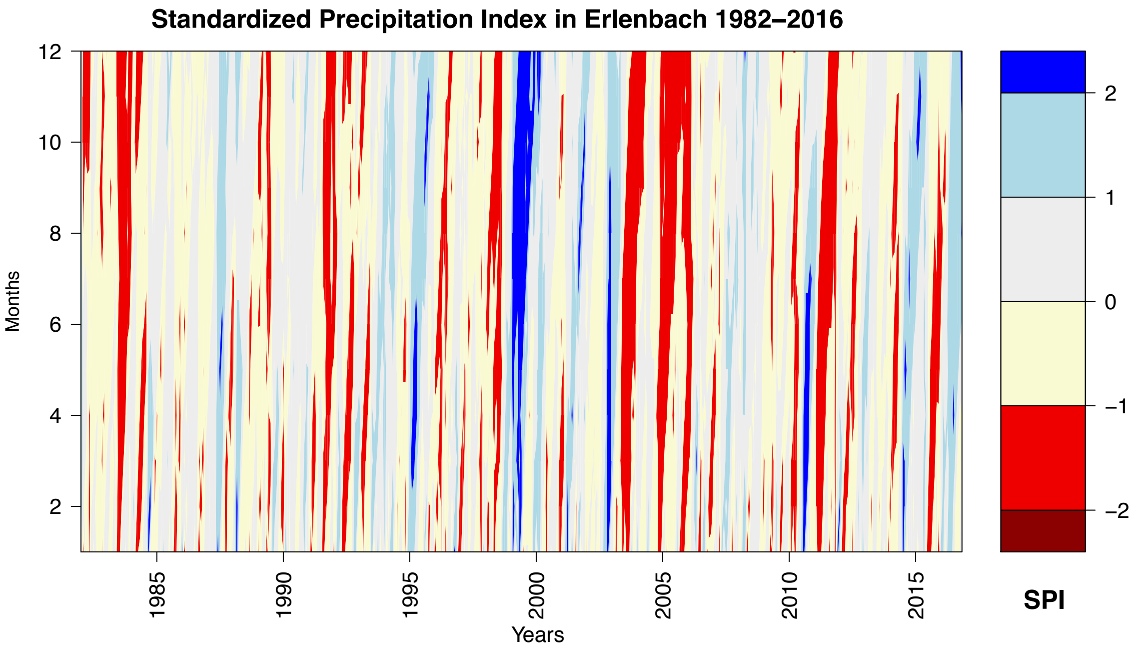


Fig. 28: Standardized Precipitation Index at Erlenbach 1982-2016.

Three-month Standardized Precipitation Index (SPI) for the Erlenbach station January 1982 to November 2016. On the x-axis the timeframe in years and months is plotted against the months on the y-axis. The plotting represents single years in slightly slanted bands. As it is a tree-month SPI January to March conditions are assigned to March for instance. The red bands mark dry periods.

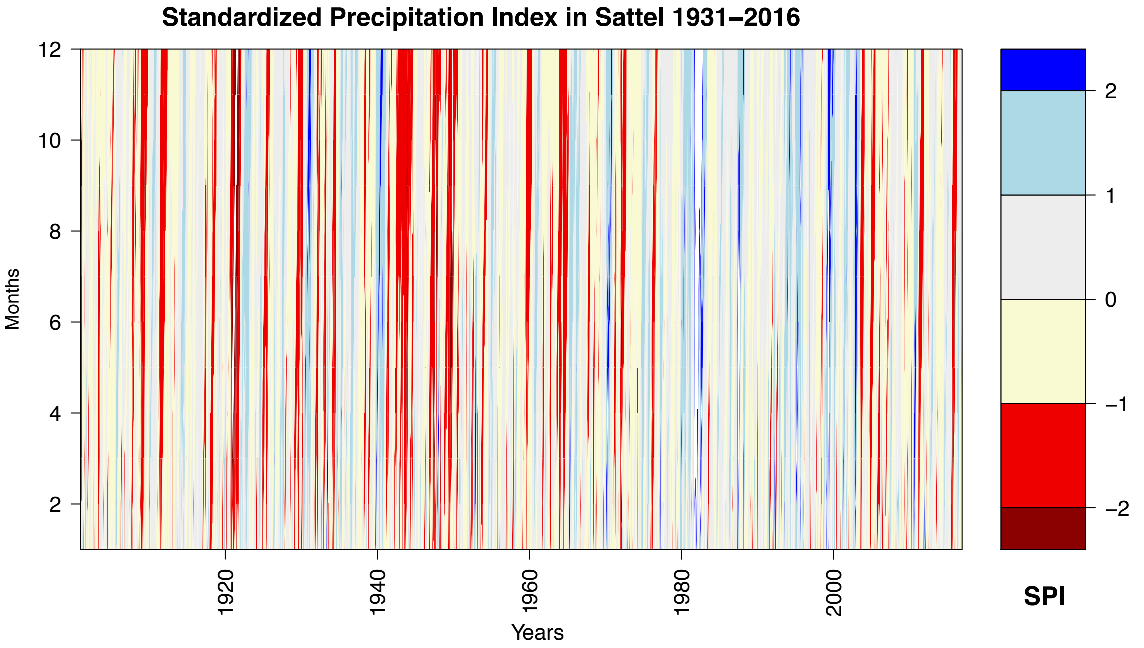


Fig. 29: Standardized Precipitation Index at Sattel-Aegeri 1901-2016.

Three-month Standardized Precipitation Index (SPI) for the Sattel-Aegeri station January 1901 to December 2016. On the x-axis the timeframe in years and months is plotted against the months on the y-axis. The plotting represents single years in slightly slanted bands. As it is a tree-month SPI January to March conditions are assigned to March for instance. The red bands mark dry periods.

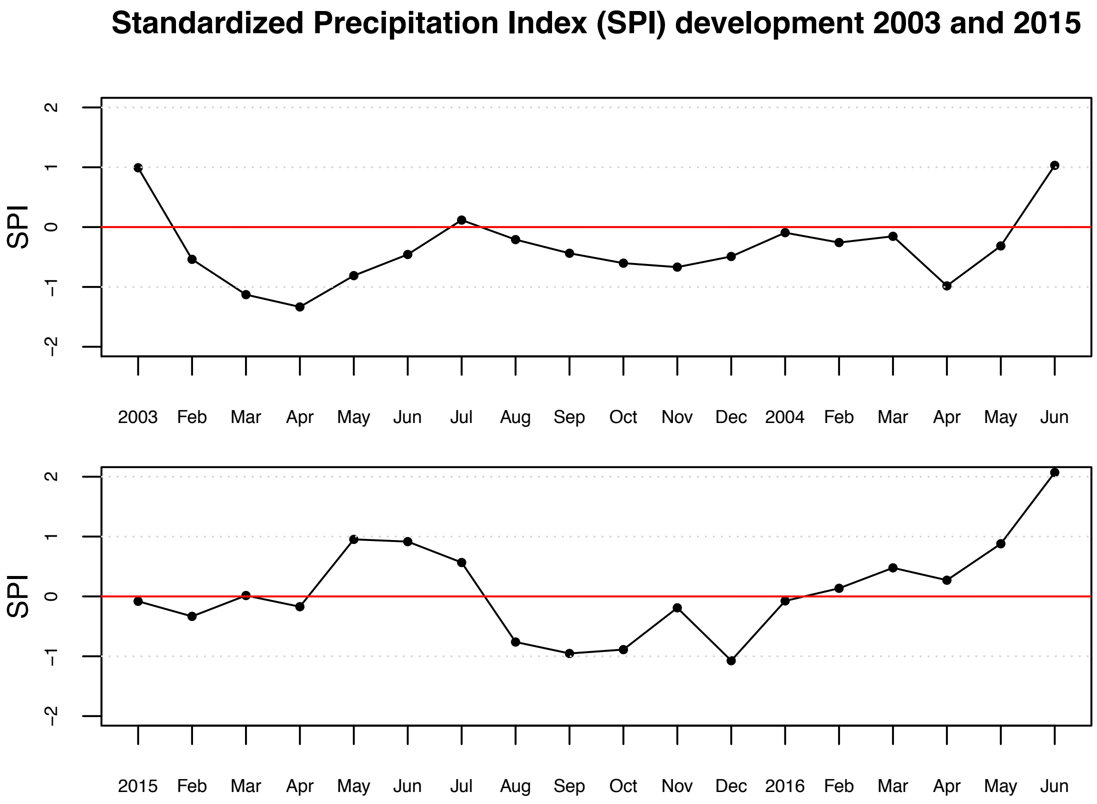


Fig. 30: SPI graph at Erlenbach for 2003 and 2015.

Three-month Standardized Precipitation Index (SPI) for the Erlenbach station in 2003-2004 and 2015- 2016. Again the March SPI represents the Jan-Mar period for instance.

So June to August temperatures are compared with the rest of the observed years. Even though the impact in 2003 was observed in winter, it has to be remarked that summer temperatures were extraordinarily high. In Erlenbach the two years were the warmest since the start of measurement in 1982 with 16.83°C in 2003 and 15.58°C and 2015 both considerable above the mean 13.38°C. In Einsiedeln, the temperatures were warmest in 2003 with 18.34°C in 2003 and third warmest in 2015 with 17.36°C, however, 1947 has the second warmest temperatures with 17.61°C. These are also all considerably higher than the mean of 14.86°C.

Knowing that air temperature in both years was very high, it is probable, that higher than average evapotranspiration occurred in the summer months. So the drought conditions modelled were most likely more severe than the SPI alone suggests. Especially in August 2015, which seems relatively minor on the SPI graph, but could have intensified a lot through high temperatures. The warm summer in 2003 could have had lasting effects on the groundwater levels, leaving them depleted until January 2004.

If the average precipitation for the June-August period is plotted against the June-August average temperature (see Fig. 31), it becomes clear, that there was a coincidence of high temperature and low precipitation in these years. The Mahalanobis distance calculated for both datasets gives an estimate of how extraordinary these coincidences are compared to the whole dataset. In Einsiedeln, the two years are strong outliers, if dry and hot conditions are considered, however, 1947 is a strong outlier also. In Erlenbach, 2003 is by far the strongest outlier, but 2015 falls behind 2010 and 2014, which were extraordinary wet years in recent time. All in all it can be assumed that the coincidence of high temperature and low precipitation produced more severe drought conditions than expected for precipitation alone, especially in August 2015. So air temperature trends should also be investigated at least for the impact observed in summer months.

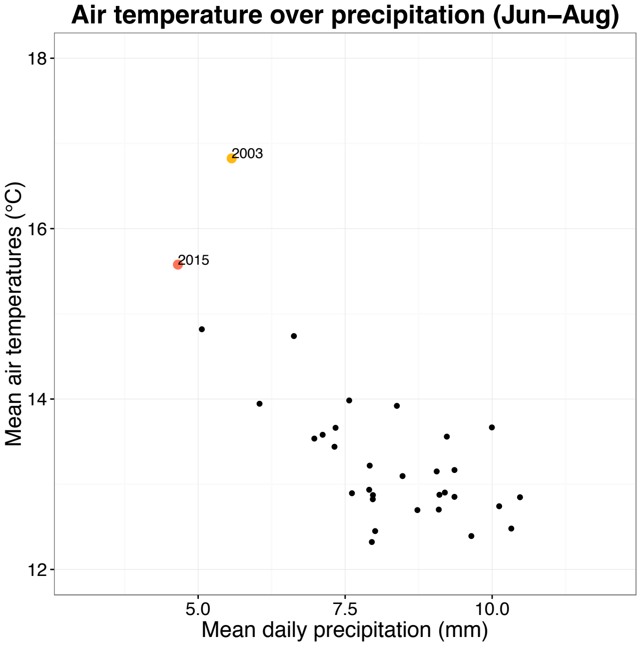


Fig. 31: Scatter plot of June-August air temperature and precipitation at Erlenbach 1982 to 2015.

7.5.2.2. Climate trends

To assess if these local drought conditions were a result of changing climate, trends in the climate variables are investigated. Similarly to Sittlisalp the three-month precipitation values are tested for trends as well as the June-August temperatures. Here the approach is taken, that if average conditions changed, the magnitude or frequency of extreme events also changed. So if for instance precipitation decreased on average, low water extremes would occur more frequently (National Academies, 2016). Probabilistic Event Attribution would additionally give an estimate of the probability of an event happening under the current climate. This requires large computing power and datasets so the analyses here are confined to trend analyses (Massey et al., 2015).

The monthly precipitation data was tested for a monotonic seasonal trend using Seasonal Mann-Kendall tests on the long-term measurements in Sattel-Aegeri. This rendered a weak significant increase in precipitation between 1901 and 2015. The trend is stronger if the timespan is reduced to 1901 to 2000, so this trend is most likely due to the unusually high precipitation period from 1980 to 2000. Shortened timespans (starting 1940, 1960 or 1980 to 2016) detect no significant recent trends of either increase or decrease in precipitation. For the short-term measurements since 1982 at Erlenbach no significant trends could be detected as well.

Linear regression for station	Erlenbach	Einsiedeln	Einsiedeln
Timeframe	1982-2015	1864-2016	1982-2016
Variable	Mean Jun-Aug air temperature °C	Mean Jun-Aug air temperature °C	Mean Jun-Aug air temperature °C
P-value	0.177	2.49e-11	0.019
Significant at level	Not significant	>0.0001	0.05
Trend estimate	0.022	0.0096	0.036
Temperature change total	0.77 °C	1.47°C	1.23°C
per decade	0.23 °C	0.096°C	0.36°C

Tab. 9: Linear regression analysis of air temperature data over different time frames for Haggenegg.

Linear regression and Mann-Kendall tests on the development of the individual three-month periods (1901-2016 and 1960-2016) show no decreasing trends in any periods. For both regression and Mann-Kendall test the only significant trend (p-level = 0.05) is a weak trend to increasing precipitation for the Nov-Jan period. This would contradict rather than support the hypothesis of water shortage occurring because of decreasing precipitation in 2003.

Additionally, the air temperature change as a proxy for evapotranspiration changes is analysed. Similar to the Sittlisalp case, there is a significant air temperature trend detectable for the longer time series in Einsiedeln. Tab. 9 lists the results of linear regression analyses on air temperature data in both Erlenbach and Einsiedeln. While the Erlenbach temperatures over the shorter timespan of 1982-2015 show no detectable trend, the same timespan in the Einsiedeln data shows a significant increase in temperature. Over the whole time series of 1864-2016, the Einsiedeln data also shows an increasing trend of 1.47°C overall. This implies a rise of 0.1°C per decade since 1864 and a rise of 0.36°C per decade since 1980, which corresponds with regional trends (MeteoSchweiz, 2013).

In summary, while there is a direct connection between low-precipitation and water shortages on the Haggenegg there are no significant trends to a decrease in precipitation amounts, which would suggest an increase in water shortage impacts. A trend can be detected in the Einsiedeln air temperature data for the long-term climate and over the impact observation timeframe. This latter trend is not detectable in the Erlenbach temperatures however.

7.5.3. Step 3: Baseline behaviour

Step three of the attribution assessment entails baseline behaviour identification. Generally speaking, water shortages are rare in the alpine region and the precipitation-rich pre-alps in Schwyz (Schorer, 2012).

Here a context analysis for the water shortage on the Haggenegg is conducted, as there is no existing research on the local site. This context analysis gathers all factors influencing the local system excluding climate change processes. Again it is assumed that if there were no changes in local circumstances, there should be no changes in baseline behaviour. Influential changes on the Haggenegg could occur if the landscape in the aquifer was changed, through changes in groundwater extraction or changes in the amount of water used.

The uppermost part of the western board of the Nätschberg is a groundwater protection zone, so there should be no influences that significantly affect groundwater levels or quality. However, this zone does not extend to the groundwater extraction site or the small catchment area above.

Since the inn was opened again, there were some infrastructural changes in the vicinity. In the small catchment area of the aquifer the expansion of the nearby dairy farm is the most important change detectable through the mapping portals (Swisstopo, 2017, webGIS.sz, 2017). The new building used for equipment storage is downstream of the groundwater extraction site, however, so this addition likely did not induce a change in groundwater levels. Landscape alterations for winter sports could also have an effect on the aquifer if the catchment area shrank or packing of the snow cover relayed recharge through later snow melt. However, the ski slopes and infrastructure were built before the inn and only affect the eastern board of the Nätschberg, outside of the groundwater catchment area (Brunni-Alpthal, 2017, Swisstopo, 2017). There is also no indication of other changes to the landscape, naturally or human-induced. Overall, landscape changes should not have affected groundwater levels.

During the observed impacts, the local inhabitants claim, that the same amount of water was used as usual. Since opening in 1984 no changes were made to the well and to the water use. However, field investigation shows that there are multiple other wells in the proximity. Groundwater is the primary water source for all the inhabitants along the Haggenegg pass street. There is a possibility that water shortages were instigated through competition between the wells. It is suspected that at least three other wells lie in the small catchment area around the well. Not all of them lie upstream of the well dedicated to the inn, but depletion downstream could also affect upstream groundwater levels (Hölting and Coldewey, 2013).

In summary, though the landscape is relatively unchanged in recent history, apart from minor building activities, the baseline behaviour probably did not stay stable. Shortage because of competing wells could have influenced the water levels during the observed impact. As there is no information, when these wells were built and how they are used, the magnitude of this influence is unknown. Therefore, the baseline behaviour either did not change or water shortage became more likely, because of more water extraction in the aquifer.

7.5.4. Step 4: Impact detection

Impact detection is the next step in the attribution assessment. An impact is detected if there is a significant difference between the behaviour driven by climate and the non-climatic baseline behaviour.

There is no climate change trend detectable in precipitation, the primary climate variable causing drought conditions. There was, however, a period of quite high precipitation between 1980 and 2000. This high precipitation period at the beginning of the impact observation could skew the perception of the locals when drought conditions returned to pre-1980 levels in 2000-2016. Locals assuming more water should be available would let dry spells seem more intense than they are compared to the long-term local climate.

A trend in air temperatures in Einsiedeln was detectable long-term and short-term since 1980. Also, exceptionally high air temperatures coincided with low precipitation periods in the impacted years. So augmentation of water shortage through increased evapotranspiration in recent years is possible. However, as no increasing drought frequency was detected, there is no evidence for more frequent drought conditions because of higher evapotranspiration. So changing climate through air temperatures could have had an influence but there is no causal relationship between the air temperature and the water shortage incidences established.

The baseline behaviour is also difficult to assess. While landscape and infrastructural changes most likely did not influence baseline behaviour, the groundwater use on the Haggenegg could have. Multiple wells competing for water resources could reduce the available water for the inn in certain seasons. The hypothesis that the impact was caused by climate change drivers has to be rejected and the null hypothesis accepted instead.

With no climate trend detected in precipitation and unclear baseline behaviour, no impact of climate change can be detected. Therefore, *Step 5: Attribution* will be omitted.

7.6. Case Classification

The attribution had to be omitted, as impact detection is impossible. Nevertheless, the case is classed into the attribution classification. Similarly to the Sittlisalp case, there was no impact detection connected directly or indirectly to climate change, but a suspicion of air temperature as a climatic driver for extraordinary drought conditions remains. However, the context analysis also suggests that competition for resources could be an important driver of the shortage. Additionally, the reference period of local observation was unusually wet for the local climate, so water shortage reports could be skewed. Consequently, the case is classed as *Class 4: Likely other causes prevalent.*

7.7. Adaptation

Adaptation to climate change is not yet needed in this case. If increasing temperatures heighten evapotranspiration in the future, it could however be useful to attain additional groundwater sources for the inn. The optimal location for a complementary well would probably be on the on the close by eastern board of the Nätschberg at the same elevation, as there is no competition with other wells. Apart from additional water sources, the innkeepers could put water restriction protocols into place, which take action in low-precipitation periods. If water is managed from the beginning of a drought period, resources may last longer.

7.8. Limitations

In this case, data was available in the proximity, but not for long-term climate analyses. Hence, three different stations had to be compared in this case. As all stations differ in elevation, exposition or distance to the case site, these differences must be kept in mind when comparing the data. Also the impact was only observed since 1984, which is a short time period for extreme event observation.

7.9. Conclusion

In conclusion, impact detection and attribution is not possible for the water shortage at Haggenegg. The short observation and low frequency of the impact complicates the assessment. Additionally, non-climatic drivers have the potential to produce similar impacts on water resources, specifically increased groundwater use in the aquifer catchment area. Still, there is a possibility, that a changing climate influenced the impact through increasing air temperatures. Subsequently, the case was classed into *Class 4: Likely other causes prevalent*.

8. Discussion

The research goals and questions are now discussed, based on the application of the attribution assessment to four local cases. The first research goal was to evaluate and adapt the climate change attribution framework for local observed impacts. It includes two sub-questions (see below). The discussion addresses this research goal and questions through a comparison of the attribution assessment steps for the different cases. This includes the potential and challenges each step poses in practice. Possible alterations for each step to fit the local scale are also proposed.

The second goal was to establish to what extent attribution on local case studies is feasible. To address this goal and its two sub-questions (see 8.2.2 Case characteristics), the final attribution assessment, classification, adaptation and limitations are evaluated. Also the characteristics or study site context that make a local case suitable or inappropriate for attribution assessment are identified.

8.1. Application of attribution framework

The attribution framework was applied to four local case studies. The evaluation where this framework was useful and where it lacked for the local case studies emerges from discussion of each of the individual steps. It summarises the approaches to each step and if necessary proposes potential alterations to the very local case. Short discussions for each step answer both of the questions to the first research goal. The last paragraph consists of a summary of the first research goal based on these findings. Here a recapitulation of the first research goal and the two sub-questions:

Goal 1: Evaluate and adapt a climate change attribution framework for local observed impacts.

Question 1: Is the attribution framework (Hansen et al., 2015) applicable to the attribution of local observed impacts in practice?

Q2: How can the attribution framework be adapted to provide the optimal guide for very local cases?

8.1.1. Step 1: Hypothesis formulation

As the method bases on a common hypothesis test approach, the hypotheses determine the general direction of the evaluations. For the cases, the hypothesis suggests climate variables suspected to influence the impact. Hansen et al. (2015) propose to gather the influencing variables of the system and consult drivers of similar impacts in literature. Here, the discussion of the basic processes of each case, setting the case into the local system context and comparison with cases was quite extensive, before hypothesis formulation. In the local case, this elaboration on local setting is especially important, as the comparison with other cases in literature is only valuable if they base on the same underlying processes. For example, influences on stream flow in a steep mountainous catchment are not the same as on a large lowland catchment.

Hansen et al. (2015) suggest that the inclusive approach of gathering all influencing variables prevents selection bias in the hypothesis. However, more often than not, local data on many established influences is not available, so the hypothesis testing concentrates on the variables where data is available. Due to this dependency on data, the hypotheses are not formulated bias-free. Because of this lack of data and because possible additional influences emerge during the later steps, the hypotheses are formulated rather broadly at the beginning and often need to be adjusted later on. Here, this was the case with the water shortage cases, where the air temperature was added as a climate driver.

Another challenging part on a local level is relating the findings back to the hypotheses. The null hypothesis states that the impact observed occurred due to drivers other than climate change. This poses a challenge, as the baseline behaviour for local cases cannot be modelled, but bases on the assumption that no changes in the surroundings mean no influences on the impact were present (see 8.1.3 Step 3: Baseline behaviour). Consequently, the null hypothesis can rarely ever be rejected, because elimination of all influences is difficult. Hypothesis testing might be too strict for local cases. Especially as the hypotheses may change during the trend analysis and baseline behaviour phases and have to be adjusted. Hypotheses are primarily useful as a guideline for the assessment.

To answer the research questions: Hypothesis formulation for the local case is useful as a guideline for the trend analyses but especially important is a diligent evaluation of the impacted system. For cases with such a small spatial extent, this pre-step is crucial and cannot be omitted. An adaptation proposition is to include this step in the attribution framework. If this step was included and the circumstances that have to be accounted for well-structured, attribution outcomes of different cases would be more comparable.

8.1.2. Step 2: Trend analysis

The second step is to analyse if there are significant changes detectable in climate. Here statistical methods assess the trends in the climate variables connected to the impact. A prerequisite for this step is appropriate climate data. If there is no climate data within a reasonable proximity available, identification of a trend is impossible. Subsequently, if trend detection is impossible, an attribution assessment is redundant. Appropriate data is therefore vital for successful attribution.

Each of these cases gathered the most suitable data according to the system context information. For local cases this means the closer the data is measured the better. Cases, which lie closer to a climate measurement station, need fewer assumptions on the suitability of the data. For instance, the case in Flüelen is located at a similar elevation and less than 3km away from all stations used. It can therefore be assumed that the measurements at this site are the same as they would be at the fish farm site. In contrast, both the Sittlisalp and Rhone Glacier case lie about 1000m higher than their corresponding stations. Consequently absolute temperatures cannot be used for any assessments, but it can be assumed that the temperatures follow the same trend. This limits the scope of useful methods for trend detection. Fortunately, due to the high measurement density in Central Switzerland, suitable data for all cases was found. For the local case it is pertinent to document the limitations posed by this data and incorporate it in the impact detection and attribution steps.

According to the data, appropriate statistical measures are chosen. Here most of the analyses are linear regression analyses and seasonal trend analyses. The advantages of the chosen models are, that they do not need many input parameters and are based on basic statistics, without many additional assumptions (Backhaus et al., 2011). The preferred statistical test is linear regression (where linear relationships are present) because it estimates a relationship between dependent and independent variables quantitatively and therefore trends over time can be quantified. For local trend analysis data available is limited, so the use of complex models is rarely realistic.

The methods also need to reflect the processes in the individual cases and the data available. Applying the same tests on a group of similar impacts would therefore often not do the site specific data and limitations justice. However, for certain impacts it could be plausible to develop specific method procedures that apply to similar impacts though tailoring of the methods to the data and circumstances of the individual case is paramount. The same procedures were used in both of the water shortage cases at Sittlisalp and Haggenegg. Although attribution was not possible in both cases, the methods steps were appropriate to assess both cases. For more frequently observed impacts that are more likely to be attributed like the Rhone Glacier case, such specific procedures could simplify the attribution process. This would also allow for easier comparison of attribution outcomes. However, it must be stressed, that especially on a local scale, the case characteristics always have to be respected and no methods apply exactly the same to similar local cases.

A step emphasised here, which is not explicitly mentioned in Hansen et al. (2015), is establishing whether there is a relationship between the reported impact and the local climate. For an impact that is well observed and documented in other sites, this is not absolutely necessary. However, for the cases on hand, the report of the impact is somewhat subjective. For the case at Haggenegg for instance, local business owners reported a water shortage. In high seasons, they did not have enough water for their inn. The suspicion arises that overuse of water could instigate such a problem, rather than precipitation deficit only, even though locals claim that habits did not change. As drought conditions calculated through precipitation data in these years were likely, some of this suspicion is dispelled. It establishes that on the more complex local level, climatic conditions do influence the impact as well. Additionally, it estimates the magnitude of the influence of the climate variable on the impact. So while this step is not crucial it is beneficial, as the laymen observation can be observed by measurements as well and it describes the local climate influence on the impact.

In summary, the trend analysis is applicable as long as appropriate data is available. As data is often quite sparse on the local level, the most suitable methods for climate trend analysis are simple trend detection methods like linear regression models or the Mann-Kendall trend analysis for seasonal assessments (Helsel and Hirsch, 2002, Backhaus et al., 2011). Locally, the contribution of the climate to the impact may vary, so putting the impact into relation to the climate benefits the overall attribution assessment. If this is not possible through statistical analysis, it should be assessed if the observed impact shows a trend similar to the climate variable, to evaluate whether a connection is plausible. Also a climate trend, which is similar to large-scale climate trends, does not automatically attribute to anthropogenic forcing.

8.1.3. Step 3: Baseline behaviour

The third step is baseline behaviour identification if the climate was stable. Human influences often disturb today's systems and these systems would not be stable in the absence of climate change. An observed change in the system could also stem from this change in baseline behaviour. Correspondingly, if there was no clear climate trend detected for the impact, but the baseline behaviour suggests that there should have been a development, an impact can still be detected. However, it cannot be attributed to climate change, as there was no climate trend found, only to another driver. From an investigative standpoint in local cases, continuing the assessment is still interesting, as the locals can adapt correctly to the impact. From a research standpoint it reveals, which other drivers can produce impacts similar to climate change. Hansen et al. (2015) stress the importance of considering all potential non-climatic drivers on the system. Neglect of any important drivers distorts the baseline, which may lead to wrongful attribution. Identification and evaluation of all these drivers is very difficult in most cases however. On a larger scale, this baseline behaviour is easier to assess, as tools like climate models are more useful on large-scale cases.

In a well-researched system, information on past behaviour may already be published. For the Rhone Glacier case, past drivers of glacial advance and retreat were already investigated quite well. Nevertheless, this is the exception rather than the rule for most local cases. For most cases there is no research containing information on baseline behaviour, but instead behaviour is presumed stable if no altering influences are detected.

In the Flüelen, Sittlisalp and Haggenegg cases, this assumption came into action. Instead of modelling a baseline, it takes circumstances important for the basic process into consideration. If circumstances changed over the time period of impact observation, the influence this change has on the impact was estimated. The sum of all contributors gives a baseline estimate. The Sittlisalp power plant for instance found no significant changes in circumstances, so the baseline is assumed to be steady. In Haggenegg human influence on the system is higher, but most influences could still be classed as minor to inconsequential. The most urban case in Flüelen, however, is also the most difficult. The setting in a residential area makes identification of all drivers impossible. The identified potential drivers are also manifold and often it is not obvious to what extent these drivers contribute. Therefore the baseline behaviour can only be estimated roughly, which limits impact detection, even though there is a connected climate trend.

In summary, the baseline identification for local cases depends on how disturbed a site is. The more potential non-climatic drivers, the more difficult the identification is. Remote alpine locations are best suited as there are the least human-managed systems, while urban sites are the least suitable (in Central Switzerland). So baseline behaviour identification is possible for relatively undisturbed local systems but for urban local cases it is very limited. For the local level, the assumption that a systems baseline has not changed if there are no significant changes in the surroundings is needed in most cases. Also it is rarely possible to quantitatively estimate the baseline behaviour so qualitative assessment is the best option. Hansen et al. (2015) also suggested baseline behaviours could often only be assessed qualitatively on a local scale.

8.1.4. Step 4: Impact detection

Impact detection compares the climate trend and the baseline behaviour. If there is a significant difference, an impact is detected. All of the information for this step is already gathered in Step 2 and Step 3, so this step needs no additional data and analyses. As the baseline behaviour is assessed qualitatively in local cases, impact detection is also qualitative. This step depends on *Step 2* and *Step 3; Step 4* is applicable on a local level, as long as the precursor steps were approached diligently. The procedure to compare the trend and baseline behaviour is quite straightforward while setting this detected impact into relation with the hypothesis is more challenging (see 8.1.1 Step 1: Hypothesis formulation). This is either because of how baseline behaviour is assessed or because hypotheses are not relevant anymore.

8.1.5. Step 5: Attribution

Attribution is the final step of the framework. It assesses the magnitude of the contribution of the climate driver to the impact. Thus, the influence of the climate driver is compared to all other drivers. This step again bases on the four steps before, particularly *Step 2* and *Step 3*. If no impact is detected it cannot be attributed and this step becomes redundant.

In two of the four cases here an impact was detected connected to steadily rising air temperatures: The Rhone Glacier case and the Flüelen fish farm case. In both cases the climate was a major driver of the impact. However, in the Flüelen fish farm it is likely, that other drivers than the climate also contributed to the warming. Therefore, the confidence in attribution is low to medium.

Attribution was only possible, where climate is suspected to be a major influence. With only four cases, this is not a representative sample of all the impacts that potentially could be attributed. But especially as the local level is so complex to assess, it would be difficult to detect minor impacts. Also the case characteristics play an important role in whether an impact can be attributed. Impacts connected to a variable with a regionally clear trend, like rising air temperature, are better candidates for attribution. Also impacts, induced by a steady trend over a longer time period are easier to assess than extreme event impacts. As extreme event attribution on a larger scale is also still in the early stages of development, it not surprising that local extreme event attribution was not possible (National Academies, 2016). The case characteristics are discussed further in the second research goal below.

Generally, this step is applicable to the local scale as is, with the concession that the attribution is qualitative and not quantitative. A simple distinction between major and minor drivers makes sense (as suggested by IPCC (2014a). Inclusion of a confidence statement is helpful for the attribution in the local cases. It allows for the incorporation of additional information: Assignment of low confidence to a major impact for instance takes place if there is substantial evidence of an influential climate trend but essential data to assess the baseline behaviour is missing (see Flüelen fish farm).

8.1.6. Synopsis first research goal

In conclusion, the attribution assessment is applicable to the local scale. However, the small-scale extent demands some concessions. Firstly, the characterisation of the study area and gathering of as much specific information on the case as possible is an important pre-assessment step. On the local level, it would be negligent not to assess the circumstances of the site before hypothesis formulation. On a larger scale, hypothesis formulation based on literature review of similar impacts and basic processes could suffice.

Secondly, all steps rely heavily on appropriate data for the case. The "best data" available does not necessarily fit well enough for a local case. The more assumptions have to be made because of the choice of data, the lower the confidence in attribution. This applies to the pre-assessment research the hypothesis are based on and to all steps of the assessment. The attribution assessment could result in no attribution in cases that seem straightforward, because of missing data. For instance, even though confidence is high that glacier shrinkage is due to climate change regionally (IPCC, 2014b) – if air temperature data for the Rhone Glacier case were only available for the last ten years, attribution according to the framework would be impossible.

Thirdly, assessments are generally qualitative and not quantitative. The distinction between major and minor drivers is already challenging on the local level. An additional confidence statement to the attribution is therefore also helpful, as it provides an evaluation of how well the attribution framework could be applied.

8.2. Attribution on local cases in Central Switzerland

After evaluating the attribution framework, the attribution in the study area Central Switzerland is in the focus next. To answer the third research question contributing to the second research goal (see box below), the final attribution statement, its limitations and the classification are evaluated for all cases. Assessment of the influence case characteristics have on successful attribution answers the fourth research question is answered. Here, *case characteristics* is an umbrella term to describe all circumstances, which potentially affects the potential for attribution. This includes but is not limited to the temporal and spatial scales of the impact and the connected climate variable and the local setting of the case. Lastly, the potential of the attribution assessment to improve adaptation to the observed impact is discussed.

Goal 2: Establish to what extent attribution on local case studies is feasible.

Q3: Is impact detection and attribution of the cases in Central Switzerland possible and to what extent?

Q4: Which case characteristics (e.g. temporal and spatial scale), facilitate or hinder detection and attribution?

8.2.1. Attribution in Central Switzerland

Impact attribution was possible to a certain degree in two of the cases. Tab. 10 gathers the attribution results and case characteristics of all the assessments. Rising air temperature is a major driver of the retreat of the Rhone Glacier with a medium confidence attribution. Also rising air temperature is a major driver for groundwater warming but with low-medium confidence only. Both water shortage cases were due to low-precipitation events, which did not show a trend in the past, though augmentation of the recent drought conditions because of a trend in rising air temperatures is possible.

The study area of Central Switzerland has distinct advantages for successful attribution compared to other local study areas. The evaluation of the first research question already answered if the individual steps of the method framework apply to these local cases. An important point raised for successful attribution was to use appropriate data for each step. For all cases reasonably suitable data over climatically relevant time periods was available. Of course, cases would profit from additional data: Longer groundwater observation in Flüelen for example could have increased the confidence in attribution considerably. But to expect better data availability would be unrealistic. The assessments here were only possible because of broad data availability in Switzerland. Also, cantonal and national mapping portals and helpful locals sharing their observations made a close review of the study sites possible.

The study area therefore provides a good vantage point for the attribution assessment; still, the attribution investigation was very challenging and at times the circumstances were too complex to make confident statements. Also the attribution may find a connection to a local climate trend but this does not automatically relate the impact to larger scale climate change. Establishing global climate change as a driver for these locally attributed cases warrants further investigation. These challenges and limitations have to be ascribed to the fact that local climate change impact attribution is a novel approach and still restricted in its possibilities. So while these results suggest local attribution is not futile and a potentially helpful tool for local system understanding in the future, its successful application is still limited.

Another limitation for local scale attribution in Central Switzerland is, that cases are not easy to find. Their small extent means that only a limited amount of people is directly affected. The researcher needs insight into the local community and trust from the locals to find cases. Lack of potential cases is likely based on the fact, that people do not want to share their problems or do not want any association to cantonal and national authorities. Also climate change is sometimes not a valid motivation for locals as it is often dismissed as nonsense or a matter of political opinion rather than scientific research. This consensus transpired from interviews with cantonal employees and adaptation project managers in the region.

On the flipside, this highlights the potential for local information to support environmental research as emphasised by Guyot et al. (2006), and Marin (2010). Local inhabitants have otherwise unattainable insight in local systems. Utilising local knowledge to observe environmental changes and climate change impacts systematically is a valid option in future local climate research.

Case	Rhone Glacier	Flüelen fish farm	Sittlisalp plant	Haggenegg inn
Observed impact	Glacial retreat	Groundwater warming	Water shortage	Water shortage
Primary climate variables	Air temperature, precipitation	Air temperature	Precipitation	Precipitation
Study site	Remote, alpine	Urban, alpine valley	Remote, alpine	Rural, pre-alpine
Station:	Andermatt	Altdorf	Altdorf	Several stations
Distance	17 km	3km	9km	2-10km
Elevation difference	1000m	Same elevation	1200m	200-600m
Attribution:	Climate major driver	Climate major driver	No impact detection	No impact detection
Confidence	Medium	Low-medium	-	-
Classification	Class 1: likely related to climate change	Class 3: Suspected climate change influence	Class 3: Suspected climate change influence	Class 4: Other drivers prevalent

Tab. 10: Case characteristics and attribution assessments for all cases.

However, because of the apprehension of many locals towards climate change and local authorities, such research endeavours have to focus on securing the cooperation of locals.

Classification scheme

Additionally to the attribution framework, the cases are categorised into a classification scheme developed for this thesis. Through comparing the magnitude of the climatic and non-climatic contributors, the classification includes the attribution statement. The relationship between the climate and the case is divided into direct climate influence and indirect climate influence, which gives additional information on the connection of the climate trend to the impact. It also includes a confidence statement, considering if data inconsistencies, lack of data and assumptions limit attribution significantly. This classification has potential for use on a local or also a larger level scale, as it simplifies the attribution statement, while still including these nuances of the attribution assessment. Attribution is a complex concept and explaining it to laymen can be taxing. Therefore such a classification could be of use when presenting attribution studies to policy makers, locals or in interdisciplinary research forums.

Adaptation

A primary motivation behind this study is also to evaluate if such local attribution could aid to optimise local adaptation measures. Each of the case studies discusses appropriate adaptation measures according to the findings of the assessment. For some cases it is certainly important knowledge that climate change is a driver. The assessment in Flüelen for example rendered, that investment into more efficient cooling equipment or relocation of the site were the only long-term adaption measures appropriate. Also relocation is only successful if future climate change is taken into account. Here the attribution assessment provides critical information for future proceedings. In the Rhone Glacier case, the attribution assessment confirms a common suspicion rather than providing novel information. The application of such a time consuming assessment is therefore not practical for such impacts outside of testing of attribution methods.

The question, if climate change attribution is possible in Central Switzerland can be answered as follows: Impact detection and attribution of certain cases in Central Switzerland is possible to a degree, depending on case characteristics, data availability and willingness to share observations by locals. Using a classification scheme could help presenting attribution to a broader audience and make attribution a more approachable subject for policy makers and researchers as well. These assessments could benefit especially in cases where climate change is not established as a problem in the public mind. In cases, where climate change is commonly accepted as a driver, the effort put into such in-depth assessment outweighs the benefits.

8.2.2. Case characteristics

The characteristics of a case determine together with data availability how large the potential for an impact attribution is. Certain characteristics of an impact make attribution more likely or heighten confidence in the assessment. These characteristics concern the temporal resolution, the spatial extent and site context amongst other factors.

The spatial scale of local observations is per definition limited to a small extent. Here local refers to the smallest scale of observable impacts – individual observations at one single location. This still leaves some leeway for the size of the spatial extent depending on the kind of impact observed. In the case of a glacier, this local extent covers an area of around 15km^2, compared to a point-measurement such as the groundwater extraction in Flüelen. The Sittlisalp and the Haggenegg case are both local cases, but the catchment area is larger and there are multiple extraction sites on the Sittlialp. This larger area can simplify and complicate the assessment. On the one hand the larger area is subject to more influences. On the other hand, some influences, which affect only part of the area, can be neglected. Generally however, the larger the extent, the more suitable the case is for the assessment. This comes as no surprise, as the principal premise of this thesis is that local attribution is more challenging because of its small extent. But among the local cases, this rule of thumb also applies.

For temporal resolution, the longer and more continuous a change is, the greater the potential for attribution. If the impact is observed over a long time period, it is easier to detect a significant trend. However, if the impact predates the data available, estimation of the magnitude of the impact or its related climate trend is challenging as well. Changes that occur continually over a time period are also more suitable for attribution. Infrequently occurring impacts like extreme event impacts are very difficult to assess and can rarely be related to climate drivers. Both water shortage cases fall into this category and it proved too great a challenge for attribution. As attribution of extreme events was rarely successful for much larger impacts up to now, it would have been surprising if such an attribution was possible on the local scale (Hansen et al., 2014, National Academies, 2016). The optimal foundation for attribution is given if the primary climate variable related to the impact shows a constant regional trend in average conditions. For instance, local attribution to constantly rising mean air temperatures in the region is more likely than attribution to changes in precipitation variability.

The surroundings of the case also weigh in on successful attribution. For one, as established in 5.1 Application of attribution framework the extent of human interaction at the case site is crucial. Generally, the less human actions disturb a site, the more comprehensive baseline identification is. Urban areas are less suited than remote alpine areas. However, often climate data is primarily measured in accessible urban areas and less data is available for high-elevation areas. The distance from the measurement station is therefore another important factor. Impacts observed in a remote area but close to a measurement station have the greatest potential for a confident attribution.

8.2.3. Synopsis second research goal

To summarise, the attribution of local impacts in Central Switzerland is feasible for some cases to a certain degree, while for others no connection to the climate can be detected. Central Switzerland provided optimal conditions for the purposes on hand, compared with other potential study areas. The data availability is better than in most areas and different case settings can be investigated due to the variability of the landscape from high alpine to lowland valley contexts.

Case characteristics and circumstances that facilitate the attribution assessment are long impact observation periods in undisturbed systems coupled with climate data measured at a close proximity or at a comparable site. Climate trends specifically are easier to assess if continuous changes were observed instead of extreme events. While baseline behaviour is easiest to assess in a very remote, undisturbed system. Generally, the smaller the area affected by the impact, the more challenging and complex is the attribution.

8.3. Significance for attribution research

This sub-chapter puts the findings into context with broader impact attribution research. As of June 2017 no published work applied the attribution framework used here to actual local case studies apart from the authors (Hansen et al., 2015, was cited by the following peer-reviewed work as of June 2017: Huggel et al., 2015, Mera et al., 2015, Huggel et al., 2016, Rosenzweig et al., 2017, Parker et al., 2017, Sirami et al., 2017). The authors included some illustrating cases where the framework was applied. These cases are arguably of regional rather than local extent. For instance, the example cases use the Gulf of Guinea on the West African coast or the Sahel Zone as a study area, which both span hundreds of square kilometres (Hansen et al., 2015). Therefore, these case studies using the attribution framework are unprecedented and thus provide an important first endeavour in assessing the potential and challenges posed in local impact attribution (see 8.1.6 Synopsis first research goal and 8.2.3 Synopsis second research goal).

The results concur with the general consensus that local impact attribution can be beneficial for the investigation of impacts on many systems. However, the results also agree with Parmesan et al. (2013), who argue, that for certain impacts regional and global attribution is sufficient and individual impact attribution is redundant. This particularly applies to research areas, where attribution to climate change is widely established, for instance attribution of alpine glacier retreat to rising air temperatures. Nevertheless, even in well-researched impacts attribution could be worth the effort in certain circumstances. Adaptation and climate justice processes often involve stakeholders such as local inhabitants and advanced attribution methods on the local level could support both processes considerably (Mera et al., 2015, Huggel et al., 2016). Clean communication of attribution efforts is paramount in interaction with stakeholders (Parker et al., 2017). Hence the development of solid attribution methods as a tool for developing adaptation plans, climate justice investigations and as a basis for communication of climate change impacts is necessary. Simple but potent classification schemes such as the one used here can support clear communication of attribution results.

Also impact detection methods requiring large computing power or unavailable datasets were not used, but with different resources, more complex methods could be tested within the attribution assessment, for instance PEA or downscaling (Massey et al., 2015, Chu and Yu, 2010).

9. Conclusion and outlook

This master thesis focuses on four case studies in Central Switzerland, where locals observed climate-related impacts. It applies a hypothesis-based method framework, developed for impact attribution, to impacts with a very small spatial extent. As this framework has not been applied to such local impact cases before, these assessments render valuable information on the potential and challenges of such attribution efforts.

Therefore, a first research goal evaluates the attribution framework through practical application and suggests adaptations for the individual steps. The most significant changes proposed are gathering of extensive local information before formulating the hypotheses and statistically linking the local impact to the driving climate variables before assessment of the climate change. These adaptations to the framework support understanding of the local system and the impact context. A prerequisite for a robust attribution assessment is the use of appropriate climate data. This necessitates measurement series of suitable variables, which are collected reliably and for a climatically significant time period, at a location reasonably close to the impact site.

The second research goal evaluates if attribution is feasible for the cases in central Switzerland and which case characteristics (e.g. temporal and spatial scale of the impact) facilitate or hinder a thorough assessment. Central Switzerland is an appropriate study area for this first attempt at assessing very local cases according to the framework. It provides high data availability and cases in various landscape and climate zones. In two cases, attribution was possible to a certain degree, attributing the impact to increasing air temperatures. Confident qualitative attribution of certain local cases was feasible and suitable adaptation measures could be proposed.

The two other cases dealt with low precipitation events and attribution was not possible as no climate trend could be detected. Generally, cases connected to a long-term trend in average climate conditions are more straightforward than changes in variability of climate. Detecting climate trends in the variability of a climate signal is more demanding because extreme weather is rare. Often such extreme impacts are also difficult to quantify, the severity of a drought for instance depends on multiple climate variables and is relative to the local system. The attribution of extreme precipitation events is very challenging on a larger scale level and is not yet feasible for these local level events as well. Before successful extreme event attribution is feasible on the local level, the detection of climate variability changes on a local level need to improve. In the future, as climate change progresses, longer measurement series could facilitate more thorough extreme event assessments.

For future case studies it should be emphasised that observations of the impact and information on the surrounding system by locals are useful for the study, a necessity even. Local information can be especially useful to estimate if the baseline behaviour changed over the observation period due to human influences. Local adaptation project leaders probably have the best vantage point to establish contact with local informants and obtain the necessary data from the local authorities. Also Simple classification schemes such as the scheme proposed here could be developed further to support the communication of local impact attribution back to the local communities.

These case studies are just a first step to evaluate if local impact attribution has potential. It does not yet establish a connection to global climate change. In further research, additional types of impacts could be assessed such as species migration or hang mass movements. These processes are prevalent impacts linked to temperature changes in mountainous regions, which pose hazards or have the potential to cause lasing disturbance to natural and human systems. Attributing such impacts could support assessment of future hazard and risk potential.

10. Literature

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Appendix

Appendix A: Impact report sheet

Protokoll zur Aufnahme von lokalen Ereignissen
Protocol for local impact report

Name: *Title:*				
Kontaktperson: *Contact:*				
Aufnahme/*Report:* Ort, Datum *Place, Date*				
Organisation: *Organisation:*				
Ereignistyp: *Type of impact*				
Key words:				
Beschreibung *Description*				
Zeitrahmen/*Timeframe:* Beginn, Ende *Start, End*			Häufigkeit: *Frequency:*	
Umstände *Circumstances*				

Getroffene Massnahmen : *Implemented adaptation measures:*	Geplante Massnahmen: *Planned adaptation measures:*

Weitere Kontaktperson: *Further Contact:*	
Weitere Kontaktperson: *Further Contact:*	
Weitere Kontaktperson: *Further Contact:*	

Weiterte Umstände
Additional Circumstances

Anmerkungen (Tipps)
Comments (Tipps)

Forschungsbereich: *Area of research:*	

Themenbereiche
Related research topics

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Personal declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Date: ______________________________ Signature: __________________________________