# Obersulzbach

# Hydrological Changes due to Glacier Retreat

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## Statutory Declaration

I declare that I have developed and written the enclosed Master Thesis completely by myself, and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked. The Master Thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.

Location, Date　　　　　　　　　　　　　　　　　　　　　　　　　　Signature

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# Abstract

The objective of this master thesis is to identify the effect of glacial retreat on runoff of the Obersulzbach, a Salzach tributary in the Central Alps in western Salzburg, Austria. As a consequence of ongoing climate change, the glaciers within the Obersulzbach valley have been generally receding since approximately 1850. It is hypothesised that this leads to modified patterns and quantities of runoff observations.

Two hydrographic gauges along the Obersulzbach provide time series from 1977 until 2013 and 1989 until 2012, respectively. The discharge data is filtered to focus on discharge from glacier melt, excluding baseflow and surface runoff from precipitation and snowmelt. This is achieved by calculating the mean daily discharge variation over predominantly dry periods as an indicator for the proportion of glacial meltwater in overall discharge, defined by a threshold of total precipitation of 10mm over at least eight days. These dry periods are selected in times of typical glacial meltwater maxima during the summer months, i.e. late July until the end of September or late July until the end of August. The trends of mean daily discharge variation over these dry periods are analysed with multiple regression and partial correlation using the software “R”. Both methods either take temperature into account directly or control for it in order to remove its effect, as temperature has a significant impact on discharge variations.

Both types of analyses, i.e. multiple regression and partial correlation, yield similar results indicating an initial increase of the mean daily discharge variation until a critical point is reached, which seems to be during the 1990s. Afterwards a decrease of discharge variation indicates a lower amount of glacial meltwater as the remaining glaciers no longer sustain such a high discharge. Its initial rise until the 1990s has a much steeper and statistically more significant increase compared to the subsequent decrease. The weak statistical significance appears to be due to the shorter time series containing dry periods (since the early / mid 1990s maximum) and at least initially a merely gradual decrease. Nonetheless, when looking at all statistically significant results the data indicates that after an initial increase of glacial meltwater, the melt contribution to overall discharge started to decrease roughly two decades ago.

There are various potential explanations for this pattern, which are discussed based on literature studies. Such reasons are an initial increase followed by a reduction in total ablation area of glaciers as well as various feedback mechanisms, including changes in albedo, preferential meltwater pathways inside the glaciers and reflected and emitted radiation from surrounding slopes, as well as longer glacier boundaries and the change of elevation of the glacier tongue.

# Kurzfassung

Das Ziel dieser Masterarbeit ist, die Auswirkungen des Gletscherrückganges auf den Abfluss des Obersulzbaches, eines südlichen Nebenflusses der Salzach in den Salzburger Zentralalpen, zu identifizieren. Als Folge des anhaltenden Klimawandels haben sich die Gletscher des Obersulzbachtales seit ca. 1850 zurückgezogen. Die Hypothese der Arbeit ist, dass dieser Gletscherrückgang sowohl das Abflussverhalten als auch die Abflussmenge verändert.

Entlang des Obersulzbaches kommen zwei hydrographische Pegelstationen zum Einsatz, für die Zeitreihen von 1977 bis 2013 bzw. von 1989 bis 2012 zur Verfügung stehen. Diese Abflussdaten werden gefiltert, um den Anteil der Gletscherspende zu isolieren und den Basisabfluss sowie nicht glazial beeinflussten Oberflächenabfluss aus Niederschlag und Schneeschmelze auszuklammern. Als Indikator für die Gletscherspende wird die mittlere tägliche Abflussvariation während vorwiegend trockener Perioden berechnet, welche mit mindestens acht Tagen Dauer und einem Schwellwert von höchstens 10mm Niederschlagssumme definiert werden. Die Daten werden entweder von spätem Juli bis Ende September, oder spätem Juli bis Ende August ausgewählt, welche typische Perioden mit maximaler Gletscherschmelze darstellen. Die aus den Daten ersichtlichen Trends der mittleren täglichen Abflussvariation werden mit multipler Regression und partieller Korrelation mithilfe der Software R analysiert. Bei beiden Methoden wird die Temperatur entweder direkt berücksichtigt oder als Kontrollvariable ausgeklammert.

Sowohl die multiple Regression als auch die partielle Korrelation dieser beiden Analyseansätze erzielen ähnliche Ergebnisse und deuten auf einen anfänglichen Anstieg der mittleren täglichen Abflussvariation hin. Ein kritischer Punkt und eine Trendwende hin zur Verminderung der Abflussvariation wurden vermutlich in den 1990ern erreicht. Dies weist auf eine verminderte Gletscherspende hin, da die schrumpfenden Gletscher geringere Abflussmengen beitragen. Die Zunahme bis zu den 1990ern zeigt im Vergleich zur anschließenden Abnahme einen steileren und statistisch signifikanteren (positiven) Gradienten. Die schwache statistische Signifikanz des Trends nach den 1990ern ergibt sich vermutlich aus der kürzeren Zeitreihe und dem langsamen Übergang hin zu einer Abnahme der Abflussvariation. Selbst bei ausschließlicher Betrachtung der statistisch signifikanten Ergebnisse zeigen die Daten einen anfänglichen Anstieg der Gletscherschmelze und in der Folge einen Rückgang, der vor ca. zwei Jahrzehnten einsetzte.

Dieses Abflussverhalten erlaubt verschiedene Erklärungen, die auf Basis einschlägiger Literatur diskutiert werden. Ursachen sind z.B. anfängliche Vergrößerung und darauffolgende Verkleinerung der Ablationsfläche sowie diverse Rückkoppelungsmechanismen. Dazu zählen Änderungen der Albedo, frühere Entwicklung von Schmelzwasserpfaden, und Variationen reflektierter bzw. emittierter Strahlung umgebender Hänge. Auch ändern längere Gletscherränder und die abgesenkte Gletscherzunge das Abflussverhalten.

# 1 Introduction

## 1.1 Background

Climate change and its impact on the environment and subsequently on humans is a very pressing topic. It is of great economic and ecological importance and influences many different environmental parameters, such as glacial discharge. The following chapter provides the background information for this thesis.

### 1.1.1 Glaciers

Generally speaking glaciers consist of two areas, the accumulation and ablation areas. The accumulation area can be found where the long-term deposition of snow exceeds the melting processes, whereas the ablation area describes the area with predominant melting processes. The excess of snow in the accumulation area is transformed into ice, which then moves downhill between several or tens of meters per year. As long as accumulation and ablation are more or less the same, the glacier is in equilibrium, which means the total mass stays roughly the same. Mass changes are influenced by climate and topography. An increase in mass is due to factors such as an increase of snowfall, the distribution of snow due to wind, avalanches and due to a lack of melting. A decrease is caused by increased melting, evaporation, erosion due to wind, avalanches as well as a lack of snowfall. Because of the influence of wind and avalanches glaciers tend to be in basins or depressions (APCC, 2014, pp. 422–423).

Glaciers are strongly influenced by precipitation, wind, radiation from the sun and temperature and consequently react strongly to any changes of those parameters. Because of this characteristic, glaciers can be seen as excellent indicators of climate change (APCC, 2014, p. 423).

The term glacier discharge indicates the amount of meltwater, which originates from the glacier ice and discharges into the Obersulzbach (Lieb and Slupetzky, 2013, p. 32).

### 1.1.2 Climate Change and its Impact on Glaciers and Glacier Discharge in Alpine Catchments

Since 1850 temperatures have risen on a global level and this increase has generally sped up in the last few decades. In the last century temperatures have increased considerably and for the first time such an increase has been caused by humans. Furthermore, it is expected that this trend will continue and that temperatures will increase even further (APCC, 2014, p. 73).

In Austria temperatures have risen by almost 2°C since 1880, compared to a global rise of only 0.85°C. This comparatively rapid increase has happened in particular since 1980. Since then global temperatures have only risen by about 0.5°C, whereas in Austria temperatures have increased by about 1°C (APCC, 2014, p. 81).

Climate change not only shows itself with an increase in mean temperature, but also with changes of several other parameters, such as distribution of precipitation, a shift of climatic zones or an increase in arid areas. These changes are also reflected in the cryosphere, not only in the Alps and similar mountain ranges but also at the poles in both land and sea ice (APCC, 2014, p. 72).

Unlike temperature, precipitation trends have a much stronger regional difference. In western Austria precipitation has increased by about 10-15%, whereas in the southeast of Austria it has decreased by roughly the same magnitude. In the alpine regions there has been a shift from snow to rainfall (APCC, 2014, p. 82). Since 1970 there has been a continuous increase in precipitation in the region of the inner Alps in Austria (Schöner et al., 2011).

These meteorological changes have an impact on glaciers and consequently on glacier runoff. The snow-fall line has risen since 1980. This rise is more prominent in summer than in winter, parallel with the more prominent temperature increase. The duration of snow cover has lessened in the last decades, especially in medium altitudes around 1000m (APCC, 2014, p. 91).

All measured glaciers in Austria have significantly lost area and volume since 1980. These glaciers react especially sensitively to summer temperatures. It is estimated that half of the ice area and volume will be lost by 2030, compared to the mean of the period 1985 to 2004. Even if temperatures were to stay the same from now on, glaciers would still continue to reduce until they reach equilibrium. In the best case scenario these glaciers will stabilise at about 20% of the current ice volume by the end of the century (APCC, 2014, pp. 91, 413, 416).

Glaciers are relevant for the Austrian water management because they store water, of which some parts are released each summer, especially during dry periods, when no precipitation is available. However, during wet conditions melt processes tend to decrease, even during the summer months. Snow stores water over a winter but ice can store water for a very long time. The various storage patterns provide a compensation effect for runoff, meaning that glaciated catchments provide water at times when runoff is low in non-glaciated catchments (Jansson et al., 2003; Singh and Singh, 2001, p. 546).

Runoff in a glaciated catchment has a positive correlation with temperature, but during the winter months has a negative correlation with precipitation. The opposite occurs in a non-glaciated catchment, which leads to a particularly strong discharge compensation effect in partially glaciated catchments. However, once glaciation in a catchment decreases, the runoff variability increases and will gradually change towards the pattern of a non-glaciated catchment (Hock et al., 2005; Singh and Singh, 2001, p. 546).

Glacier storage is altered when the glacier balance changes, which in turn means that the glacier runoff is modified. Total runoff is reduced when the glacier mass increases, which is when the water is stored in the glacier. When the glacier mass decreases the stored water is released and total runoff increases. This means that when glaciers retreat, more glacier melt runoff is expected. Thus the initial effect of climate change on runoff is an increase in glacier melt rates, resulting in an increase in runoff. There are various feedback mechanisms, which further augment the melt rate, such as a lower albedo of ice compared to snow and a modification of meltwater routing through glacier ice. The runoff pattern is presumed to change again after the initial increase in runoff. Long term changes to the glacier melt rate are expected to decrease runoff, once the glacier volume has decreased sufficiently (Hock et al., 2005).

Glacier discharge could already have reached its maximum at many glaciers. Even though it only accounts for a small percentage of the entire Austrian water balance, a decrease of glacier discharge is of great importance due to the timing of its occurrence and its impact on a regional scale (APCC, 2014, p. 413).

Alpine glaciers have various runoff patterns with a varying temporal scale. The majority of runoff occurs in summer during the ablation period, whereas in winter most of the precipitation is stored as snow. Additionally, there is a daily fluctuation pattern in runoff, caused by the difference in temperature and radiation during night and day (Hock et al., 2005).

The daily discharge pattern is especially visible during clear and sunny days. The minimum occurs in the morning and the maximum occurs in the afternoon. This pattern is mainly based on the variation of radiation at the glacier surface. The time lag between the maximum of radiation and the maximum discharge is due to the time the water takes until it reaches the gauge (Lieb and Slupetzky, 2013, pp. 83–84).

Kuhn and Batlogg (1999 as quoted in APCC, 2014, p. 426) have shown that nival runoff regimes will change their pattern when the temperature increases. The summer peak will occur earlier during the year and will be less pronounced and autumn and winter will have higher discharge values, as more precipitation will fall as rain instead of snow.

Discharge from the average non-glaciated catchment as well as any non-glaciated part within a glaciated catchment is generally going to decrease due to an increase in evaporation, which is caused by the increase in temperature. So far it is unclear how much a change in precipitation will compensate or aggravate this increase of evaporation due to the high uncertainty of precipitation projections. In the Alps it is very likely that warmer temperatures during winter will lead to an earlier onset of snowmelt and in summer a decreasing tendency of discharge is expected (APCC, 2014, p. 91).

## 1.2 Objective

As a result of the provided facts, it can be concluded that climate change has decreased the glacial extension in the Austrian Alps and thus has an impact on the discharge of glacier fed streams. The basic assumption of this thesis is that this impact on glacier discharge can be quantified by analysing long-term and diurnal discharge patterns.

Hence the overall objective of this master thesis is to identify the long-term alterations in discharge characteristics of Obersulzbach.

In order to achieve this objective two hypotheses have been specified:

- Long-term alterations in discharge characteristics of Obersulzbach are induced by changes of the catchment glaciation extent and connected to climate change.
- These alterations can be observed both in long term discharge data as well as in diurnal variations.

## 1.3 Overview

In order to clarify the determining factors of this thesis the introduction provides background information on climate change and its influence on glaciers. This is further specified in the chapter “2 Introduction to the Study Area”, where the specific circumstances of the glaciers and glacier discharge within the Obersulzbach valley are described.

The chapter “3 Methodology” outlines the software and statistical methods, such as multiple regression and partial correlation, which are used for the analysis of the discharge data. This is followed by the results of the analysis, which indicate changes in glacial discharge. Further an assessment and discussion of these results are provided and possible reasons for the changes in the discharge pattern are indicated integrating considerations based on literature studies.

The chapter “6 Conclusion” sums up the results and discussion and stresses the importance of further investigation and data collection within this study area.

# 2 Introduction of the Study Area

## 2.1 Topography and Physiography

The Obersulzbach valley is approximately 16km long and it extends from south-southeast to north-northwest. The altitude ranges from 850m to 3667m (Lieb and Slupetzky, 2013). The following table shows which altitudinal ranges are dominant within the catchment.

**Table 1: Percentage of area per altitudinal range in the Obersulzbach valley (Koboltschnig, 2007)**

| Altitudinal range [m.a.s.l.] | Area [$km^2$] | Percentage of area [%] |
|---|---|---|
| 700-1000 | 0.9 | 1.1 |
| 1000-1500 | 5.6 | 7.1 |
| 1500-2000 | 15.4 | 19.3 |
| 2000-2500 | 26.7 | 33.4 |
| 2500-3000 | 26.8 | 33.6 |
| 3000-3700 | 4.4 | 5.5 |
| **Σ** | **79.8** | **100** |

The following map shows the valley location as well as its topography. It is clearly visible that the upper part of the valley (in the south) is a mountainous and glaciated area. While the base map is a satellite image the red line, denoting the catchment border, is inserted manually.

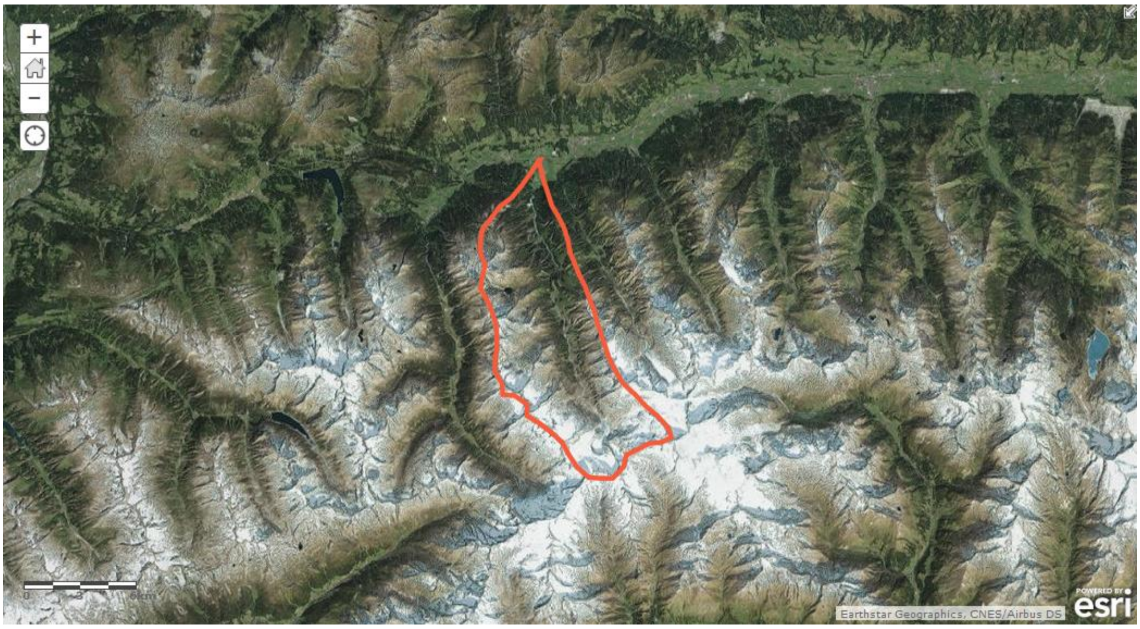


**Figure 1: Overview of Obersulzbach valley catchment (Esri, n.d.)**

The following map shows the valley head of the Obersulzbach valley, where the newly formed glacier lake and the majority of the glaciers are located. The glaciers as such are only vaguely discernible, as they are covered by snow.

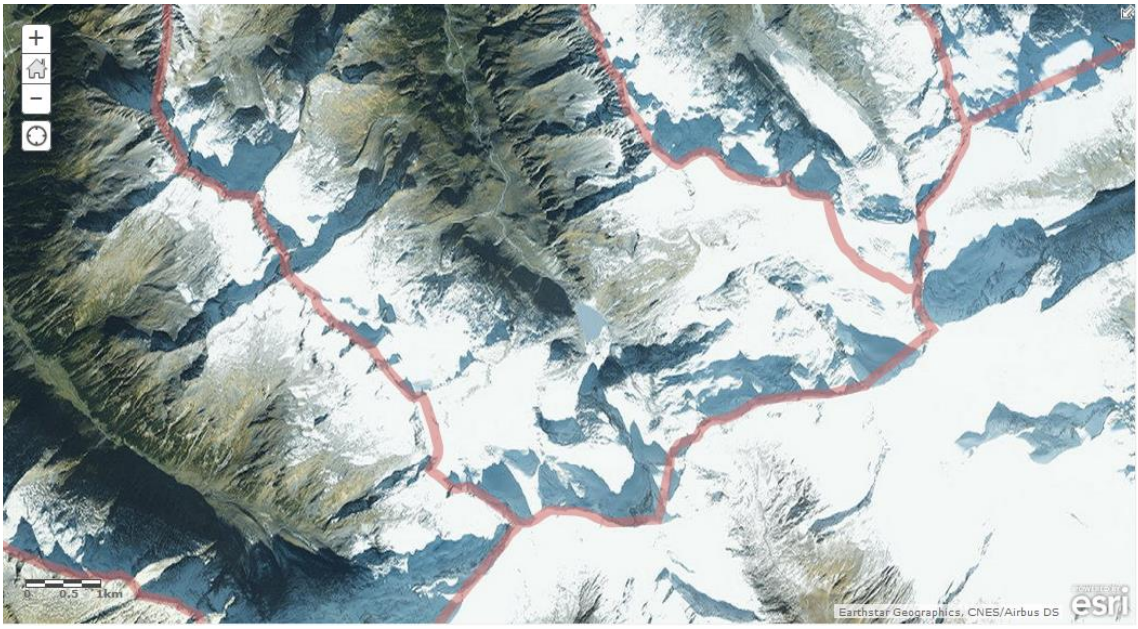


**Figure 2: Valley head of Obersulzbach valley (Esri, n.d. catchment borders provided by SaGIS)**

The geology of the Obersulzbach valley is part of a particularity of the region, comprising the Ankogel-, Granatspitz- and Venedigerkern. This so called Tauernfenster is characterised by old gneiss formations, which were transformed during the alpine orogeny. During this period old material from the Mesozoic became exposed. Consequently different geology than in the rest of the Alps dominate the structure of this region. Due to the different resistance to erosion, which the various types of gneiss display, the valley has distinct landscape characteristics within the catchment, such as a steep step in the terrain towards the lower half of the valley (Lieb and Slupetzky, 2013, pp. 19–21).

The soil types in the valley vary, depending on the location. In the upper part of the valley there is virtually no soil and it consists mostly of rock outcrop and glaciers. Further downhill Dystric-Lithosol is the dominant soil type and even further downhill, mostly Podzols can be found. At the bottom of the valley Dystric-Cambisols are the prevailing soil type (BMLFUW, 2003).

The land use of the Obersulzbach valley has never been intensive. It has been used as pasture land roughly since the Middle Ages but due to the barren landscape never extensively. In 1984 the National Park Hohe Tauern was established with the upper half of Obersulzbach valley being a part of it. This means that while many other valleys are used for producing hydropower the Obersulzbach has very little direct anthropogenic influence (Lieb and Slupetzky, 2013, pp. 40–44).

## 2.2 Climate

Koboltschnig (2007) describes the climate of the upper Pinzgau based on long-term observations at the meteorological station in Zell am See, which is situated at 766m altitude. This altitude only applies to the lower parts of the Obersulzbach valley. Nonetheless a good overview of the general region is still given. The climate is typical for the Alps. It has a high amplitude between daytime and nighttime temperatures, a lot of sun in winter and in the summer it is often cloudy. The mean air temperature (based on the period of 1961 to 1990) is 6.9°C and there are roughly 130 frost days (temperature minimum is under 0°C), 41 ice days (temperature maximum is under 0°C) and 32 summer days (temperature maximum is over 25°C). The general character of this climate is applicable for the entire upper Pinzgau, however, with increasing altitude the frost and ice days also increase (Auer et al., 2001 as quoted in Koboltschnig, 2007).

In comparison to Zell am See the mean air temperature of Pass Thurn (1200 m.a.s.l.) between the years 1962 and 1990 (data for 1961 is not available) is 6.54°C.

The mean annual areal actual evapotranspiration can be estimated by using the water balance data. In the Obersulzbach valley it is between 100 and 200mm per year, on the basis of the 30-year period of 1961 to 1990 (BMLFUW, 2003).

## 2.3 Gauging Stations

The discharge, precipitation and temperature data as well as the corresponding metadata are provided by the Hydrographic Service of Salzburg. The temporal resolution as well as the length of the data series depended on the gauging station, which means that not all data is directly comparable with each other.

In the Obersulzbach valley there are three different discharge gauging stations available:

- Sulzau
- Kees
- Türkische Zeltstadt

The following map shows the rough location of all three gauging stations. The gauging station Türkische Zeltstadt is presumably not yet displayed in the basemap from eHyd because it is still fairly new. The red arrow however indicates its estimated location. The other two gauging stations are designated with a blue triangle, as well as with a red arrow.

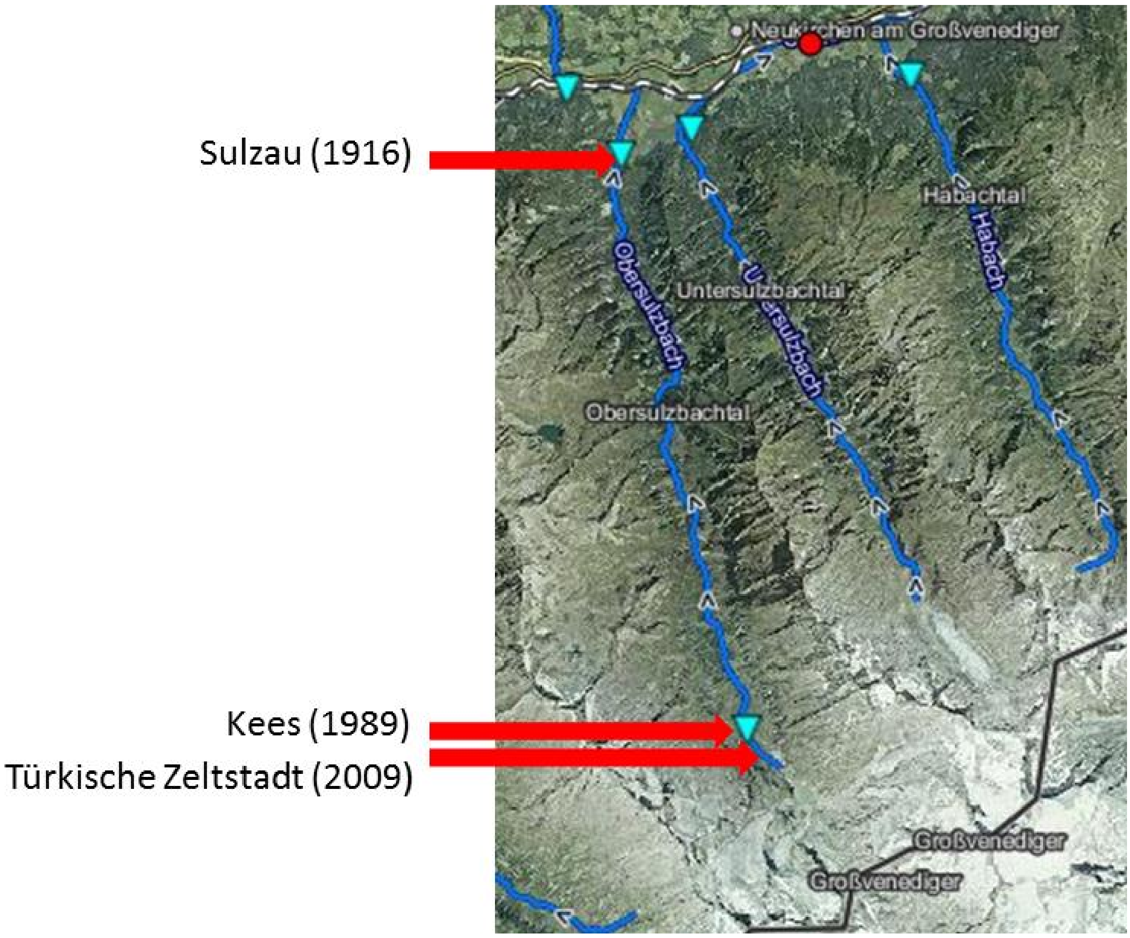


**Figure 3: Location of discharge gauging stations in the Obersulzbach valley catchment (BMLFUW, 2014)**

The gauging station Sulzau is situated at the lower end of the Obersulzbach, shortly before it flows into the river Salzach. The height above sea level of this gauging station is 882.2m and the total area of the catchment is 80.7km$^2$. At the time of writing the book Lieb and Slupetzky (2013, p. 88) stated that 18% of the catchment area was covered by a glacier. Of the three available gauging stations Sulzau is situated furthest from the glaciers, at a distance of roughly 14km. It is therefore expected that some of the hydrological signals from the glacier melt will be diluted with the impact of the non-glaciated catchment. The station was constructed in 1961 and is consequently the oldest of all available stations. Sulzau provides daily mean discharge data between 1961 and 2013, however, a temporal resolution of 15-minutes is only available between 1977 and 2013. Consequently some methods can only be applied for the shorter period.

The gauging station Kees was originally constructed at a distance of only 500m from the mouth of the glacier. It is situated at 2040m above sea level and the catchment has an area of 19.2km$^2$. Lieb and Slupetzky (2013, p. 88) estimate that 53% of the catchment area is covered by a glacier. Kees provides 15-minute data between 1989 and 2013. The gauging station is located much closer to the glaciers than Sulzau. However, after 2003 it was noticed that some high flows passed next to the gauge without being measured. Therefore the data is not considered as reliable as Sulzau (Lieb and Slupetzky, 2013, pp. 88–89).

The gauging station Türkische Zeltstadt was constructed when it was noticed that some of the discharge was not registered at Kees. The name refers to a former glacier formation which was situated where the gauging station now stands. Türkische Zeltstadt is located at an altitude of 2200m. The area of the catchment is 17.8km$^2$ and roughly 75% of the area is covered by a glacier. The gauging station is positioned directly after the newly formed glacier lake. 15-minute data is available between July 2010 and September 2013. This is unfortunately not sufficient data to investigate long term changes. This gauging station is situated closest to the glacier and will likely provide valuable data for future research (Landespressebüro Salzburg, 2010; Lieb and Slupetzky, 2013, pp. 90–91).

Temperature and precipitation are both provided from the meteorological station of Pass Thurn, which is situated at 1200m above sea level. This station is selected because it has the longest available data series. Daily precipitation data is available between 1895 and 2013 and daily temperature data is available between 1961 and 2013.

Choosing Pass Thurn for meteorological data is somewhat controversial due to its location. However, no other data is available for the necessary time period. According to the hydrological atlas of Austria the difference between the precipitation at Pass Thurn and Obersulzbach valley is significant. The atlas provides two different methods of assessing precipitation. The mean annual precipitation over the period 1961 to 1990 is modelled with uncorrected data. The results indicate 1000-1250mm of precipitation for Pass Thurn and a wide range from 1000 to 2500mm of precipitation for the Obersulzbach valley. According to this data the precipitation increases with elevation, which explains the wide range. The mean annual precipitation is also calculated using water balance data. The results are quite similar with 1000-1250mm of precipitation per year at Pass Thurn and 2000-2500mm of precipitation in the Obersulzbach valley (BMLFUW, 2003).

The following map demonstrates the distance and location of the meteorological station Pass Thurn and the entire catchment of Obersulzbach. Again, the catchment borders as well as the location of Pass Thurn are drawn manually.

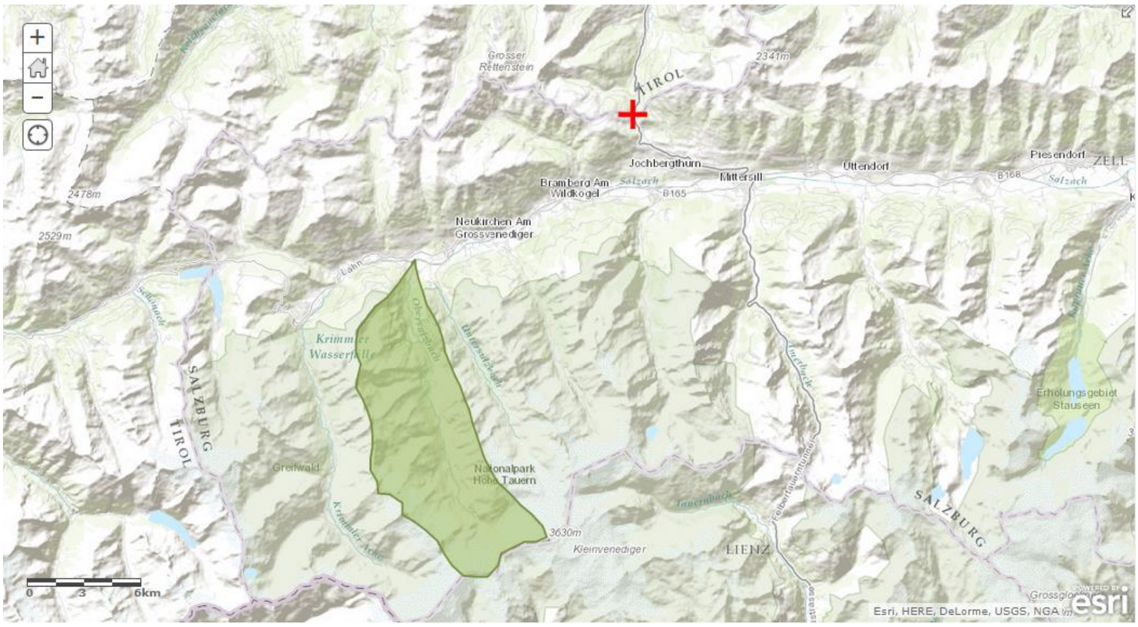


**Figure 4: Location of Pass Thurn and Obersulzbach valley, the red cross indicates the meteorological station of Pass Thurn and the green area designates the Obersulzbach valley (Esri, n.d.)**

## 2.4 Hydrological Characteristics

### 2.4.1 Glacier Lake

One of the hydrological formations within the Obersulzbach valley is the relatively new glacier lake, which is at roughly 2200m altitude. Lieb and Slupetzky (2013, pp. 103–106) state that the formation of the lake started in 1989, due to the retreat of the glacier. The Austrian Alpine Society's glacier measurement reports, however, didn't mention the formation of a lake until the hydrological year 2002/2003 (ÖAV, n.d.).

The size of the lake is influenced by both the on-going retreat of the glacier which provides meltwater and the input of sediments and subsequently leads to siltation. In 2009 the lake had an area of 10.5ha, a maximum depth of 42.4m and a volume of 2,31million $m^3$. The lake still increased in size until 2013, which was when the source was published (Lieb and Slupetzky, 2013, pp. 103–106).

### 2.4.2 Glaciers in the Catchment

Alpine glaciers in the Hohe Tauern had their most recent maximum extent between 1850 and 1855. Since then most glaciers have receded significantly. The same applies to the glaciers in the catchment of the Obersulzbach (Lieb and Slupetzky, 2013, p. 55). The following figure demonstrates how much the glacier Obersulzbachkees receded between 1910 and 2008. The alpine hut “Kürsingerhütte” in the foreground serves as a reference point.


**Figure 5: Comparison of glacier extent of the Obersulzbachkees in 1910 and in 2008 (GöF, 2014)**

The development of the glacier recession can also be demonstrated with the help of satellite images. The glacier extent can often be visualised even better by shortwave infrared. The images were taken in 1990, 2000, 2005 and 2010 and clearly show the recession of the glaciers within the catchment. The image taken in 2000 is less clear, because a snow layer covers the glaciers and some of the immediate surroundings of the glaciers, therefore making it impossible to see the glacier border. Nonetheless overall the recession of the glaciers and even the formation of the glacier lake can be clearly seen.

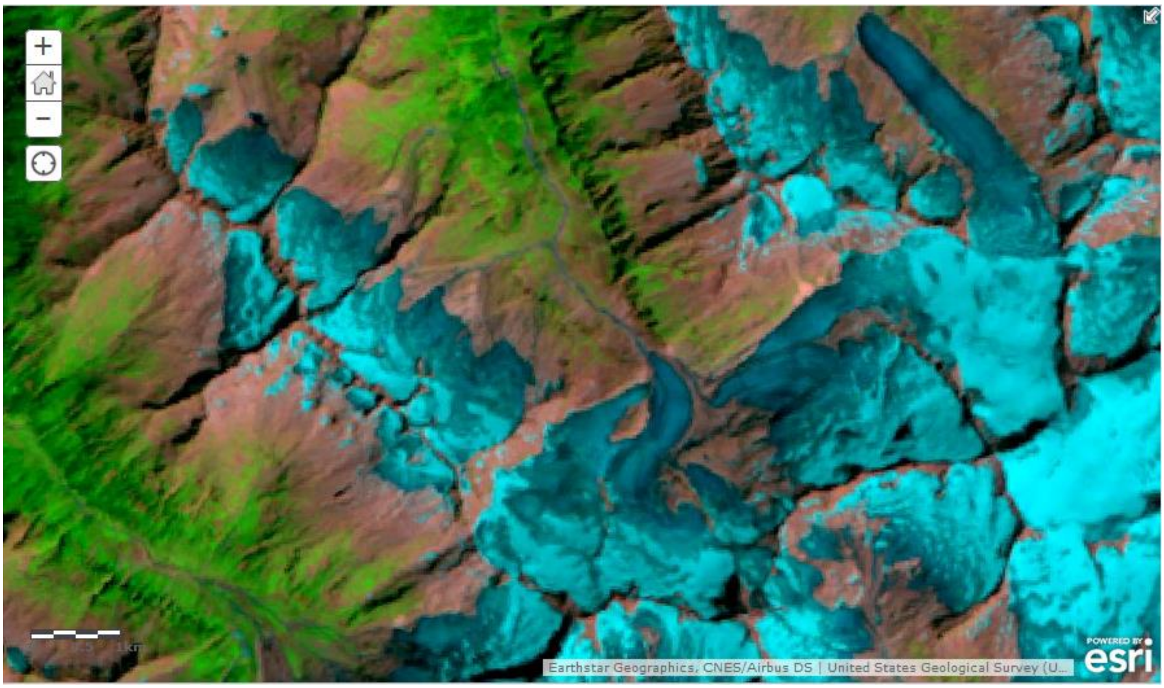


**Figure 6: Shortwave infrared satellite image of the upper Obersulzbach valley in 1990 (Esri and Global Land Survey, 1990)**

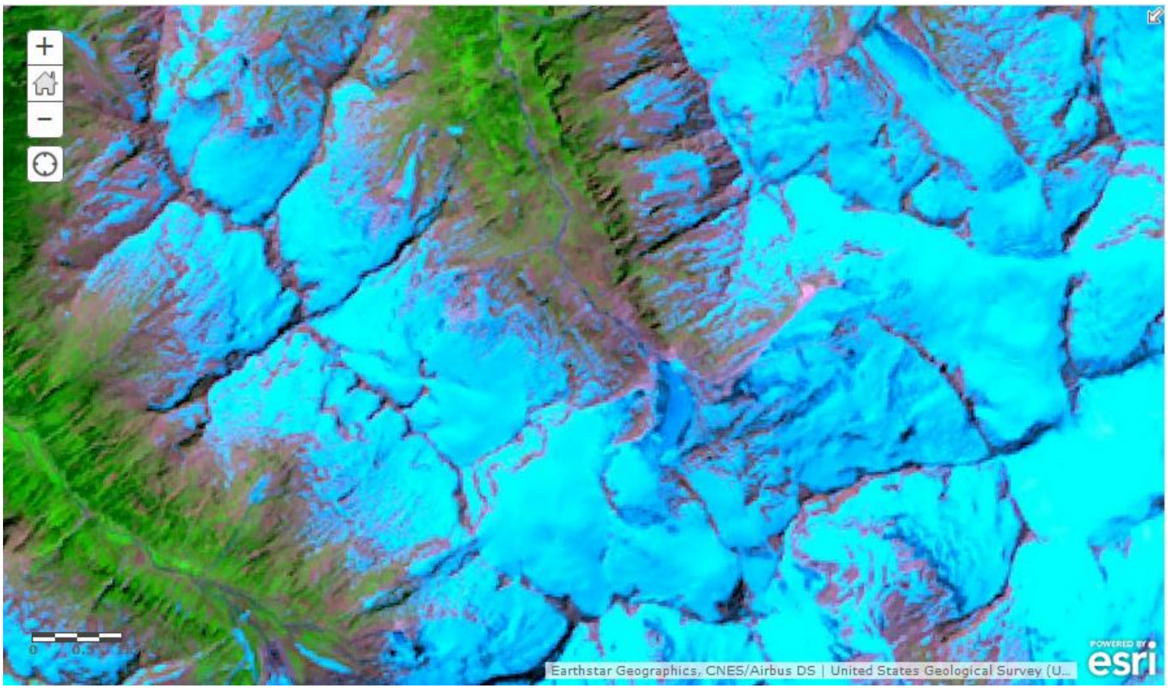


**Figure 7: Shortwave infrared satellite image of the upper Obersulzbach valley in 2000 (Esri and Global Land Survey, 2000)**

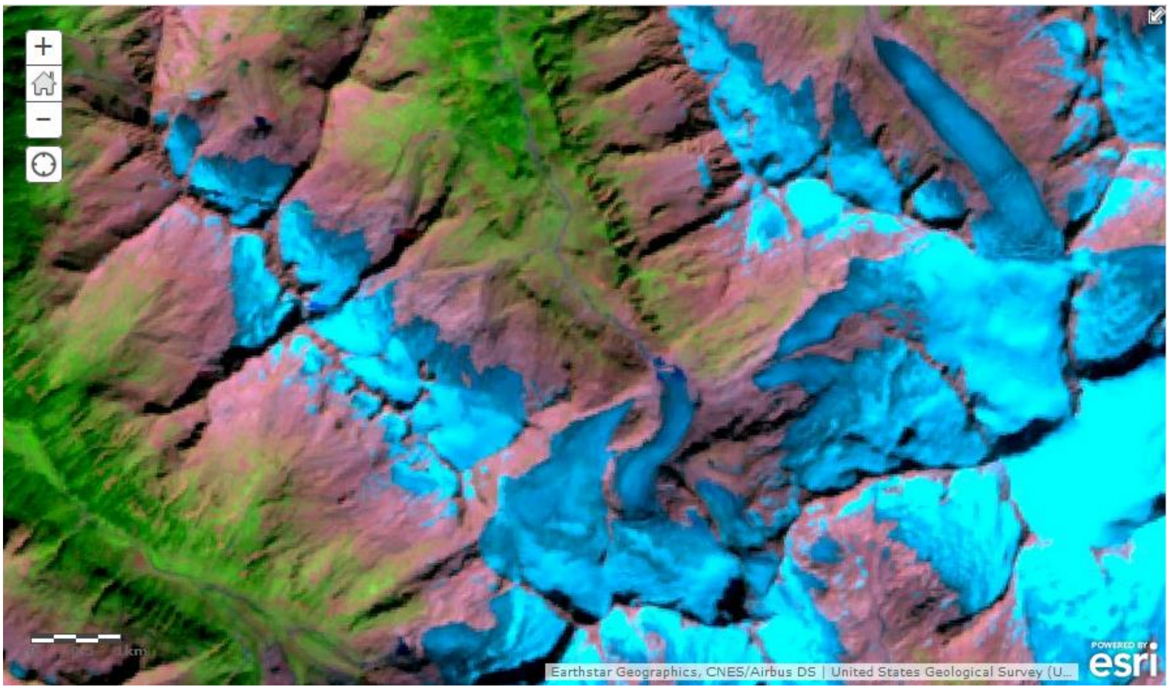


**Figure 8: Shortwave infrared satellite image of the upper Obersulzbach valley in 2005 (Esri and Global Land Survey, 2005)**

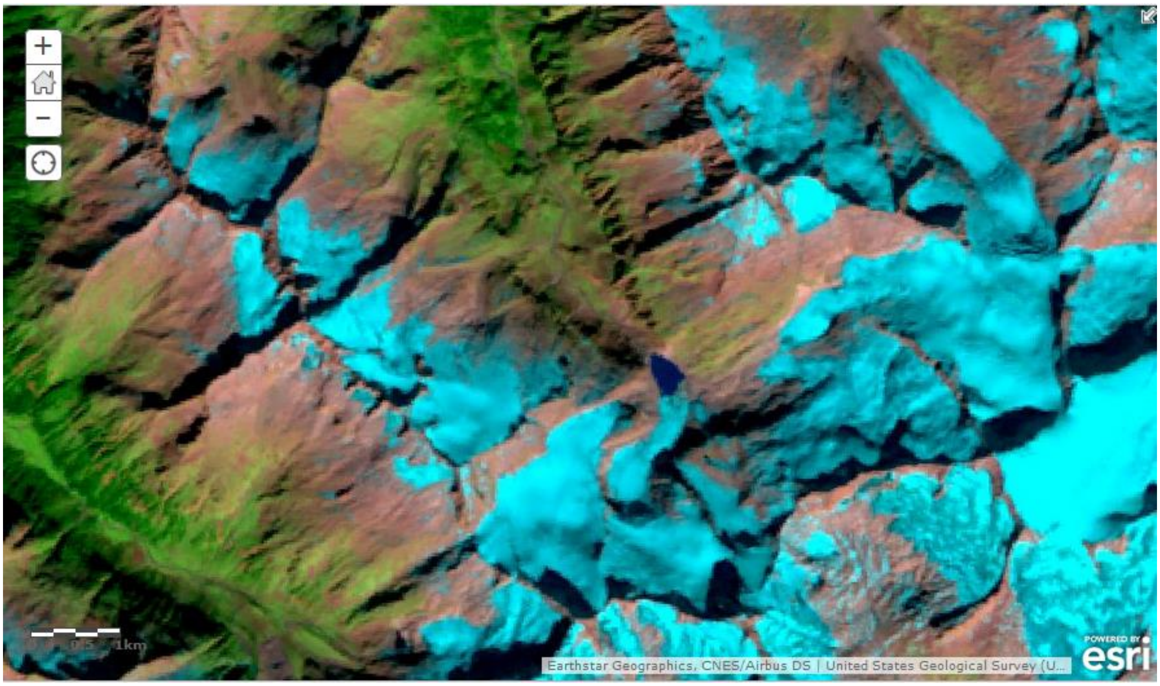


**Figure 9: Shortwave infrared satellite image of the upper Obersulzbach valley in 2010 (Esri and Global Land Survey, 2010)**

In 1850 the Obersulzbachkees had an area of 16km$^2$, by 1969 the area decreased to 11.6km$^2$ and by 2009 the area of all the glaciers which had originally formed the Obersulzbachkees only had an area of 9.75km$^2$ (Lieb and Slupetzky, 2013, pp. 29, 55). The following figure shows the interpolated decline of the glacier area.

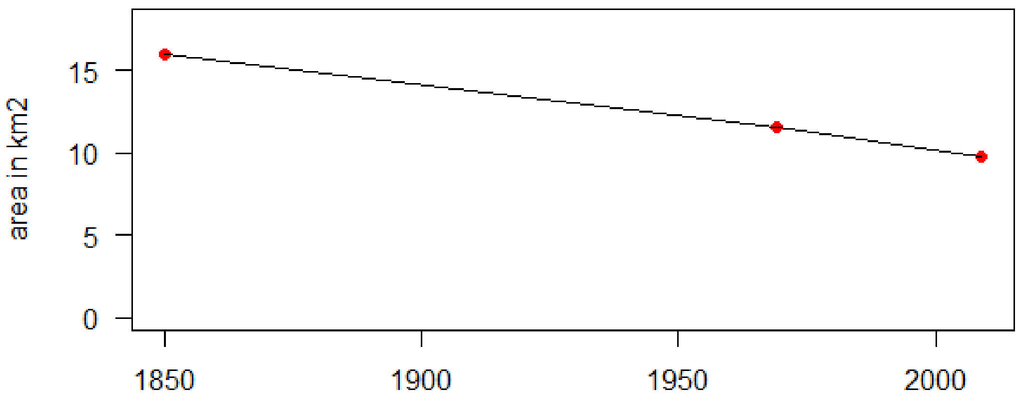


**Figure 10: Changes in glacier area of Obersulzbachkees (Lieb and Slupetzky, 2013, p. 29)**

In addition to assessments of the glacier area, the volume of the Obersulzbachkees has also been approximated. In 1850 Obersulzbachkees had an estimated volume between 1574 and 1674 million m$^3$. By 1969, this already decreased to 774 million m$^3$ and by 2001, it had 474 million m$^3$ of ice. It was then predicted that by 2013 the ice volume would be between 300 and 400 million m$^3$ (Lieb and Slupetzky, 2013, pp. 29–31). The following figure displays the decline of the glacier volume.

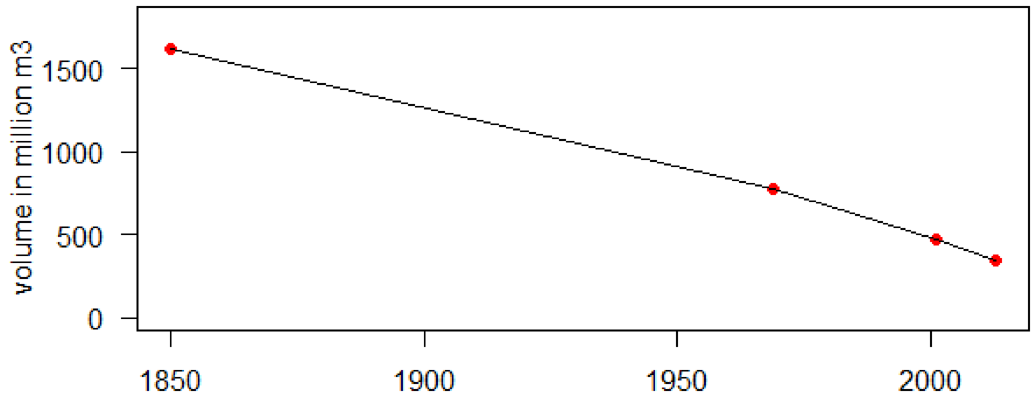


**Figure 11: Changes in glacier volume of Obersulzbachkees (Lieb and Slupetzky, 2013, pp. 29–31)**

It should be noted that the relative recession of volume and area varies considerably. In comparison with the glacial extent in 1850, the area decreased to 60.94% by 2009 of its original area, whereas the volume decreased to 24.33% of its original volume. The volume in 2009 is obtained by interpolating the volumetric data between 2001 and 2013, to better be able to compare volume and area. These changes indicate that the glacier must have thinned considerably since 1850 (Lieb and Slupetzky, 2013, pp. 29–31).

Additionally to the estimated dimensions of the area and volume, measurements of the extent of the glacial tongue of Obersulzbachkees have been taken by the Austrian Alpine Club for many years. These measurements were made more difficult when the Obersulzbachkees receded so much that in the first decade of the 21st century it split into several glaciers and additionally when a lake started to form at the bottom of the glacial tongue. The subsequent glaciers which have formed out of Obersulzbachkees are called: Krimmlertörlkees, Obersulzbachkees, upper and lower Bleidächerkees, Sulzbacherkees and Venedigerkees (Lieb and Slupetzky, 2013, p. 155).

The Austrian Alpine Club collects the measurement data and provides this data in an online archive. For the Obersulzbachkees yearly data can be found between the years 1963 and 2013. In the year 2001-2002 no measurements were possible, so the measurements of the next year (2002-2003) are divided by two and attributed to the two years in equal parts. In the year 2003-2004 no measurements were possible, however, the responsible author of the measurement report states that a recession is likely. Between 2002 and 2013 measurements were technically more difficult as the glacial lake had started to form at the tip of the glacial tongue. By 2010, the glacier receded to such an extent that since then it has not calved into the lake anymore. The area of dead ice, where the glacier ended between 2010 and 2013, made measurements complicated. The measurements provided only quantify the length of the glacial recession and therefore give no direct indication of the changes in the volume in glacier ice (ÖAV, n.d.).

According to the data provided by the Austrian Alpine Club the glacier receded 1353.8 m over the 50 year period between 1963 and 2013. The following figure demonstrates the cumulated sum of the yearly glacier recession in metres. The year without any data is calculated as zero (ÖAV, n.d.).

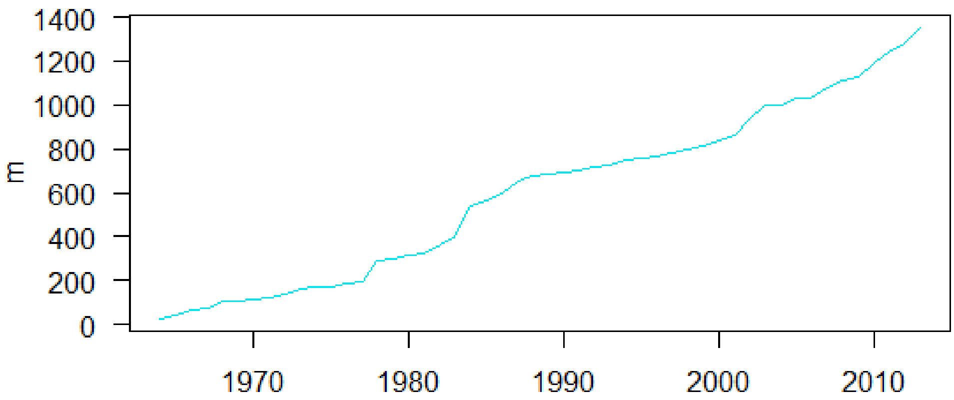


**Figure 12: Cumulative total of glacier retreat in metres of Obersulzbachkees (ÖAV, n.d.)**

In the year 1983-1984 the glacier had its maximum yearly recession of 148 m. The minimum was recorded in the year 2005-2006 with only 3 m. On average the glacier receded 27.63 m per year between 1963 and 2013. The following figure shows the distribution of the yearly glacial recession data between 1963 and 2013. It is evident from the figure that the maximum mentioned above is an outlier and is not a frequent occurrence (ÖAV, n.d.).

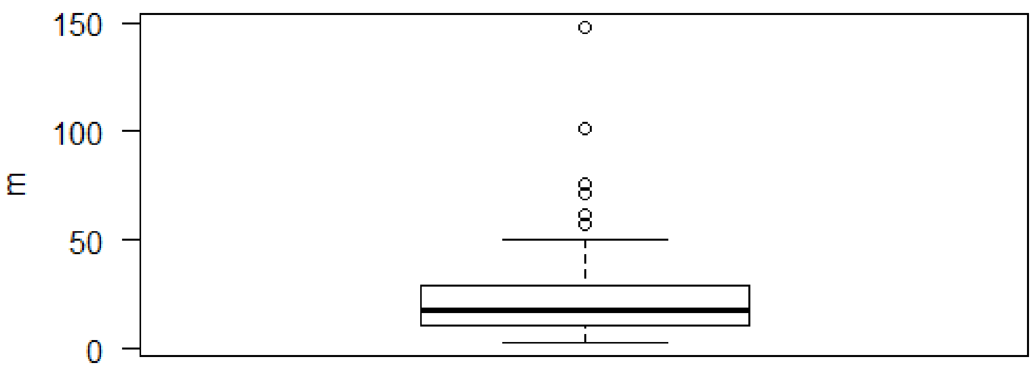


**Figure 13: Distribution of yearly glacial recession data in metres of Obersulzbachkees (ÖAV, n.d.)**

Apart from the glaciers which have developed from the former Obersulzbachkees, there are several additional glaciers in the catchment of the Obersulzbach. By looking at satellite images of the catchment it can be said that these glaciers are not as significant in terms of area as the resulting glaciers of Obersulzbachkees. These glaciers are called: Sonntagskees, Großes Jaidbachkees, Kleines Jaidbachkees, Weiglkarkees, western and eastern Kogelkees. There is no data available referring to the area of just these glaciers, but in 2007 all of the glaciers in Obersulzbach valley had an area of 13.6km$^2$ (freytag & berndt, n.d.; Lieb and Slupetzky, 2013, p. 28).

All of these changes to the extent and volume of the glacier are likely to have an impact on the melt behaviour of the glaciers and as a consequence also on the runoff patterns which are displayed by the Obersulzbach. These potential changes are the focus of the next chapters.

# 3 Methodology

Different methods have been considered in order to analyse potential changes in discharge of the Obersulzbach. The assumption on which these methods are based is that the glacier has changed both its volume and its areal extent and these changes can be noticed in the runoff of the entire catchment.

The overall methodology chosen for this thesis is a statistical analysis of the discharge and meteorological data provided. By means of this analysis past and present runoff regimes, such as diurnal patterns, will be investigated. The analysis focuses on the question whether or not any of these patterns have changed significantly over the available time period. The research also examines the interaction between hydrological and meteorological variables and how much they influence each other.

One of the main problems, when trying to identify changes to runoff is to differentiate between several additional influences which all have an impact on runoff. For example climate change has an effect on various factors apart from glacier melt (e.g. evapotranspiration, precipitation) which in turn have an influence on runoff. So while runoff changes might be caused by climate change they might not directly be related to the reduction of the glaciers in the catchment. The methods described in this chapter attempt to minimise these indirect effects.

The entire statistical analysis is conducted with the open source software R, which provides a very flexible statistical environment. One of the advantages of R are the many packages freely available online. Several of these packages are used for this analysis, including lfstat, which required the package R commander, scatterplot3d, TTR, rgl and ppcor (Adler and Murdoch, 2014; Fox, 2005; Koffler and Laaha, 2014; Ligges and Mächler, 2003; R Core Team, 2014; Seongho, 2012; Ulrich, 2013).

The data for this analysis is provided by three gauging stations available in the Obersulzbach valley. Better statistical significance is obtained when the gauging station Sulzau is used, due to the availability of a longer time series. As mentioned in the chapter "2 Introduction of the Study Area" Sulzau is the gauging station which is farthest away from the glacier and therefore is likely to have the weakest hydrological signal from the glacier. Kees is also used during the analysis. Unfortunately fewer years are available for the analysis.

Both gauging stations use a recording gauge to measure the water level. The water level is subsequently converted into discharge values by the hydrographic service. The discharge data is provided in the unit $m^3/s$.

## 3.1 Pre-processing of Data

It is commonly understood that discharge from a glaciated catchment has a distinct pattern over the year, with very little discharge in winter, when much of the precipitation is retained in the form of snow and significantly higher discharge in spring, summer and autumn, which is the melt season for snow and glacier ice.

A sample hydrograph is presented in the following figure. The year 1989 is arbitrarily chosen, the only condition for this choice is that it is a year where both gauging stations Sulzau and Kees provide data. The pattern does not significantly differ from other years.

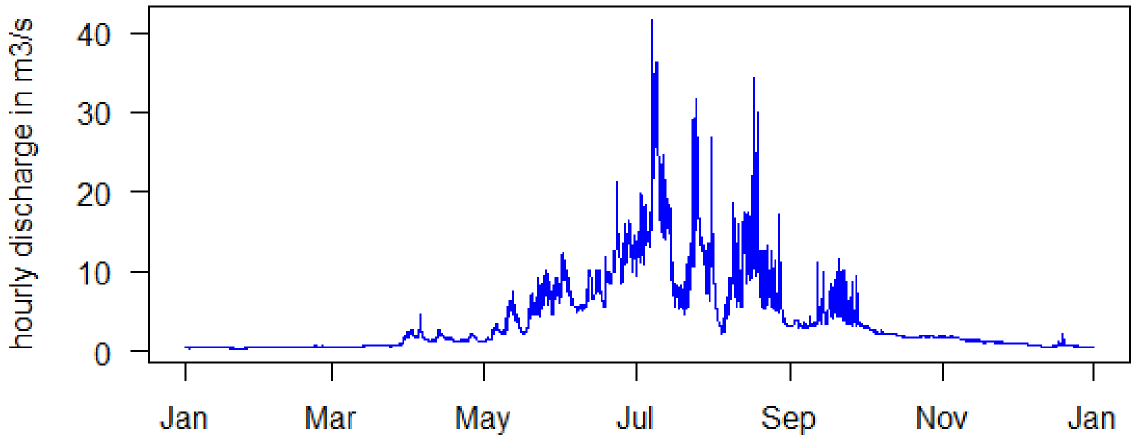


**Figure 14: Hydrograph of Obersulzbach in the year 1989 as measured at the gauging station Sulzau**

This hydrograph represents the entire discharge of the stream and not only the glacier melt. It is commonly understood that the vast majority of glacier melt occurs in summer. In order to exclude the majority of snowmelt from the further analysis only data from the months of late July, August and September are used. While in high alpine regions snowfall is still possible even in these months, it is far less likely to reach an amount which can significantly alter discharge data (Lambrecht and Mayer, 2009). July, August and September are also used in similar glacier runoff studies, for example by Moore and Demuth (2001). The following figure demonstrates the discharge pattern within these months. Other authors of glacier runoff studies, such as Moore et al. (2009) or Stahl and Moore (2006) frequently only used August for an analysis which is also attempted for this thesis.

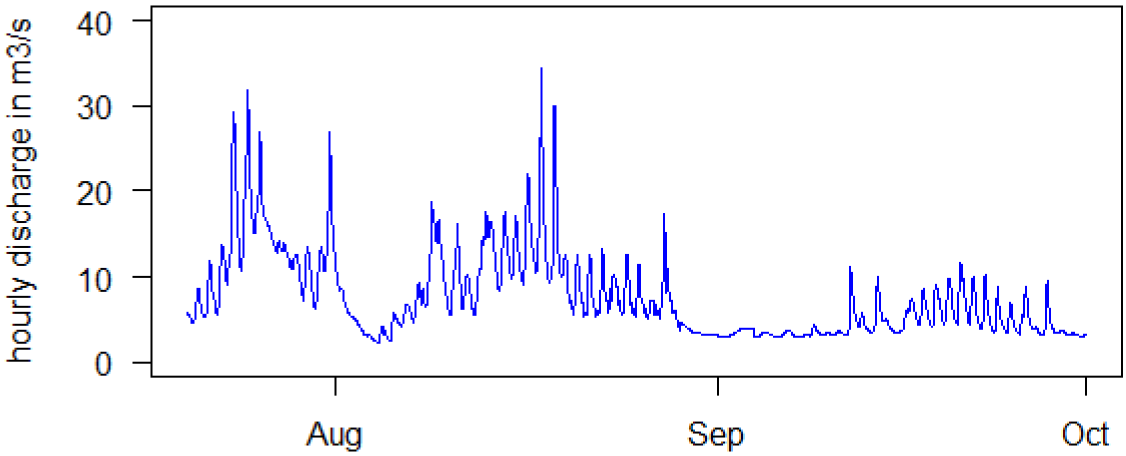


**Figure 15: Hydrograph of Obersulzbach between late July and end of September 1989 as measured at the gauging station Sulzau**

Not only snowmelt but also precipitation can obscure the glacier melt within the discharge values. Precipitation can occur throughout the year and is presumably responsible for some of the higher peaks within figure 15. In order to exclude the immediate impact of precipitation on runoff, dry periods are selected. The precipitation gauging station used for this analysis is Pass Thurn, as it is the only station which provides a sufficiently long time series. Pass Thurn is located on an opposite slope of the Salzach valley and not within the Obersulzbach valley (see figure 4, chapter "2 Introduction of the Study Area"). The impact of this location on the amount of precipitation is significant. Nevertheless it is assumed that when it rains in the general region, it rains both at Pass Thurn as well as in the Obersulzbachtal. Therefore precipitation data is still used but under the assumption that the total precipitation amount in Obersulzbach is likely to be higher (see chapter "2 Introduction of the Study Area").

After some experimentation, the precipitation threshold is set at a maximum of 10mm of total precipitation over the entire dry period, as this is deemed to be too little precipitation to significantly influence the total runoff of the catchment, while still providing sufficient dry periods for the statistical analysis.

Each period has to have a minimum of 8 days, however, more days are used if possible until the precipitation threshold is surpassed. The threshold of 8 days was set, as this is considered to be a sufficiently long dry period to fully exclude any immediate precipitation impact and also provides sufficient dry periods for the analysis. The selection request is formulated in such a way that a day in August or September is searched, which has at least 8 previous days of no rain, so consequently the beginning of this period could fall into the end of July. As the monthly separation is an arbitrary process anyway, these days are also included in the analysis.

Under these requirements 70 dry periods are chosen for Sulzau when applying the full season between late July and end of September, however, Kees only provides 50 dry periods for the same months, as the available discharge data only starts in 1989 and already ends in 2012. The first selected dry period is in August 1977 and the last period is in September 2013. When the search is further limited by only looking for dry periods between late July until end of August the number of available dry periods is greatly reduced to only 29 and 23 for Sulzau and Kees, respectively. This reduction of data means that often a statistical significance cannot be achieved.

Once the dry periods are calculated it is assessed through the means of visual inspection of the hydrographs, if the first day of each of these periods should be included into any further analysis. As a precaution the first day of each period is excluded to avoid any residual immediate impact of previous precipitation events on the discharge. Consequently the minimum duration of dry periods is 7 days.

The following figure demonstrates three of these dry periods and highlights the simultaneous discharge of Obersulzbach as measured at the gauging station Sulzau within the sample hydrograph of 1989. It is notable that all three periods differ from each other. Both the first and the last period show a clear diurnal discharge pattern, whereas the second period is less pronounced. This is potentially due to a temperature difference. During the second period temperatures at Pass Thurn are lower than during the first and third period.

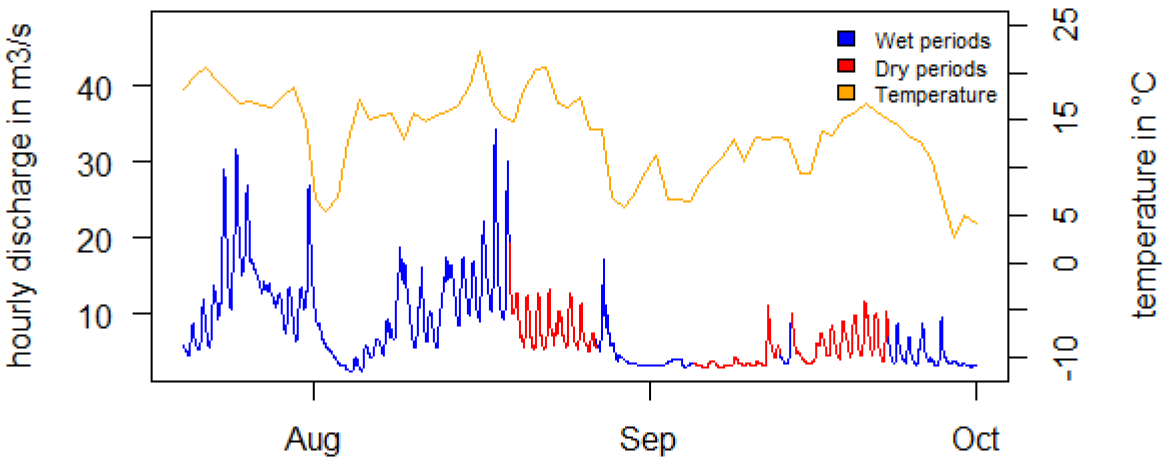


**Figure 16: Hydrograph of Obersulzbach visualising periods with little precipitation between late July and end of September 1989 as measured at the gauging station Sulzau and temperature as measured at the meteorological station Pass Thurn**

Within these dry periods both the direct influence of snow as well as precipitation are kept at a minimum and therefore glacier melt can be observed more distinctly. The lack of precipitation during these dry periods is demonstrated by the next figure. Again red bars indicate the dry periods. Given that the precipitation threshold is set at 10mm per dry period, precipitation does occur during these chosen periods. It is however considered insufficient precipitation to significantly alter runoff.

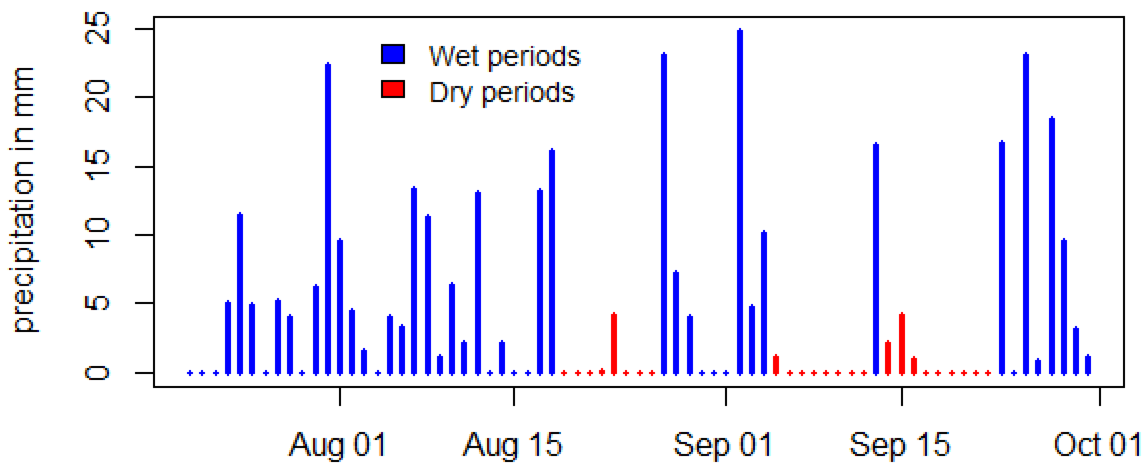


**Figure 17: Precipitation between late July and end of September 1989 as measured at the meteorological station Pass Thurn**

Baseflow however, which represents a more indirect influence of precipitation and snowmelt, is still included within the discharge data and might still influence any further analysis. In order to exclude baseflow, which might differ considerably between dry periods, the daily discharge variation is calculated.

Glacier runoff has a significantly different pattern than runoff from a non-glaciated catchment. These differences are shown in many ways, one of which is the distinct diurnal pattern of discharge. Glacier melt increases during the day, when the temperatures and radiation are higher. During the night these influences decrease and so does the amount of glacial discharge. A non-glaciated catchment does not have these influences on its runoff regime and therefore doesn't have a distinct diurnal runoff pattern. This pattern is more prominent the more parts of a catchment are covered by the glacier. How a glacier influences the runoff regime of a particular catchment can therefore be assessed based on the diurnal discharge pattern (Lieb and Slupetzky, 2013, pp. 83–84).

This pattern is considered through calculating the difference of the maximum and minimum discharge per day. This daily indicator will be referred to as diurnal discharge variation in this thesis. For this analysis data with a high temporal resolution is needed providing both the daily maximum and minimum discharge. Consequently hourly discharge data is used. Because of this requirement only the discharge data between 1977 and 2013 can be used at Sulzau, as the previous years only have a daily temporal resolution. As a result 37 years are available for this analysis. At Kees the years between 1989 and 2012 are used for this analysis.

The following figure demonstrates the diurnal discharge variation of both gauging stations Sulzau and Kees during the third dry period in the year 1989. Generally speaking, the maximum discharge is in the afternoon and the minimum discharge in the early morning. This pattern is mostly determined by radiation (Lieb and Slupetzky, 2013, p. 83). Even though this is a characteristic example there are additional variations within the discharge pattern. These may be due to other factors like temperature and season. The figure also displays the time lag of discharge between the two gauging stations.

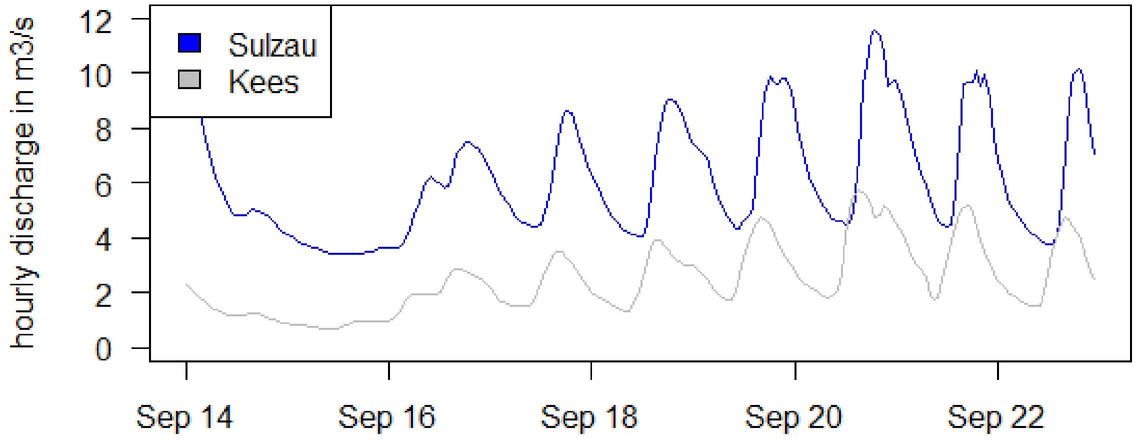


**Figure 18: Hydrograph of Obersulzbach during a dry period in September 1989 showing the daily discharge variation as measured at the gauging stations Sulzau and Kees**

To further visualise the available data all dry periods are averaged. Each dry period has as many discharge variation values as days, that is to say at least seven per dry period. These values are then averaged, yielding one mean daily discharge variation value per dry period. The following figures show the mean daily discharge variation as measured at the gauging station Sulzau and Kees for all 70 and 50 dry periods, respectively plotted over time.

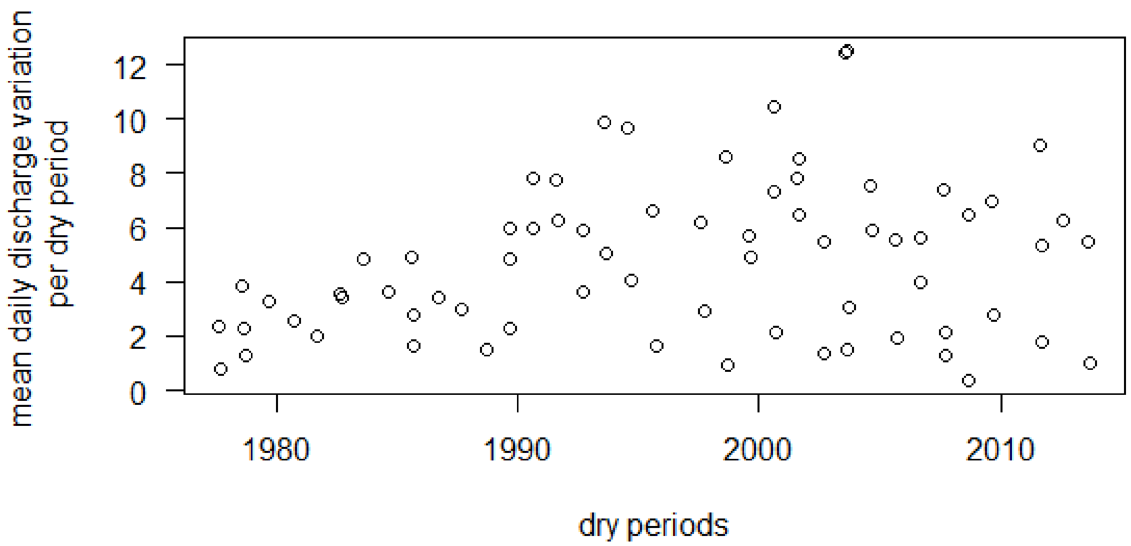


**Figure 19: Mean daily discharge variation per dry period as measured at the gauging station Sulzau plotted over time**

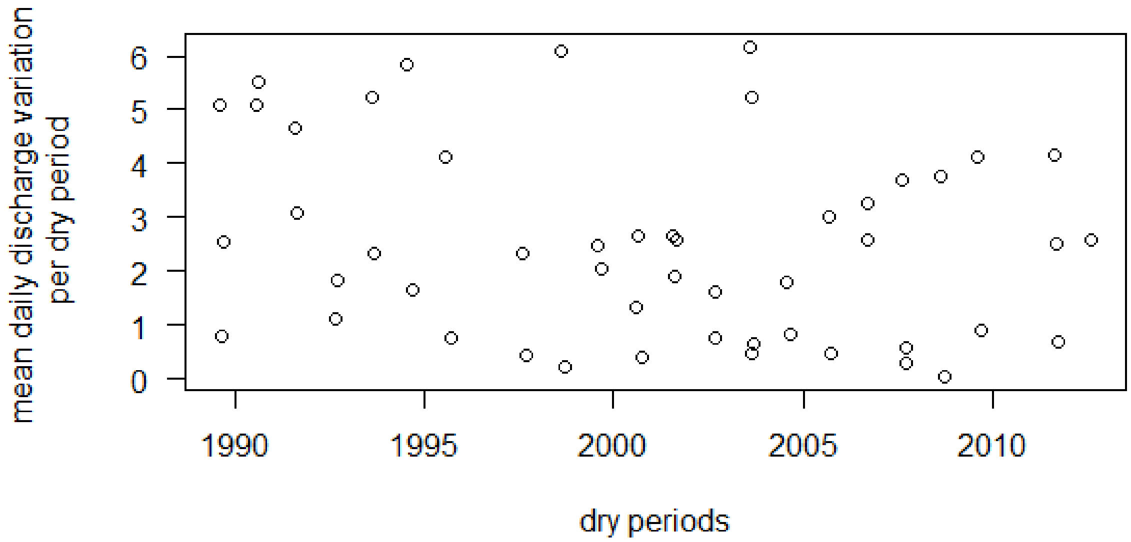


**Figure 20: Mean daily discharge variation per dry period as measured at the gauging station Kees plotted over time**

The plot showing the mean daily discharge variation at Sulzau only indicates a barely discernible trend over time, whereas the gauging station of Kees shows virtually no trend, due to the shorter time series and therefore, this data cannot be used for a proper analysis. One of the reasons for this may be that temperature which strongly influences glacier runoff is not accounted for.

The following plot demonstrates quite clearly that temperature has a noteworthy impact on the mean daily discharge variation and should therefore be taken into consideration in any further analysis.

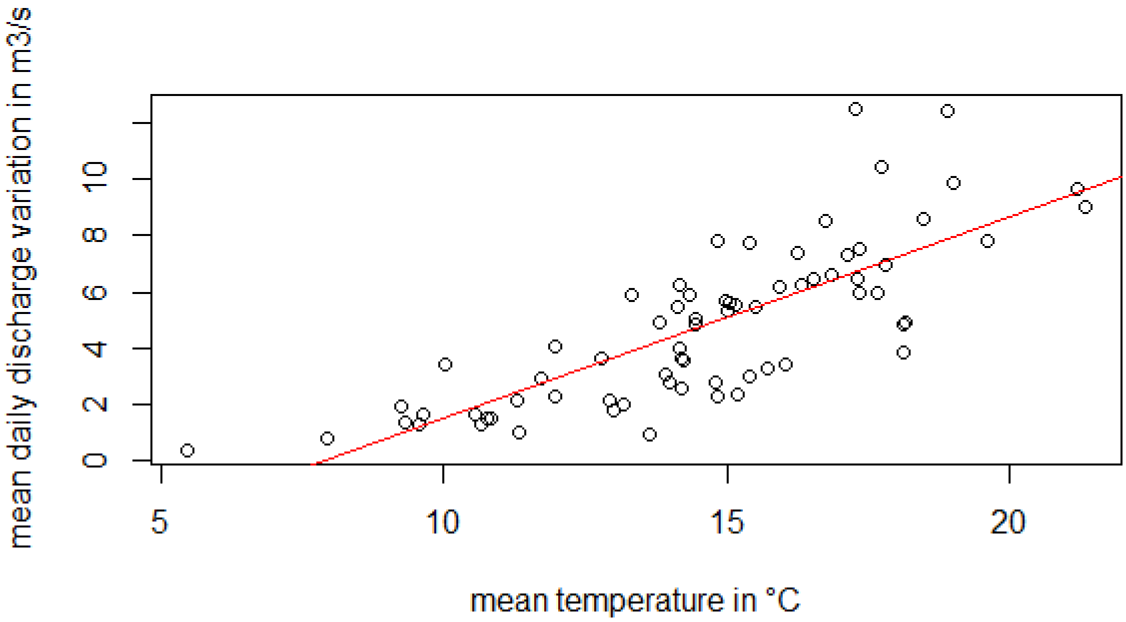


**Figure 21: Mean daily discharge variation per dry period as measured at the gauging station Sulzau plotted over mean temperature as measured at the meteorological station Pass Thurn**

There are several possible ways to deal with temperature in this context and two different alternatives are chosen for this thesis. Both multiple regression as well as partial correlation are applied and will be discussed in the next section.

For temperature data Pass Thurn is used. Just like with the precipitation data it needs to be taken into account that Pass Thurn is not actually situated within the Obersulzbach valley (see figure 4, chapter "2 Introduction of the Study Area"). The meteorological station is located at 1200m altitude, a height between Sulzau and Kees, situated at 882.2m and 2040m, respectively. This means the altitude of the meteorological station of Pass Thurn differs considerably from the altitude of the glaciers within the Obersulzbach valley. Because of this the temperature is only used as a relative value, mostly to indicate an increase or decrease, rather than using it to indicate possible melt temperatures.

## 3.2 Regression and Correlation

According to Rosin (2008, p. 130) simple linear regression explains the relationship between an independent variable (x) and a dependent variable (y). The term "simple" refers to the fact that only one independent/ explanatory variable is used. Frequently the following equation is used:

$$y_i = \beta_0 + \beta_1 * x_i + \varepsilon_i$$

$$x_i = independent\ variable$$
$$y_i = dependent\ variable$$
$$\beta_0, \beta_1 = regression\ coefficients$$
$$\varepsilon_i = residuals$$

For this thesis the daily discharge variation during dry periods represents the dependent variable y and the independent variable x is time.

The residuals ε of the equation represent the random errors between the model and the actual data. In the case of bivariate data, the residuals quantify the distance between the regression line and the observations, whereas in the multivariate case, residuals express the distance between the regression plane and the data. In both cases the basic assumption is that these residuals are normally distributed and independent (Rosin, 2008, p. 131).

For the data of this thesis the residuals of the regression plane are tested for normal distribution with the Shapiro-Wilk test. The Shapiro-Wilk test is considered one of the most reliable tests for normality (Schmidt, 2009, p. 7). The results of the mean daily discharge data from Sulzau show that this data is not normally distributed, as it only has a p-value of 0.029. A value of under 0.05 means that the null hypothesis stating that the data is normally distributed is rejected (Schmidt, 2009, p. 8).

Therefore the question remains, whether or not the data should be transformed, as it is sometimes done for non-normally distributed data, in order to meet the requirements for the regression analysis. It is concluded that in this particular case a transformation would not be appropriate for the following reasons:

- Statistical outliers can be responsible for the rejection of the null-hypothesis, even though the rest of the data is normally distributed or at least almost normally distributed. In order to visualize the actual data distribution a boxplot is created. The following figure is made to demonstrate the results. It reveals that the majority of the data is in fact normally distributed with the median (-0.119) only differing slightly from its ideal value 0. There are four statistical outliers, which may well have altered the results of the Shapiro-Wilk test (Schmidt, 2009, p. 4).

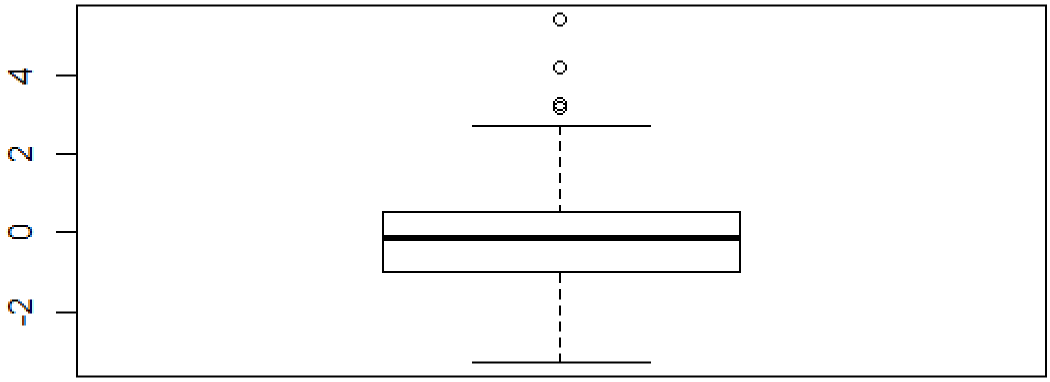


**Figure 22: Distribution of the mean daily discharge variation data as measured at the gauging station Sulzau**

  In order to verify this assumption the Shapiro-Wilk test is applied to the same data, however, without the four statistical outliers. This altered data set has a p-value of 0.596, which is considerably higher than 0.05 and therefore indicates a normally distributed data set.

- According to Schmidt (2009, p. 1) the tests of significance and not the coefficients are affected by a regression analysis with considerably non-normally distributed data. As mentioned above the residuals are only slightly different from a normal distribution. Nonetheless this aspect is looked at by comparing significance values of one set of non-normally distributed data and the same data after a transformation, in this case by taking the square root. The data is taken from a multiple regression analysis, where both time and temperature explain the daily discharge variation. The significance of the coefficient of regression over the years of the original data is 0.003 and the same value for the transformed data is 0.005. These p-values differ, nevertheless they are both within the same order of magnitude. The same applies for the $R^2$ of the multiple regression with the original data having a value of 0.668 and the transformed data providing the value 0.715. The p-value of the entire multiple regression (as opposed to just the slope coefficient as above) is exactly the same for both data sets with 2.2e-16. It is concluded that the significance tests do not differ considerably and therefore it is unlikely that a major error is made by not transforming the data.

- Schmidt (Schmidt, 2009, p. 9) also cautions against needlessly transforming data, as it is possible to alter the data sufficiently to change the coefficients of regression of the entire analysis, making them less reliable. It is even advised against looking at the actual value of a regression which is calculated with transformed data and only the general direction of the data can still be analysed.

Taking all of these points into account it is decided not to transform the data for this thesis.

A correlation only slightly differs from the regression. Correlation estimates the correlation coefficient, which determines the strength of the connection between two variables. The number one indicates an ideal linear correlation, whereas zero indicates that the data has no correlation at all. The algebraic sign indicates whether the correlation is negative or positive. The correlation coefficient is denoted as R (Fürst and Holzmann, 2012, pp. 3.3–3.8).

The p-value of the correlation and regression coefficient is stated in addition to the slope and correlation coefficient. It indicates, whether the null hypothesis (which states that the correlation or regression coefficient equals zero) is rejected or not. A very small p-value signifies that the coefficient is very unlikely to equal zero (Rosin, 2008, p. 135). A p-value of 0.05 or less is set as a threshold for statistical significance. This value is used as it seems to be the convention in similar studies (Moore and Demuth, 2001; Schöner et al., 2011; Stahl and Moore, 2006) and will therefore simplify a comparison between studies.

The coefficient of determination indicates how much of the data variability can be explained through the independent variable. It is often referred to as $R^2$. It can have a value between zero and one, one being the ideal coefficient of determination, as the independent variable can explain all of the variability of the model (Rosin, 2008, p. 135).

### 3.2.1 Multiple Regression

Rosin (2008, p. 139) writes that a multiple regression tries to explain one dependent variable (y) with the help of various independent variables ($x_1$, $x_2$, …). A possible way to express a multiple regression in an equation is as follows:

$$y_i = \beta_0 + \beta_1 * x_{1i} + \beta_2 * x_{2i} + \cdots + \varepsilon_i$$

$$y_i = dependent\ variable$$
$$x_{1i} = first\ independent\ variable$$

$$x_{2i} = second\ independent\ variable$$
$$\beta_0, \beta_1, \beta_2 = regression\ coefficients$$
$$\varepsilon_i = residuals$$

Such a multiple regression model is used for this thesis as it is considered insufficient to only use the date as an independent variable. In addition, temperature is included as a second independent variable into the calculations, in order to be able to better estimate and remove the effect of temperature on discharge and especially on any changes of daily discharge variation, which is still the dependent variable.

To better visualise the data the previously calculated dry periods are analysed in 3D plots. The mean daily discharge variation is the dependent variable being explained by the independent variables time and temperature. A regression plane is calculated for the plotted points, which shows two inclines, one for the mean daily discharge variation over time and one according to temperature. It is therefore possible to look at a plotted line, where the temperature remains constant, and to consequently get a trend for increase or decrease of the mean daily discharge variation over time, which is the objective of this analysis. The values for the plane inclination are also calculated by R.

The data analysed with the help of 3D plots is taken from both gauging stations Sulzau and Kees. Further separation is done by analysing data from late July until the end of September and also data from late July until the end of August.

### 3.2.2 Partial Correlation

Just like a multiple regression, a partial correlation is also made up of at least three variables. The analysis is based on the assumption that one of these variables (e.g. z) is disturbing the correlation between at least two other variables (e.g. x and y) or might even falsely indicate a relationship between two variables that does not exist. A partial correlation is able to establish the connection between x and y by taking into account the influence of z and deleting this influence by keeping the z variable constant (Fürst and Holzmann, 2012, pp. 3.19–3.20).

In the case of this thesis the disturbing variable is considered to be temperature. It is attempted to show the connection between time and daily discharge variation during the established dry periods by taking temperature into account and keeping it at a constant level. As before, time is considered to be the independent variable and daily discharge variation is the dependent variable.

The partial correlation is also done with the help of the software R. The specific method used is a spearman correlation, as this does not require a normally distributed data for the input (Fürst and Holzmann, 2012, p. 3.7).

The analysed data is used from the gauging stations Sulzau and Kees. The considered time frame is between late July and the end of September and between late July and the end of August.

# 4 Results

The following chapter presents the statistical results obtained with the software R after applying the methods explained in the previous chapter “3 Methodology” in the software R.

The resulting data sets covering dry periods are referred to with the following variable labels: “daily discharge variation” and “temperature”, both of which indicate the mean value per dry period and the variable “time”, indicating the first day of the respective dry period.

Each multiple regression generates a “regression plane”, which is also specified as a variable in R. The regression plane approximates the slope (rate of change) of daily discharge variation over the independent variables temperature and time, respectively.

Depending on the context, which is specified whenever results are provided, all variables can refer to different years (varying time frames between 1977 and 2013), different gauging stations (Sulzau or Kees) and to different months (late July until the end of August or late July until the end of September).

In the following chapter all values are rounded to three decimal places.

## 4.1 Temperature Context

As mentioned in the chapter “3 Methodology” both analyses, multiple regression as well as partial correlation, use temperature for the calculations. The mean temperature per dry period over the years 1977 until 2013 does not have any visible trend, as is demonstrated by the next figure. Furthermore, the p-value of this trend is 0.771, meaning that there is no statistical significance. Similar results are obtained when analysing different time frames, which correspond to time frames used for the multiple regression as well as partial correlation.

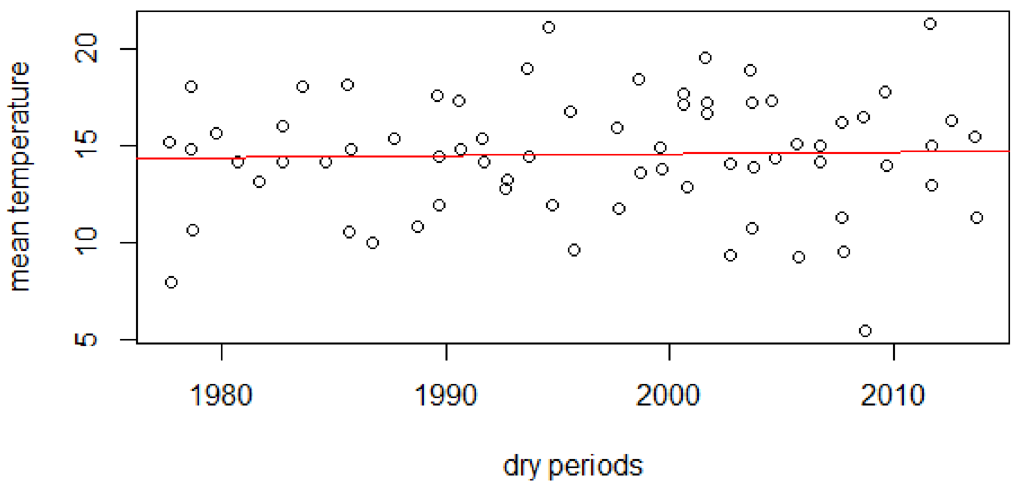


**Figure 23: Trend of the mean temperature per dry period as measured at the meteorological station Pass Thurn as measured at the meteorological station Pass Thurn between 1977 and 2013**

## 4.2 Regression and Correlation

As mentioned in the chapter “3 Methodology” two different types of analysis are employed in this thesis, multiple regression as well as partial correlation.

The significance levels encoded by R are as follows:

**Table 2: Codes for p-values as used per default by R and subsequently by this thesis**

| p-value | Code |
|---|---|
| 0-0.001 | *** |
| 0.001-0.01 | ** |
| 0.01-0.05 | * |
| 0.05-0.1 | . |
| 0.1-1 | |

Generally, p-values are considered statistically significant when they have a value smaller than 0.05.

### 4.2.1 Multiple Regression

#### *4.2.1.1 Results for Data from the Gauging Station Sulzau between late July and the end of September*

The 3D plot based on the multiple regression for Sulzau discharge between late July and the end of September, and between the years of 1977 and 2013, is the first to be shown in the ensuing plot, as it provides the highest number of dry periods and therefore the richest input data. Because of this high number of input data this particular plot is used to demonstrate the need for a separation of the discharge data into an earlier and a later sequence. This approach will not only be applied to the multiple regression, but also to the partial correlation as well as to the second gauging station Kees. In the following figure, but also in any further figures of the same type, red dots indicate data closer to the front of the plot. In this case the front of the plot (red dots) means lower temperatures, whereas the darker the dots get, the further the data is situated in the back of the plot, meaning higher temperatures.

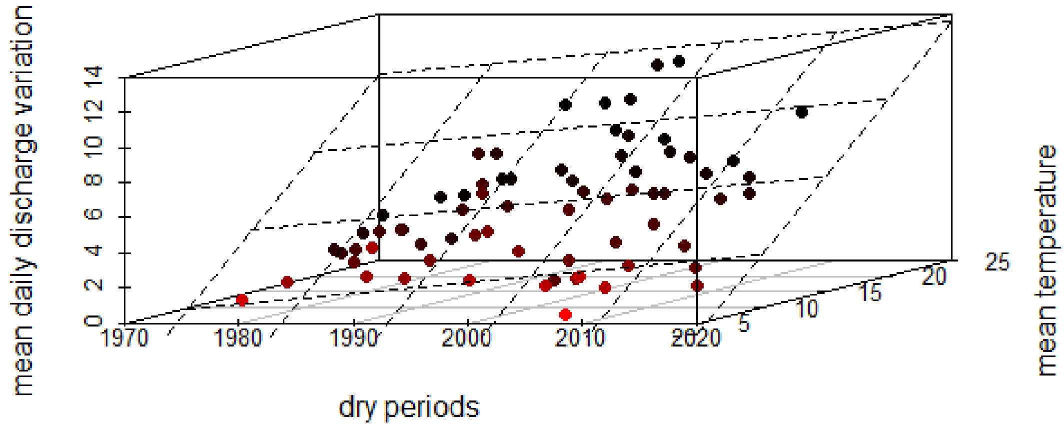


**Figure 24: Multiple regression plot for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September**

The command "summary" performed on the regression plane, which was made with the command "lm", prompts R to summarise the most important results of the multiple regression.

Between 1977 and 2013 the daily discharge variation increases by 0.06 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 3: Coefficients of multiple regression for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September**

| | **Parameter values** | **p-value** |
|---|---|---|
| **Intercept** | -125.856 | 0.002 ** |
| **Slope over time** | 0.060 | 0.003 ** |
| **Slope over temperature** | 0.711 | <0.001 *** |

The distribution of residuals can be characterised with these statistics:

**Table 4: Residuals of the multiple regression for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September**

| **Min** | **1Q** | **Median** | **3Q** | **Max** |
|---|---|---|---|---|
| -3.275 | -0.989 | -0.119 | 0.541 | 5.399 |

The residual standard error is 1.664 based on a DF (=degrees of freedom) of 67. The multiple $R^2$ is 0.668 and the adjusted $R^2$ is 0.659. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals of the regression plane are estimated with the command "confint" and are as follows:

Table 5: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -202.357 | -49.355 |
| **Slope over time** | 0.022 | 0.099 |
| **Slope over temperature** | 0.583 | 0.839 |

As the 3D plot does not clearly show the residuals in relation to the regression plane, another plot is generated to display individual values above or beneath the plane. In the following figure the green dots represent residual values situated beneath the regression plane and black dots are situated above. These results show that both in the beginning as well as in the end of the study period most values are below the regression plane, whereas in the middle most of the values seem to be above. This has led to the conclusion that a linear regression fitting a plane through all observations might not be the best fit for the data.

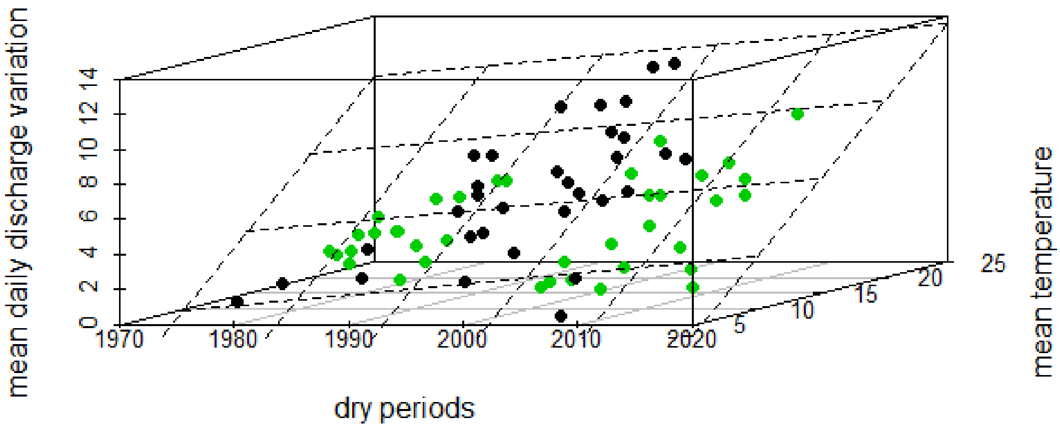


**Figure 25: Multiple regression plot for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September showing residuals above (black) and below (green) the regression plane**

The next figure demonstrates the same pattern, albeit from a different perspective. The angle of view projects the plane to show the magnitude of residuals. This clarifies the pattern with values early and late in the study period situated beneath the regression plane and in the middle situated above. This pattern suggests that the residuals indicate a non-linear trend.

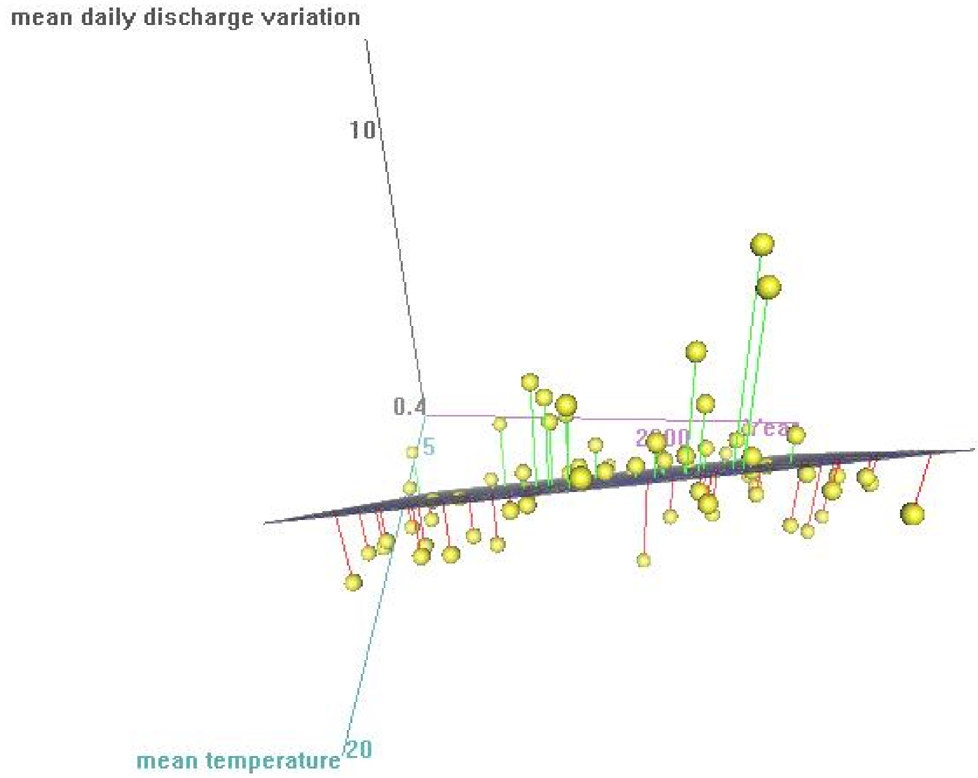


**Figure 26: Multiple regression plot for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September showing the magnitude of residuals in relation to the regression plane without the influence of temperature**

The 3D plots demonstrate a non-linear trend, or a change in direction of a possibly linear trend throughout the entire study time frame. This change of inclination seems to occur sometime during the 1990s. Due to the limited amount of data no non-linear regression is estimated, but rather a strategy of separating data into earlier and later periods is implemented. Consequently the next step of analysis is to split the entire study period into two separate analyses, in order to fit two linear regressions. As no exact turning point can be visually identified, two different scenarios are attempted. On one occasion the data set is split in the year 1990 and as an alternative in the year 1995. In both cases 1990 and 1995 is added to the first data sequence and the second sequence only starts in 1991 and 1996, respectively.

The data distribution is as follows:

**Table 6: Distribution of dry periods according to years, months and gauging stations**

| Gauging station | Years used | Number of dry periods between late July and end of August | Number of dry periods between late July and end of September | Years in total |
|---|---|---|---|---|
| **Sulzau** | 1977-2013 | 29 | 70 | 37 |
| | 1977-1990 | 8 | 23 | 14 |
| | 1990-2013 | 21 | 47 | 23 |
| | 1977-1995 | 12 | 33 | 19 |
| | 1995-2013 | 17 | 37 | 18 |
| **Kees** | 1989-2012 | 23 | 50 | 24 |
| | 1995-2012 | 16 | 35 | 17 |

Table 6 shows that the earlier sequence has fewer years, when the data is split in 1990 but both sequences have almost the same amount of years when the data is split in 1995. The number of dry periods is always higher in the second sequence, regardless of where the data series is split.

The following figures display the two resulting 3D plots with the time series split in 1990.

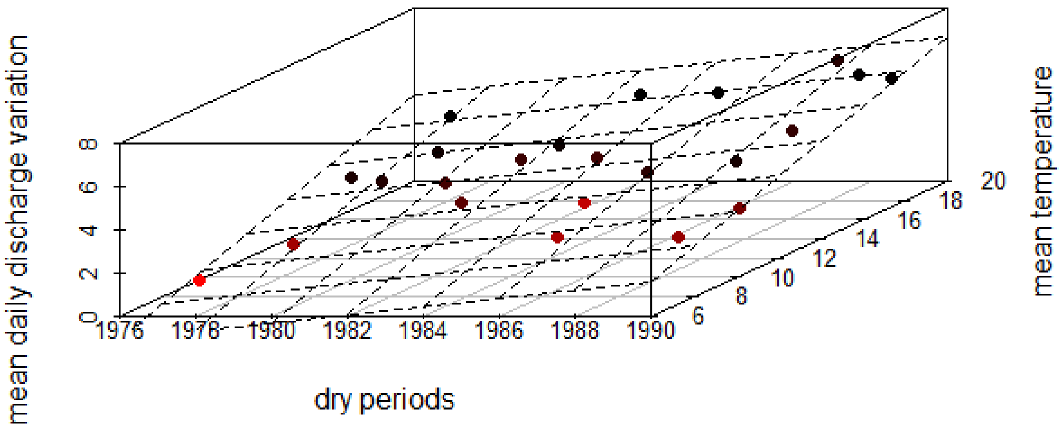


**Figure 27: Multiple regression plot for the daily discharge variation at Sulzau (1977-1990) from late July until the end of September**

Between 1977 and 1990 the daily discharge variation increases by 0.191 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 7: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1977-1990) from late July until the end of September**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -379.954 | <0.001 *** |
| **Slope over time** | 0.191 | <0.001 *** |
| **Slope over temperature** | 0.367 | <0.001 *** |

The distribution of residuals is characterised as:

**Table 8: Residual of the multiple regression for the daily discharge variation at Sulzau (1977-1990) from late July until the end of September**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -1.485 | -0.406 | 0.121 | 0.306 | 3.040 |

The residual standard error is 1.006 based on a DF of 20. The multiple $R^2$ is 0.687 and the adjusted $R^2$ is 0.655. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 9: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1977-1990) from late July until the end of September**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -579.587 | -180.321 |
| **Slope over time** | 0.090 | 0.291 |
| **Slope over temperature** | 0.208 | 0.526 |

The following plot shows the second sub-period with the time series split in 1990.

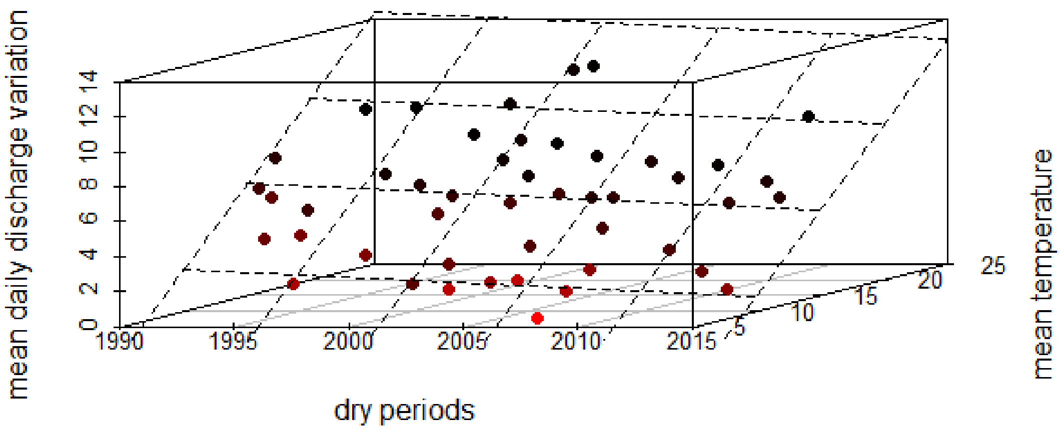


**Figure 28: Multiple regression plot for the daily discharge variation at Sulzau (1990-2013) from late July until the end of September**

Between 1990 and 2013 the daily discharge variation changes by -0.06 $m^3/s$ per year, excluding the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values are provided below:

**Table 10: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1990-2013) from late July until the end of September**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | 113.453 | 0.119 |
| **Slope over time** | -0.060 | 0.100 . |
| **Slope over temperature** | 0.801 | <0.001 *** |

The distribution of residuals given is:

**Table 11: Residuals of the multiple regression for the daily discharge variation at Sulzau (1990-2013) from late July until the end of September**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -3.865 | -0.830 | -0.056 | 0.504 | 5.083 |

The residual standard error is 1.52 with DF=44. The multiple $R^2$ is 0.764 and the adjusted $R^2$ is 0.753. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 12: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1990-2013) from late July until the end of September**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -30.173 | 257.080 |
| **Slope over time** | -0.132 | 0.012 |
| **Slope over temperature** | 0.662 | 0.940 |

Correspondingly, the following two 3D plots represent the partitioned multiple regressions with the data series split in 1995.

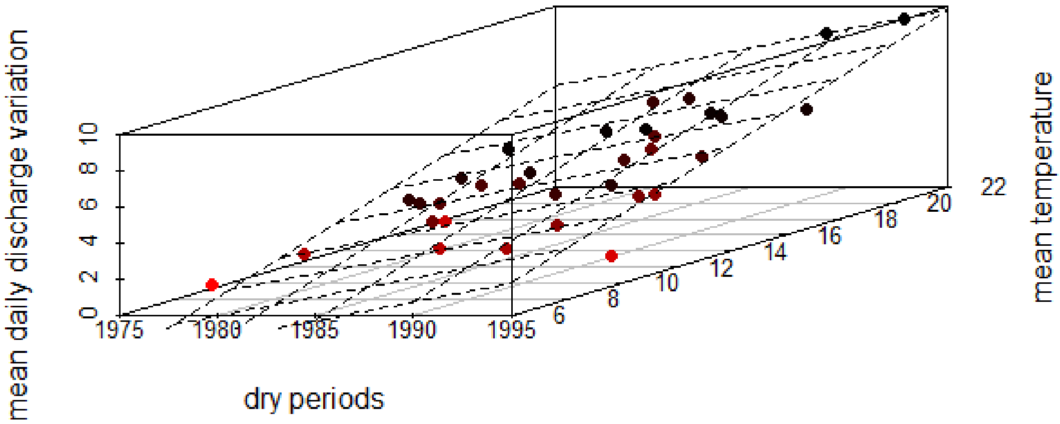


**Figure 29: Multiple regression plot for the daily discharge variation at Sulzau (1977-1995) from late July until the end of September**

Between 1977 and 1995 the daily discharge variation increases by 0.21 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 13: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1977-1995) from late July until the end of September**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -420.135 | <0.001 *** |
| **Slope over time** | 0.210 | <0.001 *** |
| **Slope over temperature** | 0.501 | <0.001 *** |

The distribution of the residuals given is characterised as:

Table 14: Residuals of the multiple regression for the daily discharge variation at Sulzau (1977-1995) from late July until the end of September

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -1.956 | -0.546 | -0.340 | 0.498 | 2.728 |

The residual standard error is 1.177 on DF=30. The multiple $R^2$ is 0.763 and the adjusted $R^2$ is 0.748. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

Table 15: 95% confidence interval of multiple regression for the daily discharge variation at Sulzau (1977-1995) from late July until the end of September

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -566.391 | -273.879 |
| **Slope over time** | 0.136 | 0.284 |
| **Slope over temperature** | 0.357 | 0.645 |

The later period with time series split in 1995.

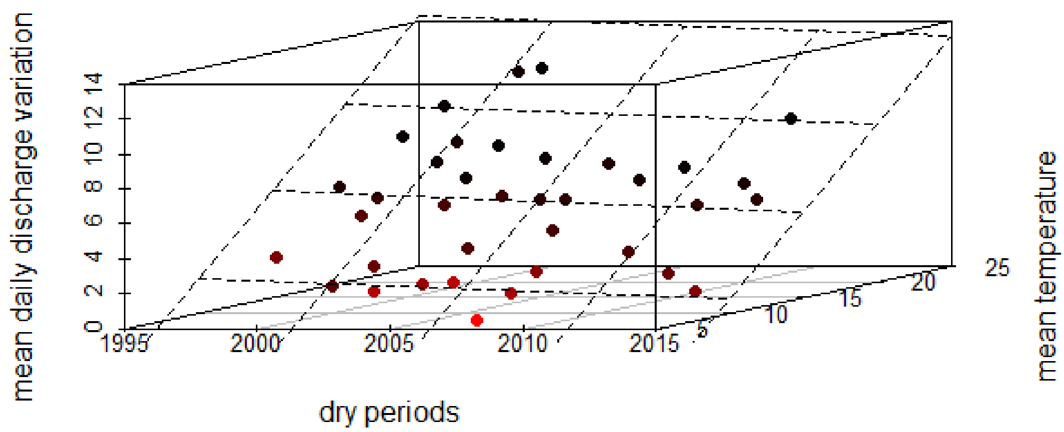


Figure 30: Multiple regression plot for the daily discharge variation at Sulzau (1995-2013) from late July until the end of September

Between 1995 and 2013 the daily discharge variation changes by -0.058 $m^3/s$ per year, excluding the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values are provided below:

**Table 16: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1995-2013) from late July until the end of September**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | 110.040 | 0.362 |
| **Slope over time** | -0.058 | 0.333 |
| **Slope over temperature** | 0.823 | <0.001 *** |

The distribution of residuals given can be characterised with these statistics:

**Table 17: Residuals of the multiple regression for the daily discharge variation at Sulzau (1995-2013) from late July until the end of September**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -3.849 | -0.761 | -0.118 | 0.347 | 5.012 |

The residual standard error is 1.664 on 34 DF. The multiple $R^2$ is 0.741 and the adjusted $R^2$ is 0.726. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 18: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1995-2013) from late July until the end of September**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -131.947 | 352.028 |
| **Slope over time** | -0.179 | 0.062 |
| **Slope over temperature** | 0.650 | 0.995 |

#### *4.2.1.2 Results for Data from the Gauging Station Kees between late July and the end of September*

As the time series available from the gauging station Kees only starts in 1989 it is not possible to demonstrate the initial increase followed by a decrease of discharge recognised at the Sulzau gauge. Nonetheless, for comparability two multiple regression plots are made, one showing the entire available data set comparable to the second sequence plot of the Sulzau gauging station starting after 1990 and another only starting after the year 1995, comparable to the shorter second sequence plot of Sulzau.

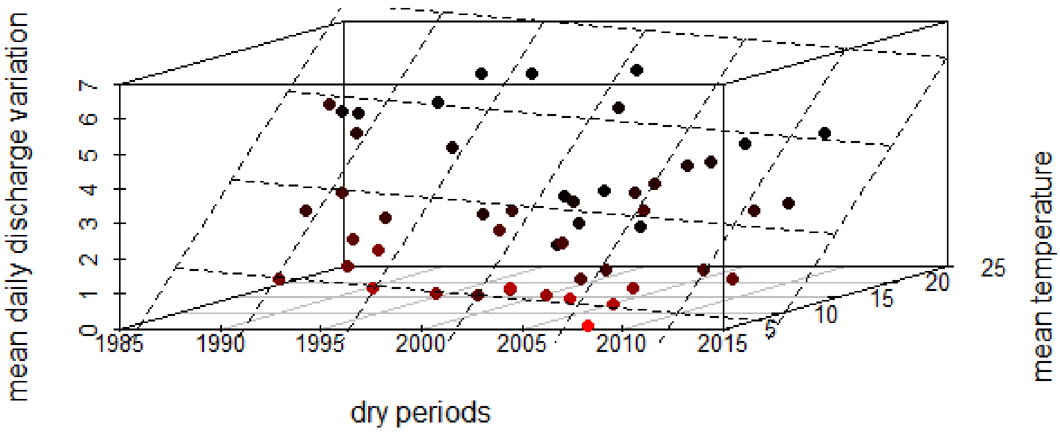


**Figure 31: Multiple regression plot for the daily discharge variation at Kees (1989-2012) from late July until the end of September**

Between 1989 and 2012 the daily discharge variation changes by -0.052 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 19: Coefficients of the multiple regression for the daily discharge variation at Kees (1989-2012) from late July until the end of September**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | 99.767 | 0.043 * |
| **Slope over time** | -0.052 | 0.036 * |
| **Slope over temperature** | 0.416 | <0.001 *** |

The distribution of residuals is as follows:

**Table 20: Residuals of the multiple regression for the daily discharge variation at Kees (1989-2012) from late July until the end of September**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -2.133 | -0.809 | -0.042 | 0.653 | 2.499 |

The residual standard error is 1.13 on DF=47. The multiple $R^2$ is 0.614 and the adjusted $R^2$ is 0.598. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 21: 95% confidence interval of the multiple regression for the daily discharge variation at Kees (1989-2012) from late July until the end of September**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | 3.482 | 196.052 |
| **Slope over time** | -0.100 | -0.004 |
| **Slope over temperature** | 0.314 | 0.517 |

The following 3D plot displays data after 1995.

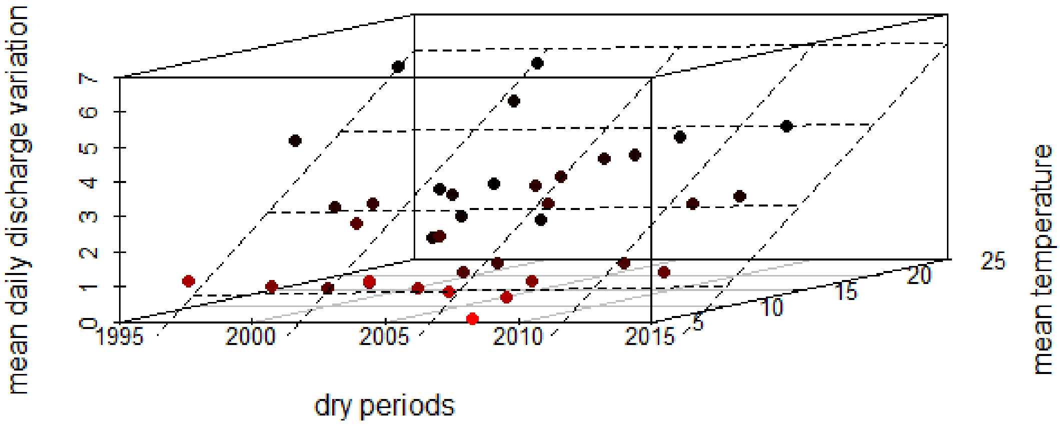


**Figure 32: Multiple regression plot for the daily discharge variation at Kees (1995-2012) from late July until the end of September**

Between 1995 and 2012 the daily discharge variation increases by 0.01 $m^3/s$ per year, excluding the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values are provided below:

**Table 22: Coefficients of the multiple regression for the daily discharge variation at Kees (1995-2012) from late July until the end of September**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -24.082 | 0.765 |
| **Slope over time** | 0.010 | 0.797 |
| **Slope over temperature** | 0.374 | <0.001 *** |

The distribution of residuals given is characterised as:

**Table 23: Residuals of the multiple regression for the daily discharge variation at Kees (1995-2012) from late July until the end of September**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -1.715 | -0.934 | -0.246 | 0.645 | 2.559 |

The residual standard error is 1.119 on 34 DF. The multiple $R^2$ is 0.572 and the adjusted $R^2$ is 0.546. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 24: 95% confidence interval of the multiple regression for the daily discharge variation at Kees (1995-2012) from late July until the end of September**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -186.471 | 138.307 |
| **Slope over time** | -0.071 | 0.091 |
| **Slope over temperature** | 0.261 | 0.487 |

#### *4.2.1.3 Results for Data from the Gauging Station Sulzau between late July and the end of August*

A similar pattern is also expressed by the data when only late July until August are analysed. However, the statistical significance is sometimes weaker, possibly due to fewer available data points, as only 29 dry periods occur during these months.

The following plots show the same gauging stations with the time series split at the same years as above, however data does not include September anymore. All data includes late July until the end of August only.

This multiple regression plot shows the entire data available from Sulzau from the year 1977 until 2013.

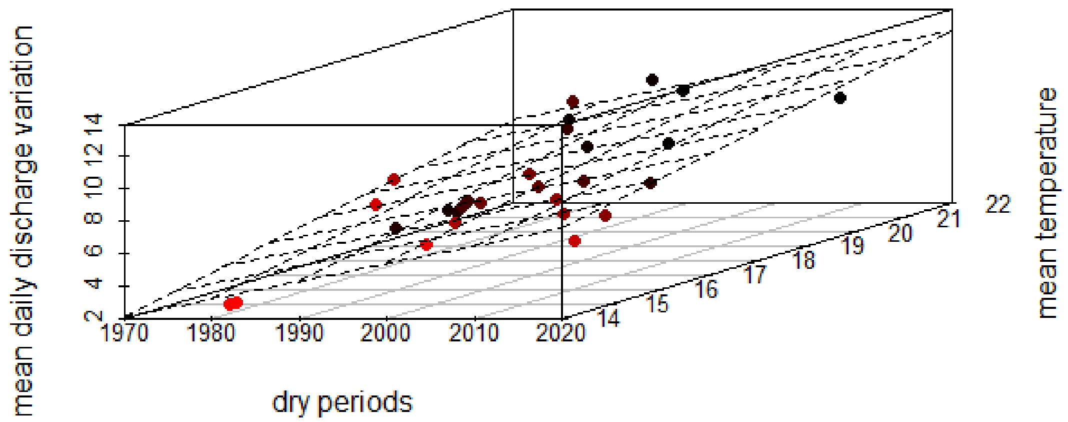


**Figure 33: Multiple regression plot for the daily discharge variation at Sulzau (1977-2013) from late July until the end of August**

Between 1977 and 2013 the daily discharge variation increases by 0.11 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 25: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1977-2013) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -222.618 | 0.005 ** |
| **Slope over time** | 0.110 | 0.006 ** |
| **Slope over temperature** | 0.633 | 0.009 ** |

The distribution of residuals is:

**Table 26: Residuals of the multiple regression for the daily discharge variation at Sulzau (1977-2013) from late July until the end of August**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -2.313 | -1.406 | -0.429 | 0.624 | 4.698 |

The residual standard error is 1.955 with DF=26. The multiple $R^2$ is 0.432 and the adjusted $R^2$ is 0.388. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 27: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1977-2013) from late July until the end of August**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -371.539 | -73.696 |
| **Slope over time** | 0.035 | 0.185 |
| **Slope over temperature** | 0.175 | 1.092 |

Again this data set is split both in the year 1990 as well as 1995. The following multiple regression plots show the data sets for 1977 - 1990 and 1990 - 2013. The first plot, displaying data for 1977 - 1990 includes only 8 dry periods, fewer than any other data set. Evidently this has an impact on the statistical significance. Nonetheless this data is provided in this thesis, in order to show the complete set of possible regressions.

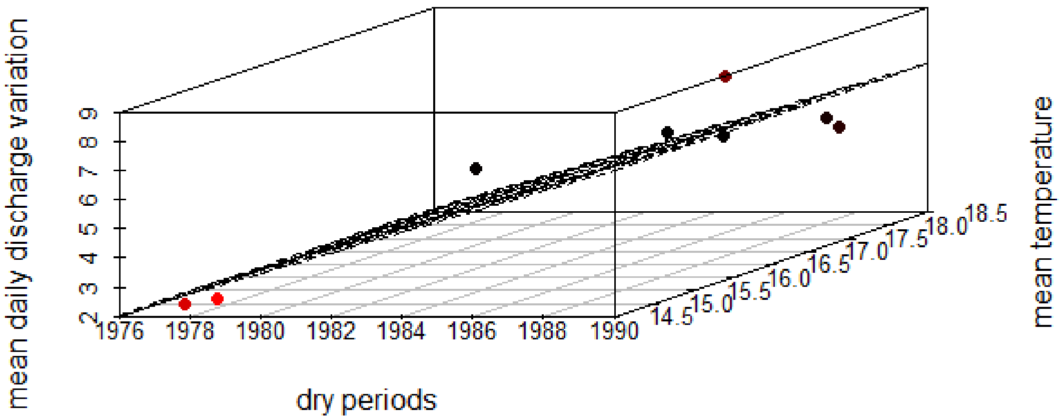


**Figure 34: Multiple regression plot for the daily discharge variation at Sulzau (1977-1990) from late July until the end of August**

Between 1977 and 1990 the daily discharge variation increases by 0.353 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below (as mentioned above, due to the low n the following parameters are not considered stable enough for interpretation and are only provided for completeness of documentation):

**Table 28: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1977-1990) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -695.773 | 0.009 ** |
| **Slope over time** | 0.353 | 0.009 ** |
| **Slope over temperature** | 0.024 | 0.944 |

The residuals distribution is shown in a different format due to the fewer available data points:

**Table 29: Residuals of the multiple regression for the daily discharge variation at Sulzau (1977-1990) from late July until the end of August**

| Period 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|
| -0.379 | 1.003 | -0.512 | 0.251 | -0.396 | -0.734 | -1.117 | 1.884 |

The residual standard error is 1.18 on 5 DF. The multiple $R^2$ is 0.799 and the adjusted $R^2$ is 0.719. The p-value for the overall multiple regression is 0.018.

The 95% confidence intervals are as follows:

**Table 30: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1977-1990) from late July until the end of August**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -1123.044 | -268.501 |
| **Slope over time** | 0.135 | 0.571 |
| **Slope over temperature** | -0.806 | 0.854 |

The following plot shows the data between 1990 and 2013.

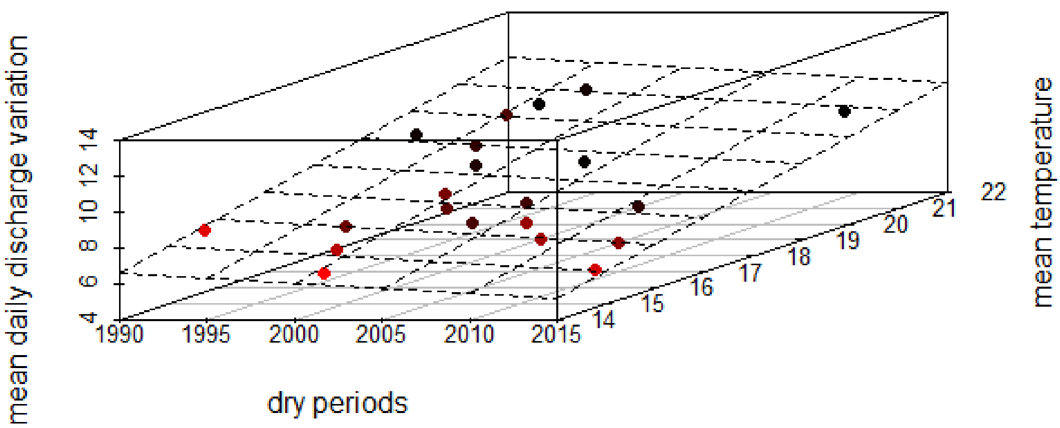


**Figure 35: Multiple regression plot for the daily discharge variation at Sulzau (1990-2013) from late July until the end of August**

Between 1990 and 2013 the daily discharge variation changes by -0.056 $m^3/s$ per year, excluding the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values are provided below:

**Table 31: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1990-2013) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | 108.944 | 0.389 |
| **Slope over time** | -0.056 | 0.376 |
| **Slope over temperature** | 0.620 | 0.012 * |

The residuals distribution is given as follows:

**Table 32: Residuals of the multiple regression for the daily discharge variation at Sulzau (1990-2013) from late July until the end of August**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -1.574 | -0.987 | -0.520 | 0.399 | 4.641 |

The residual standard error is 1.727 based on a DF of 18. The multiple $R^2$ is 0.335 and the adjusted $R^2$ is 0.261. The p-value for the overall multiple regression is 0.026.

The 95% confidence intervals are as follows:

**Table 33: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1990-2013) from late July until the end of August**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -150.107 | 367.994 |
| **Slope over time** | -0.185 | 0.073 |
| **Slope over temperature** | 0.155 | 1.085 |

The following plots show the data, when split in the year 1995.

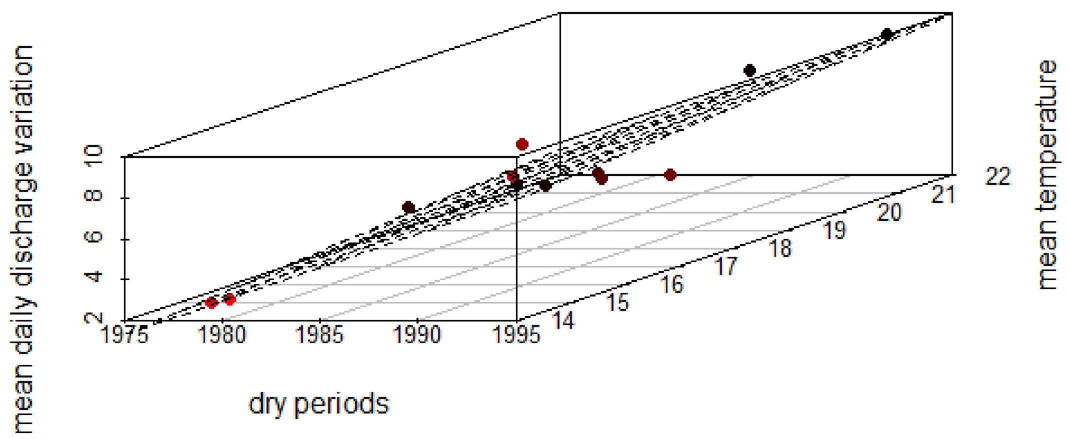


**Figure 36: Multiple regression plot for the daily discharge variation at Sulzau (1977-1995) from late July until the end of August**

Between 1977 and 1995 the daily discharge variation increases by 0.33 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 34: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1977-1995) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -654.607 | <0.001 *** |
| **Slope over time** | 0.330 | <0.001 *** |
| **Slope over temperature** | 0.249 | 0.297 |

The distribution of the residuals can be characterised with these statistics:

**Table 35: Residuals of the multiple regression for the daily discharge variation at Sulzau (1977-1995) from late July until the end of August**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -1.985 | -0.746 | -0.146 | 0.611 | 2.183 |

The residual standard error is 1.261 on 9 DF. The multiple $R^2$ is 0.814 and the adjusted $R^2$ is 0.773. The p-value for the overall multiple regression is < 0.001.

The 95% confidence intervals are as follows:

**Table 36: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1977-1995) from late July until the end of August**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -939.016 | -370.198 |
| **Slope over time** | 0.185 | 0.475 |
| **Slope over temperature** | -0.260 | 0.757 |

The following plot shows the second part of the time series split in 1995.

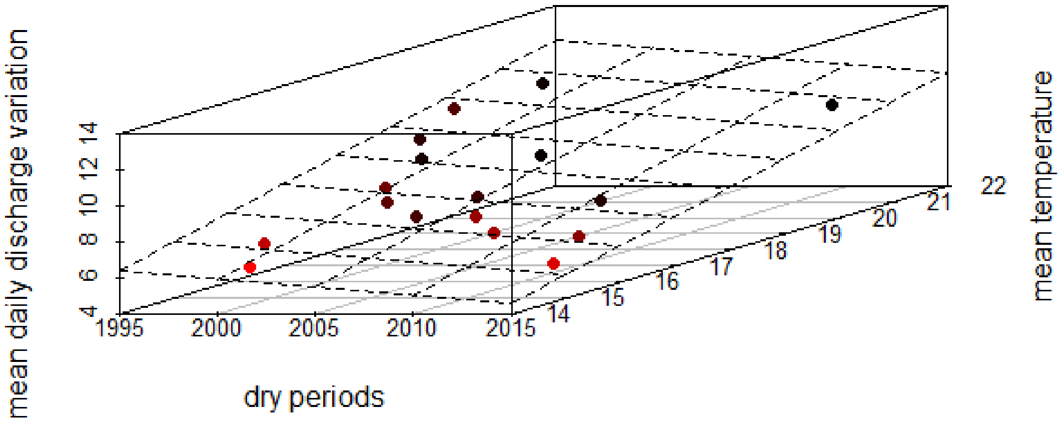


**Figure 37: Multiple regression plot for the daily discharge variation at Sulzau (1995-2013) from late July until the end of August**

Between 1995 and 2013 the daily discharge variation changes by -0.092 $m^3/s$ per year, excluding the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values are provided below:

**Table 37: Coefficients of the multiple regression for the daily discharge variation at Sulzau (1995-2013) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | 180.171 | 0.344 |
| **Slope over time** | -0.092 | 0.333 |
| **Slope over temperature** | 0.721 | 0.029 * |

The distribution of residuals is characterised as:

Table 38: Residuals of the multiple regression for the daily discharge variation at Sulzau (1995-2013) from late July until the end of August

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -2.012 | -1.032 | -0.421 | 0.518 | 4.509 |

The residual standard error is 1.87 on DF=14. The multiple $R^2$ is 0.325 and the adjusted $R^2$ is 0.229. The p-value for the overall multiple regression is 0.064.

The 95% confidence intervals are as follows:

Table 39: 95% confidence interval of the multiple regression for the daily discharge variation at Sulzau (1995-2013) from late July until the end of August

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -214.549 | 574.890 |
| **Slope over time** | -0.289 | 0.105 |
| **Slope over temperature** | 0.087 | 1.355 |

#### *4.2.1.4 Results for Data from the Gauging Station Kees between late July and the end of August*

As mentioned above, the gauging station Kees cannot be compared to the earlier sequence of Sulzau data, as the Kees recordings only start in 1989. Only two 3D multiple regression plots are made for Kees, one showing the entire available data set, which is analogous to the plots of the gauging station Sulzau starting from 1990 and another starting from the year 1995.

The following multiple regression plots show the period 1989 – 2012.

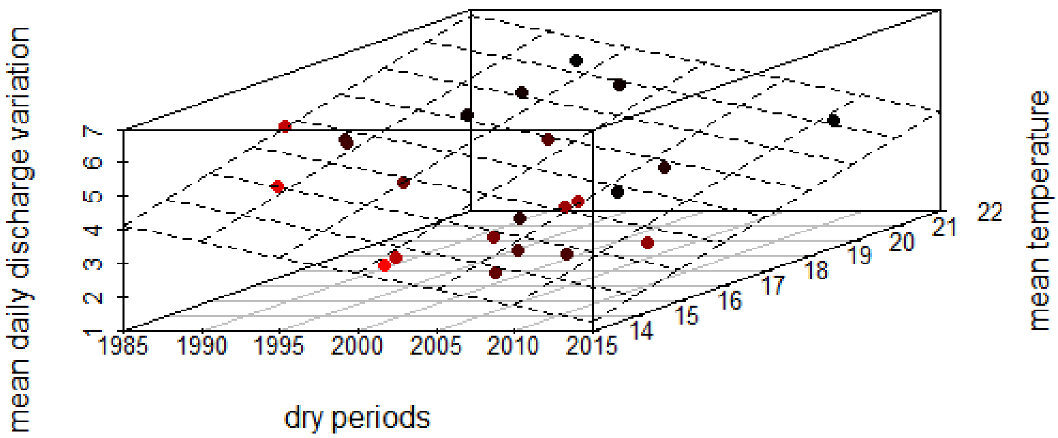


Figure 38: Multiple regression plot for the daily discharge variation at Kees (1989-2012) from late July until the end of August

Between 1989 and 2012 the daily discharge variation changes by -0.095 $m^3/s$ per year, excluding the influence of temperature. The parameter values and p-values are provided below:

**Table 40: Coefficients of the multiple regression for the daily discharge variation at Kees (1989-2012) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | 188.101 | 0.041 * |
| **Slope over time** | -0.095 | 0.039 * |
| **Slope over temperature** | 0.341 | 0.077 . |

The residuals distribution is:

**Table 41: Residuals of the multiple regression for the daily discharge variation at Kees (1989-2012) from late July until the end of August**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -2.428 | -1.137 | 0.127 | 0.938 | 1.069 |

The residual standard error is 1.372 with DF=20. The multiple $R^2$ is 0.277 and the adjusted $R^2$ is 0.205. The p-value for the overall multiple regression is 0.039.

The 95% confidence intervals are as follows:

**Table 42: 95% confidence interval of the multiple regression for the daily discharge variation at Kees (1989-2012) from late July until the end of August**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | 8.749 | 367.454 |
| **Slope over time** | -0.185 | -0.005 |
| **Slope over temperature** | -0.040 | 0.722 |

The following regression plot displays the shortened time series between 1995 and 2012.

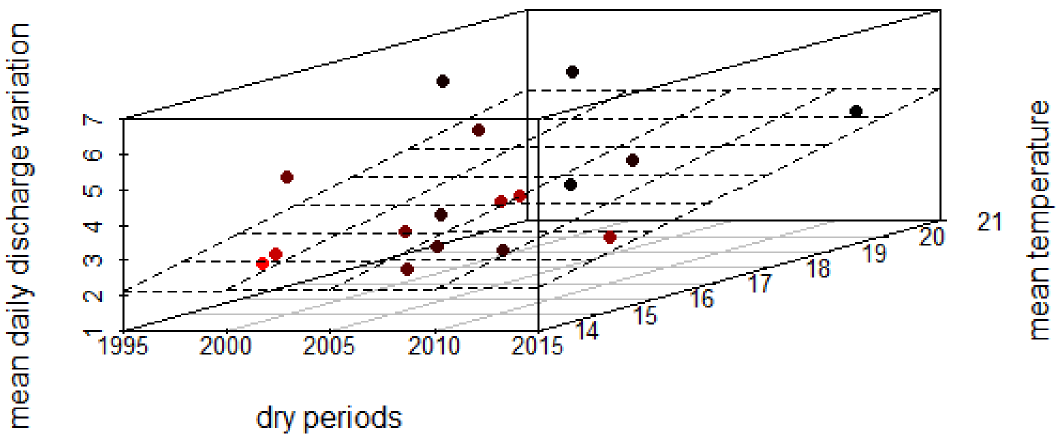


**Figure 39: Multiple regression plot for the daily discharge variation at Kees (1995-2012) from late July until the end of August**

Between 1995 and 2012 the daily discharge variation increases by 0.003 $m^3/s$ per year, excluding the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values are provided below:

**Table 43: Coefficients of the multiple regression for the daily discharge variation at Kees (1995-2012) from late July until the end of August**

| | Parameter values | p-value |
|---|---|---|
| **Intercept** | -9.323 | 0.951 |
| **Slope over time** | 0.003 | 0.967 |
| **Slope over temperature** | 0.367 | 0.167 |

The distribution of residuals is as follows:

**Table 44: Residuals of the multiple regression for the daily discharge variation at Kees (1995-2012) from late July until the end of August**

| Min | 1Q | Median | 3Q | Max |
|---|---|---|---|---|
| -1.952 | -0.849 | -0.434 | 0.891 | 2.316 |

The residual standard error is 1.437 on 14 DF. The multiple $R^2$ is 0.139 and the adjusted $R^2$ is 0.016. The p-value for the overall multiple regression is 0.352.

The 95% confidence intervals are as follows:

**Table 45: 95% confidence interval of the multiple regression for the daily discharge variation at Kees (1995-2012) from late July until the end of August**

| | 2.5% | 97.5% |
|---|---|---|
| **Intercept** | -326.045 | 307.399 |
| **Slope over time** | -0.156 | 0.162 |
| **Slope over temperature** | -0.174 | 0.909 |

The following tables summarise the most important data and present a comparison between the different time frames, as well as gauging stations.

The following table summarises the most important parameter values for the gauging station Sulzau.

**Table 46: Summary of the results obtained by using multiple regression for the daily discharge variation at Sulzau**

| Years | Months | Slope* | p-value* | $R^2$** |
|---|---|---|---|---|
| **1977-2013** | late July – end of August | 0.110 | 0.006 | 0.432 |
| | late July – end of September | 0.060 | 0.003 | 0.668 |
| **1977-1990** | late July – end of August | 0.353 | 0.009 | 0.799 |
| | late July – end of September | 0.191 | <0.001 | 0.687 |
| **1990-2013** | late July – end of August | *-0.056* | *0.376* | *0.335* |
| | late July – end of September | *-0.060* | *0.100* | *0.764* |
| **1977-1995** | late July – end of August | 0.330 | <0.001 | 0.814 |
| | late July – end of September | 0.210 | <0.001 | 0.763 |
| **1995-2013** | late July – end of August | *-0.092* | *0.333* | *0.325* |
| | late July – end of September | *-0.058* | *0.333* | *0.741* |

The following table summarises the most important parameter values for the gauging station Kees.

**Table 47: Summary of the results obtained by using multiple regression for the daily discharge variation at Kees**

| Years | Months | Slope* | p-value* | $R^2$** |
|---|---|---|---|---|
| **1989-2012** | late July – end of August | -0.095 | 0.039 | 0.277 |
| | late July – end of September | -0.052 | 0.036 | 0.614 |
| **1995-2012** | late July – end of August | *0.003* | *0.967* | *0.139* |
| | late July – end of September | *0.010* | *0.797* | *0.572* |

*Slope and p-value refer to the mean daily discharge variation increase or decrease over time, as shown by the multiple regression plots.

**$R^2$ refers to the entire multiple regression, indicating how well all included variables fit to the regression plane.

Values in italic indicate p-values higher than 0.05 and therefore those not considered of sufficient statistical significance. This is mostly due to a low number of observations as well as a near horizontal slope.

### 4.2.2 Partial Correlation

The same variables and time periods are explored through partial correlation analysis, controlling for temperature, which means keeping it at a constant level, thereby excluding temperature influence on the dependent variable. Partial correlation is not visualised like multiple regression.

The R command used for the partial correlation is “pcor.test” and the method used is spearman.

#### *4.2.2.1 Results for Data from the Gauging Station Sulzau between late July and the end of September*

The correlation coefficient of daily discharge variation with time (covering 70 dry periods from 1977 until 2013) is 0.322, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 48: Results of the partial correlation for the daily discharge variation at Sulzau (1977-2013) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| 0.322 | 0.104 | 0.005 | 0.092 | 0.519 |

Just like multiple regression, partial correlation analyses are split in the years 1990 and 1995.

The correlation coefficient of daily discharge variation with time (covering 23 dry periods from 1977 until 1990) is 0.637, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 49: Results of the partial correlation for the daily discharge variation at Sulzau (1977-1990) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| 0.637 | 0.406 | <0.001 | 0.294 | 0.834 |

The correlation coefficient of daily discharge variation with time (covering 47 dry periods from 1990 until 2013) is -0.437, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 50: Results for the partial correlation for the daily discharge variation at Sulzau (1990-2013) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| -0.437 | 0.191 | 0.001 | -0.646 | -0.168 |

The correlation coefficient of daily discharge variation with time (covering 33 dry periods from 1977 until 1995) is 0.742, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 51: Results for the partial correlation for the daily discharge variation at Sulzau (1977-1995) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| 0.742 | 0.551 | <0.001 | 0.531 | 0.867 |

The correlation coefficient of daily discharge variation with time (covering 37 dry periods from 1995 until 2013) is -0.279, controlling for the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values for this analysis are as follows:

**Table 52: Results for the partial correlation for the daily discharge variation at Sulzau (1995-2013) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| -0.279 | 0.078 | 0.090 | -0.557 | 0.054 |

#### *4.2.2.2 Results for Data from the Gauging Station Kees between late July and the end of September*

A partial correlation analysis is also executed with data from the gauging station Kees, where data is only available from 1989 to 2012. Both the entire data set is analysed as well as data only from 1995 until

2012, to be able to better compare it with results from the gauging station Sulzau. Just like with data from the gauging station Sulzau, the analysis is done for both time frames, between late July until the end of September and between late July until the end of August.

The correlation coefficient of daily discharge variation with time (covering 50 dry periods from 1989 until 2012) is -0.286, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 53: Results for the partial correlation for the daily discharge variation at Kees (1989-2012) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| R | $R^2$ | p-value | 2.5% | 97.5% |
| -0.286 | 0.082 | 0.041 | -0.525 | -0.005 |

The correlation coefficient of daily discharge variation with time (covering 35 dry periods from 1995 until 2012) is 0.302, controlling for the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values for this analysis are as follows:

**Table 54: Results for the partial correlation for the daily discharge variation at Kees (1995-2012) from late July until the end of September**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| R | $R^2$ | p-value | 2.5% | 97.5% |
| 0.302 | 0.091 | 0.073 | -0.040 | 0.581 |

#### *4.2.2.3 Results for Data from the Gauging Station Sulzau between late July and the end of August*

The same partial correlation analysis is conducted with data from the gauging station Sulzau ranging only from late July until the end of August. The commands for the software R are identical.

The correlation coefficient of daily discharge variation with time (covering 29 dry periods from 1977 until 2013) is 0.433, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 55: Results for the partial correlation for the daily discharge variation at Sulzau (1977-2013) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| 0.433 | 0.187 | 0.014 | 0.071 | 0.694 |

The correlation coefficient of daily discharge variation with time (covering only 8 dry periods from 1977 until 1990) is 0.952, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 56: Results for the partial correlation for the daily discharge variation at Sulzau (1977-1990) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| 0.952 | 0.906 | <0.001 | 0.705 | 0.993 |

The correlation coefficient of daily discharge variation with time (covering 21 dry periods from 1990 until 2013) is -0.284, controlling for the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values for this analysis are as follows:

**Table 57: Results for the partial correlation for the daily discharge variation at Sulzau (1990-2013) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| -0.284 | 0.081 | 0.209 | -0.258 | 0.596 |

The correlation coefficient of daily discharge variation with time (covering 12 dry periods from 1977 until 1995) is 0.882, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 58: Results for the partial correlation for the daily discharge variation at Sulzau (1977-1995) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| **R** | **$R^2$** | **p-value** | **2.5%** | **97.5%** |
| 0.882 | 0.778 | <0.001 | 0.599 | 0.969 |

The correlation coefficient of daily discharge variation with time (covering 17 dry periods from 1995 until 2013) is -0.174, controlling for the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values for this analysis are as follows:

**Table 59: Results for the partial correlation for the daily discharge variation at Sulzau (1995-2013) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| R | $R^2$ | p-value | 2.5% | 97.5% |
| -0.174 | 0.030 | 0.510 | -0.616 | 0.352 |

### *4.2.2.4 Results for Data from the Gauging Station Kees between late July and the end of August*

The correlation coefficient of daily discharge variation with time (covering 23 dry periods from 1989 until 2012) is -0.402, controlling for the influence of temperature. The parameter values and p-values for this analysis are as follows:

**Table 60: Results for the partial correlation for the daily discharge variation at Kees (1989-2012) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| R | $R^2$ | p-value | 2.5% | 97.5% |
| -0.402 | 0.242 | 0.049 | -0.704 | 0.023 |

The correlation coefficient of daily discharge variation with time (covering 16 dry periods from 1995 until 2012) is 0.251, controlling for the influence of temperature. This value, however, is not statistically significant. The parameter values and p-values for this analysis are as follows:

**Table 61: Results for the partial correlation for the daily discharge variation at Kees (1995-2012) from late July until the end of August**

| Parameter values | | | 95% confidence interval | |
|---|---|---|---|---|
| R | $R^2$ | p-value | 2.5% | 97.5% |
| 0.251 | 0.063 | 0.349 | -0.299 | 0.677 |

The following table summarises the most important results of the partial correlation for the data from the gauging station Sulzau.

**Table 62: Summary of the results obtained by using partial correlation for the daily discharge variation at Sulzau**

| Years | Months | R | $R^2$ | p-value |
|---|---|---|---|---|
| **1977-2013** | late July – end of August | 0.433 | 0.187 | 0.014 |
| | late July – end of September | 0.322 | 0.104 | 0.005 |
| **1977-1990** | late July – end of August | 0.952 | 0.906 | <0.001 |
| | late July – end of September | 0.637 | 0.406 | <0.001 |
| **1990-2013** | late July – end of August | *-0.284* | *0.081* | *0.209* |
| | late July – end of September | -0.437 | 0.191 | 0.001 |
| **1977-1995** | late July – end of August | 0.882 | 0.778 | <0.001 |
| | late July – end of September | 0.742 | 0.551 | <0.001 |
| **1995-2013** | late July – end of August | *-0.174* | *0.030* | *0.510* |
| | late July – end of September | *-0.279* | *0.078* | *0.090* |

The following table summarises the most important results of the partial correlation for the data from the gauging station Kees.

**Table 63: Summary of the results obtained by using partial correlation for the daily discharge variation at Kees**

| Years | Months | R | $R^2$ | p-value |
|---|---|---|---|---|
| **1989-2012** | late July – end of August | -0.492 | 0.242 | 0.049 |
| | late July – end of September | -0.286 | 0.082 | 0.041 |
| **1995-2012** | late July – end of August | *0.251* | *0.063* | *0.349* |
| | late July – end of September | *0.302* | *0.091* | *0.073* |

Values in italic indicate results that have a p-value which is higher than 0.05 and which are therefore not considered to have sufficient statistical significance. This is mostly due to a low number of values as well as a weak slope.

All the results obtained are presented in this chapter, even though some of them do not meet the criteria of statistical significance. An analysis of the results will be conducted in the next chapter “5 Discussion”.

# 5 Discussion

The pattern of glacier discharge, which is shown in the chapter “4 Results”, is mentioned frequently in corresponding literature (Casassa et al., 2009; Farinotti et al., 2011; Huss, 2011; Lambrecht and Mayer, 2009; Yao et al., 2013). It is stated that an initial increase in discharge or also in diurnal discharge variation is expected, until a critical point is reached, after which a decrease in discharge or diurnal discharge variation will occur.

As stated in Casassa et al. (2009) “Initial stages of warming will also result in an amplification of the diurnal run-off amplitudes due to melt, followed in a second stage by a decrease of diurnal amplitudes as the glaciers shrink beyond their critical point.”

According to the APCC (2014, p. 425) it can be presumed that most Austrian glaciers have already reached their maximum yearly discharge or have even already passed this point. By this stage the direct positive correlation of discharge and temperature diminishes, as the glacier area can no longer sustain a continuous discharge increase. The temperature, however, will in all likelihood nonetheless increase. With a less significant influence of temperature, the correlation with glacier area becomes more evident. The APCC (2014, p. 429) emphasises that the glacier discharge in the Austrian Alps is likely to have already reached its maximum, due to the decrease of glacier area.

The time frames for this critical point differ from paper to paper, due to the different size and melt behaviour of glaciers. Many state that this critical point has already occurred, whereas others state that it is likely to happen in the near future. Casassa et al. (2009), however, suggest that glaciers in Switzerland might have reached this critical point during the 1990s. This corresponds with the estimation made for the discharge of the Obersulzbachkees in this thesis, which is split once in 1990 and once in 1995. This assessment is made based on visual inspection of the data, as is discussed in depth in the chapter “4 Results”.

The results obtained after splitting the data as discussed above will be debated in the following paragraphs.

## 5.1 Analysis of Results

### 5.1.1 Sulzau vs. Kees

Data from the gauging stations Sulzau and Kees can only be compared during the second sequence of the time series, as the gauging station Kees only started discharge measurements in the year 1989. Therefore the first sequence, which generally delivers more significant results, cannot be compared. There is only one data category delivering statistically significant results for both gauging stations. In this case, the partial correlation is applied on data including September and starting in 1989 or after 1990 for the gauging stations Kees and Sulzau, respectively. In this case Sulzau indicates a negative correlation coefficient of -0.437 and an $R^2$ of 0.191 and Kees provides a negative correlation coefficient of -0.286 and an $R^2$ of 0.082. Both results show a negative correlation, however, the coefficient of determination has a slightly different magnitude. This demonstrates that for data from the gauging station Sulzau more than twice as much of the variation is explained by the correlation in comparison to data from the gauging station Kees. Nevertheless, more statistically significant results would be needed to be able to make any conclusive assumptions with regard to the difference between both gauging stations.

### 5.1.2 Late July until end of August vs. late July until end of September

Generally speaking both data sets deliver similar results. Whenever one of the data sets indicates a positive or negative slope or correlation coefficient, the other data set does the same, with both multiple regression as well as partial correlation. Nonetheless some differences can be pointed out.

As the data set between late July and end of September has more dry periods, the p-value tends to be lower, indicating better statistical significance. In the example of partial correlation five analyses, as opposed to four are statistically significant. This difference seems negligible but it becomes clearer when looking at the actual p-values. Whenever they are not the same, so in five different analyses per analysis type, the p-values are lower for the time series including September.

While the time frame between late July and the end of September tends to have a bigger statistical significance, likely due to data volume, the time frame between late July and the end of August tends to have higher values for the slope gradient and correlation coefficient, respectively. Using multiple regression excluding September the slope is steeper five times, whereas only twice the slope value is steeper when September is excluded. This is slightly less significant with partial correlation, where only four correlation coefficient values are higher when excluding September, compared to three higher correlation coefficient values when including September.

### 5.1.3 First Sequence vs. Second Sequence of Time Series

As mentioned before the time series is once split in the year 1990 and once in the year 1995. The earlier sequence has fewer years, when the data is split in 1990 (14 vs. 23) but both sequences have almost the same amount of years when the data is split in 1995 (19 vs. 18). The number of dry periods is always higher in the second sequence, regardless of where the data series is split.

Even though the first sequence has fewer or the same amount of dry periods, the results are always statistically significant, both for the multiple regression as well as for the partial correlation. The slope and correlation coefficient values are always positive, indicating an upward trend and the slope values always have a relatively high value. The maximum slope value is 0.353 for the multiple regression of the years 1977 until 1990 with data between late July until the end of August. The minimum slope value is 0.191 for the multiple regression of the years 1977 until 1990 when using data which includes September.

In total it seems to be quite clear that there is a strong and statistically significant upward trend between the beginning of the data in 1977 and the 1990s, regardless of gauging station or months used for the analysis.

The second sequence sends a less clear signal, even though it has more or almost the same amount of dry periods. The statistical significance threshold is rarely reached, with only one out of eight multiple regression/ partial correlation results with Sulzau data and only four out of eight multiple regression / partial correlation results with Kees data meeting the criteria. Only these results can be analysed for further discussion. Just two results from the multiple regression reache the threshold, when using data from the gauging station Kees starting from 1989, either including September or not. The slope values are -0.052 and -0.095, respectively, which is not as strong as any value from the first sequence. All other statistically significant results are obtained with the partial correlation, two from the gauging station Kees and only one from the gauging station Sulzau. The correlation coefficient value -0.437 ($R^2$ = 0.191) is acquired with data from Sulzau after 1990 and including September. The correlation coefficient value when Kees data is used under the same selection criteria is -0.286 ($R^2$ = 0.082). Only one result reaches statistical significance when September is excluded. The result -0.492 ($R^2$ = 0.242) is obtained when Kees data is used starting from the year 1989. This also shows that no results from the second sequence are statistically significant when the time series is started after 1995, presumably because this reduces the number of input data even further. Overall, however, it seems that the most important reason for the lack of statistical significance is the very weak slope and correlation during this time period. Nonetheless, it can be observed that all of the statistically significant results have a negative trend.

In total it seems evident that during the second sequence the strong upward trend from the first sequence has ended and that it appears that a negative trend has started, albeit not a trend which is as strong as for the first sequence. Given that the trend is weak more data would be very useful in order to successfully be able to obtain statistically more significant results.

During the first sequence of data, there is apparently no big difference in the results, whether the data is split in 1990 or 1995. However, during the second sequence statistically significant results only occur when the data is split in 1990, presumably because more dry periods are available for the analysis.

### 5.1.4 Multiple Regression vs. Partial Correlation

The magnitude of the results for the multiple regression and the partial correlation cannot be compared directly, as they are calculated with different statistical methods. Nonetheless, whenever the results are statistically significant the direction of the slope/ correlation (positive or negative) is identical.

The coefficient of determination is almost always higher for the multiple regression compared to the partial correlation, whenever both results are statistically significant. The only exception is between 1977 and 1990 between the months late July and the end of September, which is a dataset which needs to be interpreted with caution, as it only consists of eight dry periods in total, which is statistically highly problematic. The statistically significant coefficients of determination are as follows:

**Table 64: Coefficients of determination obtained by applying multiple regression and partial correlation on the daily discharge variation data**

| Gauging station | Years | Months | $R^2$ of Multiple Regression | $R^2$ of Partial Correlation |
|---|---|---|---|---|
| **Sulzau** | 1977-2013 | Late July – end of August | **0.432** | 0.187 |
| | | Late July – end of September | **0.668** | 0.104 |
| | 1977-1990 | Late July – end of August | 0.799 | **0.906** |
| | | Late July – end of September | **0.687** | 0.406 |
| | 1977-1995 | Late July – end of August | **0.814** | 0.778 |
| | | Late July – end of September | **0.763** | 0.551 |
| **Kees** | 1989-2012 | Late July – end of August | **0.277** | 0.242 |
| | | Late July – end of September | **0.614** | 0.082 |

Values in bold indicate the higher coefficient of determination within each row.

A possible explanation of the difference in $R^2$ is that the multiple regression takes temperature into account, thereby explaining more of the dependent variable, whereas partial correlation removes the effect of temperature.

### 5.1.5 Association with Temperature

As demonstrated in the chapter “4 Results” no trend can be obtained for the mean temperature per dry period over any of the time frames used for the multiple regression as well as partial analysis. There is some likelihood that this time period is too short to demonstrate a trend. According to Lieb and Slupetzky (2013, p. 33) the area of Obersulzbachtal does nonetheless experience a general warming of the climate, just like the entire alpine region. Even though no trend is detectable when looking at the available data the use of temperature data is vital for both analyses, as the immediate impact of a warmer/ colder weather is reflected in the discharge data.

According to the literature temperature tends to have a very high correlation with discharge as long as discharge increases. A higher temperature leads to a higher discharge rate and the glacier area is expected to decrease in size. However, once the critical point is reached temperature is likely to further increase, whereas discharge is starting to decrease, as the glacier area can no longer sustain high discharges. This pattern is not visible with the temperature data of Pass Thurn probably due to the relatively short time span used for this analysis (Chen and Ohmura, 1990; Li et al., 2012; Singh and Kumar, 1997; Stahl and Moore, 2006).

For the general alpine area it is nonetheless expected, that temperature will increase over the next few decades (APCC, 2014, p. 319).

During the analysis of this thesis temperature data is used in order to show the influence of temperature on melting processes on the glacier for each dry period. Temperature does play a critical role for these melting processes, however, it is also used as a proxy for radiation, also affecting ice melt (Koboltschnig, 2007). Therefore some of the unexplained noise of the results might be due to the inevitable differences between these two data sets. Unfortunately no radiation data is available for analysis and therefore these differences cannot be quantified.

## 5.2 Discussion of Results

### 5.2.1 Ablation Area, Albedo and Snow

The glacier area has decreased significantly and continuously since 1850, as illustrated in the chapter "2 Introduction of the Study Area". In 1850 the Obersulzbachkees had an area of 16km$^2$, by 1969 the area decreased to 11.6km$^2$ and by 2009 the area of all the glaciers which had originally formed the Obersulzbachkees only covered an area of 9.75km$^2$ (Lieb and Slupetzky, 2013, pp. 29, 55).

Even though the total glacier area has continually decreased the glacier meltwater has initially increased, as shown in the chapter "4 Results". Given that the meltwater originates from the glacier area, it seems counter-intuitive that these two parameters are not linked. This apparent discrepancy could be explained with the concept of accumulation and ablation areas. These two areas are separated by the so called equilibrium line, situated at an elevation, where the mass balance is zero. Above the equilibrium line is the accumulation area, describing the area of the glacier where net accumulation is greater than net ablation. Beneath the equilibrium line is the ablation area, an area with higher net ablation than net accumulation (Savoskul and Smakhtin, 2013, p. 4). The concept of the equilibrium line is typically used for glaciers in equilibrium, characterising glaciers with a net mass balance of zero. As mentioned above this is not the case in the Obersulzbach valley, as the glacier has been continually receding since 1850. In such a case the terms firn line, annual equilibrium line or current equilibrium line can be used, which describe the position of the snow line at the end of each summer (Lieb and Slupetzky, 2013, pp. 29, 34, 55).

Most of the glacier melt discharge comes from the ablation area, rather than the accumulation area. This is to a large degree due to a different albedo of snow and bare ice (Casassa et al., 2009). This means that the total size of the glacier area has a smaller impact on runoff, compared to the size of the ablation area. Consequently it may not be very important if the total area of the glacier recedes, as long as the ablation area is able to retain or even increase its size. Moore and Demuth (2001) state that the "[…] rapid retreat of the firn line and the resulting increase in exposed, low-albedo ice more than compensated for the loss of glacier area by terminal retreat."

In fact it is rather probable that the absolute size of the ablation area will initially increase, when the glacier first starts receding. As mentioned above the firn line, which reflects the annual snow accumulation and melt processes, adjusts yearly to the current climate condition. It can react much faster than the glacier tongue. Therefore the firn line might move upwards relatively early during a time of glacier recession, while the glacier tongue might still be stationary or might move upward at a slower pace. During this time the ablation area will become bigger than would be possible for a steady state glacier (Casassa et al., 2009; Kern and László, 2010; Osmaston, 2005; Paul et al., 2007).

Paul et al. (2007) stress that in the case of mass balance data for ten alpine glaciers between 1981 and 2003 the "[…] continuous mass loss has also diminished or even eliminated most of the firn reserves from previous years, as the equilibrium line was generally above its steady-state position and quite often even above the highest glacier point." The same argument is also pointed out by Osmaston (2005), who mentions that "[…] a retreating glacier has a greater extent than would be in equilibrium with its actual current ELA [equilibrium line altitude]. Thus the rise in its hypothetical balanced ELA lags behind and is less than that of its current ELA."

This increase in ablation area is possible until the glacier tongue has caught up and the glacier is back in a state of equilibrium or until the firn line has reached the top or at least the upper part of the glacier within the catchment. In the latter case the glacier tongue may still recede, but because the entire glacier area only consists of an ablation area, it is no longer possible to increase in size. As a result the ablation area size can only decrease from this point onwards. A third possibility is that the firn line has not quite reached the top yet, but that the absolute area in the higher regions is not quite as big, due to the mountain topography (Barnett et al., 2005 as quoted in Stahl and Moore, 2006; Casassa et al., 2009; Moore and Demuth, 2001; Osmaston, 2005).

As shown in the chapter "4 Results" the discharge does not maintain its increase and even seems to decrease in the second half of the available time series. This could indicate that the ablation area has already started to decrease. The available results suggest that this turning point occurred sometime in the 1990s. After this point, the ablation area clearly was not able to sustain the discharge anymore.

This particular phenomenon clearly does not only occur at Obersulzbachkees. Hock et al. (2005) describe a similar pattern for Vernagtferner glacier, situated in western Austria. They mention that the “diurnal amplitude of the run-off significantly increased in the period 1974-2000, consistent with an increase in the bare ice area.” This is even quantified as follows: “In the 1970s, when mass balance was positive and 10-30% of the glacier area consisted of bare ice at the end of the balance year, typical mean diurnal variation of discharge during the melt season was 0.5-1 m3s-1 with the maximum amplitudes of ~5 m3s-1, based on hourly mean values. In the 1990s, bare ice area was as large as 90% as a result of strongly negative mass balances. Mean diurnal variation of summer discharge was up to 3 m3s-1 with maximum amplitudes exceeding 10 m3s-1” (Hock et al., 2005).

However, this does not only apply to individual glaciers but has also been assumed for the entire alpine region. Casassa et al. (2009) mention that “[…] the available run-off records for the Alps show a run-off increase in recent decades in highly glacierized basins due to warmer temperatures that result in snow line rise, glacier wastage and enhanced melt. Basins with intermediate glacierization already show a declining run-off trend, indicating that areal reduction of glaciers prevails over enhances melt due to thinning.”

Additionally to the size of the ablation area, the albedo of the entire glacier also plays a vital role. The ablation area has a much lower albedo than the accumulation area, as the surface is not continuously covered with snow. Bare ice is much darker and can therefore absorb much more radiation. This is intensified by the presence of dust particles, black carbon, soot, aerosols and the growth of algae on the glacier, which are covered by high albedo snow in the accumulation area. In the ablation area, however, these particles tend to accumulate, especially when the glacier is losing in height and during longer periods of fair weather, which frequently occurs during years of glacier recession. Meltwater or precipitation are often not able to wash all the particles away, as they melt themselves a few millimetres into the ice. Hence they accumulate on the surface of the ablation area. More particles mean that the glacier is becoming even darker and the albedo is lowered even further. Additionally due to the lowering of the glacier dark firn bands from previous years are uncovered, which tend to be darker. This is partly because precipitation typically falls as snow in these altitudes, which is not as effective at washing particles away like liquid precipitation (Casassa et al., 2009; Haeberli et al., 2007; Hock et al., 2005, p. 245; Huss et al., 2014; Moore et al., 2009; Moore and Demuth, 2001; Oerlemans et al., 2009 as quoted in Huss et al., 2014; Paul et al., 2007). A darker glacier surface also means that a higher discharge is possible, even if the temperature during a particular dry period is the same as for previous years, simply because of the change in albedo. Additionally if, due to a warmer spring, the snow covering the glacier melts earlier in the season, the glacier will get darker sooner, which will affect the runoff.

Moreover, this dust may increase due to the accumulation of wind-blown dust from the snow-free rock surfaces surrounding the glacier, which may previously have been covered by snow (Haeberli et al., 2007).

Not only the snow on the glacier is relevant, but also the snow and albedo on the surrounding rocks, which can also affect the glacier melt processes (Paul et al., 2007). This will be discussed in more detail in the subchapter "5.2.3 Glacier Disintegration, Glacier Boundaries and Reflected and Emitted Radiation from Surrounding Slopes".

In order to verify the specific effect of ablation area and albedo on the actual runoff in the Obersulzbach valley, a runoff model would have to be made and calibrated. For this a lot more data would be necessary, especially better climate data, which should ideally be measured within the investigated catchment. Such a model goes beyond the scope of this thesis and consequently neither of the above mentioned influences can be quantified for the glacier runoff in the Obersulzbach valley.

### 5.2.2 Preferential Meltwater Pathways

Preferential meltwater pathways are a tunnel-like drainage system within the glacier. As the thickness of a glacier as well as the extent of the firn and snow cover is reduced the drainage system changes as well and becomes more efficient. Water flow velocities are much higher through ice than though snow and firn, because ice has a much smaller water retention capacity. As the storage capacity decreases, the drainage system increases in efficiency and is capable of discharging more water. This drainage system, also called preferential meltwater pathways, improves throughout the season. This means that later in the season more water can be discharged compared to earlier stages during the melt season and more pronounced diurnal discharge peaks and amplitudes occur (Fountain and Walder, 1998; Hock et al., 2005; Hock and Hooke, 1993 as quoted in Jansson et al., 2003; Singh and Singh, 2001, p. 537).

It is therefore conceivable that an earlier onset of these preferential meltwater pathways may happen, if the weather in spring is warmer than average and hence favourable for melting. Under those circumstances it might be possible that during a particular dry period in summer more water is discharged, even though the temperature during that particular period might not be warmer. Changes in the season and an earlier onset of spring and therefore warmer temperatures are in fact all too likely under the current climate predictions (APCC, 2014, p. 415).

Unfortunately no data is available to prove or disprove the degree of impact of this effect for the study area Obersulzbachkees. Detailed modelling as well as a long-term tracer experiment could potentially indicate how much these preferential meltwater pathways influence the glacier discharge in the Obersulzbach valley.

### 5.2.3 Glacier Disintegration, Glacier Boundaries and Reflected and Emitted Radiation from Surrounding Slopes

When a glacier recedes different dynamics and feedback mechanisms occur. One of these mechanisms takes place due to changes in the albedo between ice and snow surfaces compared to rock surfaces. Bare rock has a lower albedo and therefore heats up more quickly than ice or snow does and consequently is able to emit this heat, even during the night. This leads to a faster melting process of the glacier and creates a small gap, called randkluft, where bare rock and the glacier meet that is to say at the glacier boundary. This gap tends to grow even further due to turbulent heat fluxes. This process means that glacier boundaries produce an exceptionally high amount of meltwater, compared to the entire glacier body. Consequently it needs to be taken into account how long the boundary of a glacier is, relative to its size (Paul et al., 2007).

The glaciers within the Obersulzbach valley have receded significantly and the Obersulzbachkees has disintegrated into several new glaciers, as mentioned in the chapter “2 Introduction of the Study Area” (Lieb and Slupetzky, 2013, p. 155). However, no data could be found as to the length of the boundaries of the glaciers. It is a possibility that this length has actually increased, even in absolute terms, due to the glacier disintegration. For example the boundary of the original Obersulzbachkees previously only had to encompass one glacier, whereas now there are six different ones. As mentioned before no hard data is available to prove this argument. In order to get a vague idea satellite imagery is used from the Global Land Survey (Esri and Global Land Survey, 2010, 1990). With the help of two satellite images in shortwave infrared from the years 1990 and 2010, the glacier boundaries are drawn as precisely as possible with the given resolution and scale. This first assessment shows that in the year 1990 there were roughly 43.91km of glacier boundaries, while in the year 2010 there were 45.42km. This shows a slight increase, however, it is emphasised that these numbers are only rough estimations.

The following figure demonstrates the recession of the glacier boundaries within these 20 years.

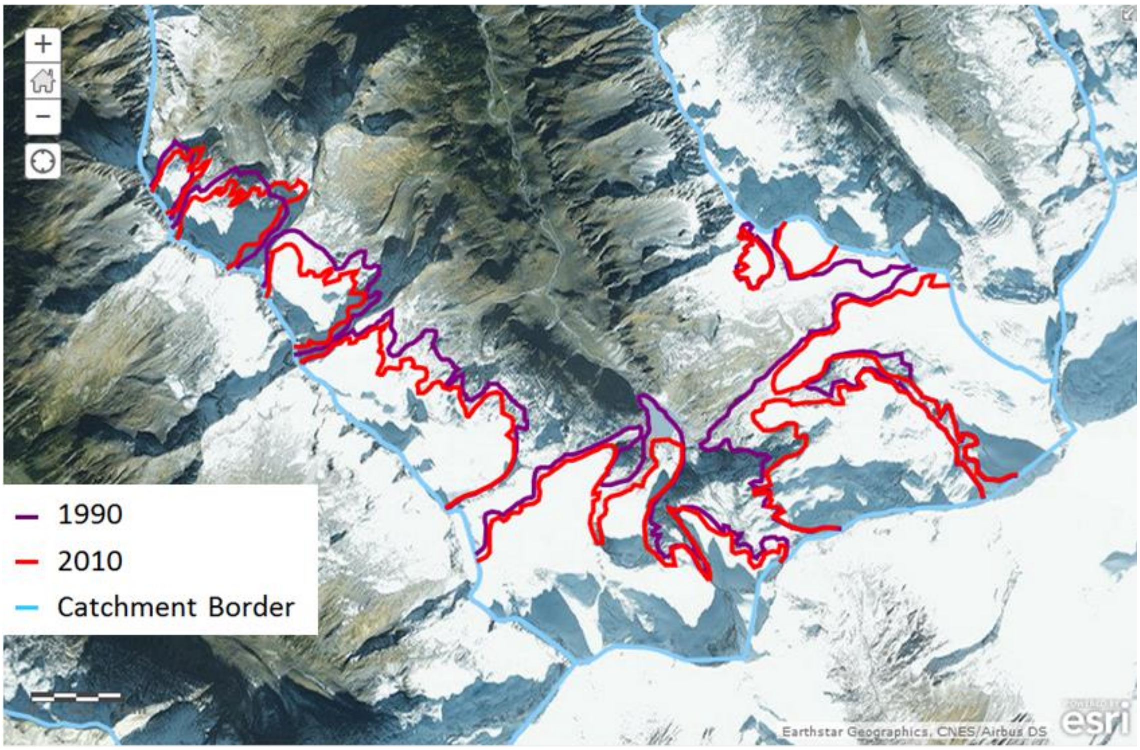


**Figure 40: Estimation of the glacier boundaries within the Obersulzbach valley in the years 1990 and 2010 (Esri, n.d.; Esri and Global Land Survey, 2010, 1990)**

The thermal heating from the surrounding rock can influence the entire glacier and not just the boundaries, although the effect at the boundaries is more significant. The glacier recedes and gives way to bare rock, which has lower albedo and thermal inertia and can emit this heat, consequently leading to an increase in glacier melt (Greuell and Smeets, 2001; Paul et al., 2007). However, according to Klok and Oerlemans (2002) the reflected radiation from surrounding slopes has a comparatively small effect on the overall meltwater production, contributing only roughly 4% in comparison to the annual mean shortwave incoming radiation on the glacier.

### 5.2.4 Elevation of Glacier Tongue

According to Fischer (2010) the actual elevation of the glacier tongue also plays an important part during glacier recession. In this particular paper the glacier Hintereisferner, located in the Tyrol, is analysed. The results show that the glacier tongue lost 160m of thickness over a 50 year period (between 1953 and 2003), which suggests an increase of temperature of 1°C. Analogous to the temperature increase there is also a reduction of the incoming solar radiation due to the surface lowering, however, this shading effect is negligible in comparison to the increase in temperature. Overall the paper states that the temperature increase has a smaller impact on glacier recession than changes in albedo (Fischer, 2010).

Surface lowering or downwasting of a glacier tongue can take place when a glacier has a negative mass balance. This phenomenon is also likely to occur at Obersulzbachkees. As previously mentioned in the chapter “2 Introduction of the Study Area” Obersulzbachkees lost roughly 60% of its volume between 1850 and 2009, but only lost roughly 25% of its area. This indicates that the glacier must have thinned considerably during this period (Lieb and Slupetzky, 2013, pp. 29–31).

Given that the surface of Obersulzbachkees has very probably been lowered considerably a slight temperature change could potentially have an impact on the glacier melt behaviour as well, although it is very difficult to assess the degree of influence of this elevation change.

# 6 Conclusion

As mentioned before, the overall objective of this master thesis is to identify the long-term alterations in runoff characteristics of Obersulzbach. More specifically two hypotheses were defined:

- Long-term alterations in runoff characteristics of Obersulzbach are induced by changes of the catchment glaciation extent and connected to climate change.
- These alterations can be observed both in long term runoff data as well as in diurnal variations.

The first hypothesis is evidently accepted by the vast majority of scientific papers. As indicated in the chapter “2 Introduction of the Study Area” climate change is responsible for the recession of the glaciers within the Obersulzbach valley, thereby influencing one of the main sources of discharge.

The second hypothesis is discussed more thoroughly with the help of the data provided by the Hydrographic Service Salzburg in the chapters “4 Results” and “5 Discussion”. It seems that the glacier discharge, measured at the gauging stations Sulzau and Kees, increased from the beginning of the data provided (1977) until the 1990s and since then the glacier discharge during dry periods in the summer months has decreased. This discharge pattern is affected by several factors, such as a temperature increase, a change in the ablation area, glacier albedo and snow cover. Additionally, changes in the preferential melt pathways, glacier boundaries and glacier elevation also influence the discharge pattern. Particularly the decrease in glacier size, more specifically of the ablation area, influences the current ongoing decrease in discharge. From the current perspective it seems as though this trend might continue, as the glacier is likely to continue receding and will therefore have less glacier area to provide melt runoff.

In order to better understand all the fundamental processes leading to this change in runoff volume and pattern a comprehensive runoff and glacier melt model would be beneficial. Unfortunately no such model is done in this case, as this would have gone beyond the scope of this thesis. Additionally, the lack of high resolution meteorological data would have hindered such an attempt and the resulting model would likely not have had sufficient accuracy. Especially better precipitation data would be necessary to be able to properly assess the precipitation input. Such a meteorological station would preferably be situated within the actual Obersulzbach valley and ideally more than one such station should provide data, with the purpose of taking the hypsometric difference of the valley into account. More accurate temperature measurements would also be necessary in order to be able to assess the melting processes on the glacier. In total a longer time series of the entire data set, including discharge, precipitation and temperature would also be beneficial. Furthermore, more volume and area measurements of the glacier would provide better estimations of the former and current glacier dimensions, which would in turn also help improve a runoff and glacier melt model.

With more high resolution data and longer time series an adequate model could be made and would certainly help understand the local hydrological processes and might even enable forecasts for the future development of the discharge of the Obersulzbach.

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