

Meltwater Stream Temperature Responses to Air Temperature and Characteristics

A thesis submitted to the University of Salford in fulfilment of the requirement of the Degree of
Master of Environmental Life Science by Research

By

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Table of contents

Table of Contents	I
List of Tables	IV
List of Figure	V
Acknowledgments	X
Declaration	XI
Abstract	XII

	Page
1. Introduction	1
1.1 Background to study area	1
1.2 Study Area	3
1.3 Hypotheses	4
1.4 Study Period	5
2. Literature Review	6
2.1 Energy Availability	6
2.2 Determining Factors	9
2.3 Glacier Recession	10
2.4 Thermal Energy	12
2.5 Vulnerability	14
2.6 Inputs and Outputs	15
2.7 Climate Change	17
2.8 Conclusion	18
3. Methods	20
3.1 Aims	20
3.2 Data Collection	21
3.3 Measurements	22

	3.21 Water	22
	3.22 Discharge	22
	3.4 G.I.S. Geographical Information Systems	23
4. Results		28
	4.1 Monthly Trends	28
	4.2 Individual Diurnal Days/ Hysteresis Loops	33
	4.3 Relationship between Melt & Temperature	42
	4.4 Monthly comparisons of Discharge	53
	4.5 Diurnal comparison graphs	56
5. Discussion		63
	5.1 Air Temperature	63
	5.2 Comparison Studies	64
	5.3 Discharge	67
	5.4 Precipitation	70
	5.5 Future	71
	5.6 Individual months	73
	5.7 Radiation	75
	5.8 Overall comparisons	77
6. Conclusion		81
7. References		84

List of Tables	Page
Table 1. Catchment Characteristics	2

List of Figures	Page
Figure 1. Catchments area of of Findelengletscher and Gornergletscher	2
Figure 2. Schematic diagram	7
Figure 3. Study Area, 2 Contrasting Glaciers in Close Proximity.	8
Figure 4. Findelengletscher.	10
Figure 5. Gornergletscher.	11
Figure 6. Changes in monthly discharge.	12
Figure 7. Mean monthly temperatures.	17
Figure 8. Digital Elevation model.	25
Figure 9. Decrease in glacier length and width.	26
Figure 10 Highlighted Glacier boundaries Findelengletscher.	27
Figure 11. Findelenbach 12/9/07, 12:00:00 to 15/10/07, 00:00:00.	30
Figure 12. Gornera 03/08/07, 13:00:01 to 03/09/07, 12:01:00.	31

Figure 13. Gornera 10/9/07, 14:00:00 to 12/9/07, 2:00:00.	33
Figure 14. Findelenbach 10/9/07, 14:00:00 to 11/9/07 14:00:00.	34
Figure 15. Discharge in relation to Water Temperature Gornera.	34
Figure 16. Discharge in relation to Water Temperature, Findelenbach.	36
Figure 17. Gornera. Hysteresis 11/9/07.	37
Figure 18. Findelenbach, 15/9/07.	38
Figure 19. Gornera daily rises and falls in Discharge.	39
	40
Figure 20. Findelenbach, cold day 18/9/07.	
Figure 21. Cool day of 18/9/07 at Findelenbach.	40
Figure 22. Discharge in relation to temperature at Findelenbach.	42
Figure 23. Discharge in relation to temperature at Gornera.	43
Figure 24. Warm day from Findelenbach from 13/8/07.	44

Figure 25. Warm Day Gornera on the 13/8/07.	44
Figure 26. Findelenbach, 13/8/07.	45
Figure 27. Gornera 13/8/07.	46
Figure 28. Findelenbach, 5/8/07.	47
Figure 29. Findelenbach 5/8/07.	47
Figure 30. Gornera, Warm day 5/8/07.	48
Figure 31. Gornera 5/8/07.	48
Figure 32. Findelenbach, Cool day 17/8/07.	49
Figure 33. Gornera, Cool day 17/8/07.	50
Figure 34. Findelenbach, Cool day 19/8/07.	51
Figure 35. Findelenbach, Cool day 19/8/07.	51
Figure 36. Gornera, Cool day 19/8/07.	52
Figure 37. Gornera, Cool day 19/8/07.	52
Figure 38. Comparison of Water Temperature. 3/08/07, 13:01:00 to 3/9/07, 12:01:00.	54

Figure 39. Comparison of Discharge, 3/8/07, 13:01:00 to 3/9/07, 12:01:00.	55
Figure 39. Comparison of all the data Warm Day 5/8/07.	55
Figure 40. Warm Day Comparison 13/8/07.	58
Figure 41. Cool day Comparison 17/8/07.	59
Figure 42. Cool day Comparison 19/8/07.	59
Figure 43. Cool day comparison 25/8/07.	60
Figure 44. Warm day comparison 27/8/07.	60
Figure 45. Findelenbach 05/8/07, 13:00:00 to 12/9/07 10:00:00.	61
Figure 46. Findelenbach 05/8/07, 13:00:00 to 12/9/07 10:00:00	62
Figure 47. Mean monthly discharge for the 1956-2007 Period.	66
Figure 48. Differences between seasons based on typical changes in discharge and water temperature.	69

Figure 49. Gornera in the future.	71
Figure 50. Findelenbach in the future .	72
Figure 51. Findelenbach River taking its natural course.	76
Figure 52. Gornera Gauging station.	76
Figure 53. Radiation, and its heat flux.	80

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Declaration

This is to certify that the copy of my thesis, which I have presented for consideration for my postgraduate degree embodies the results of my own course of research, has been composed by myself and has been seen by my supervisor before presentation.

Signature

Date

Abstract

The aim of this project is to examine the relative importance of size of glacier catchment area, air temperature, stream characteristics including distance travelled by meltwater in determining water temperature in meltwater rivers draining from Alpine Glaciers. Hood et al. (2013) suggested that percentage glacierisation was the determining influence on water temperature in streams draining large glacierised basins in Alaska. Percentage glacierisation however is an unusual basin characteristic in that it largely depends on the location of the gauging station, and not on catchment physical properties. As meltwater temperature is influenced by incoming radiation, the length of time of exposure of meltwater is an important influencing factor on temperature. Length of time of exposure depends on fluvial characteristics, and distance between glacier portal and measurement/gauging station. This thesis examines how basin size, air temperature, radiation, melt stream length and stream characteristics contribute to meltwater in influencing these variable on meltwater temperature. The Swiss Alpine basin containing the glaciers Findelengletscher, Gornergletscher, (containing Grosser Aletschergletscher) all with temperature and discharge records in selected months (August and September) in 2007 with research from Collins where more than 10 years' continuous records were investigated. Primary data was collected in the field in the Swiss Alps for air and water temperature and discharge, with secondary research collected by Collins used to show trends from previous years and support the results. Literature show the consistent links between climatic change and trends in rising discharge in glacier fed streams. Distance from glacier portal and surface area of meltwater rivers are important factors in influencing water temperature that are not related to percentage basin glacierisation. Water temperature is positively related to air temperature and negatively associated with river flow and its thermal capacity. Evidence of stream characteristics, glacier size and air temperature being key contributing factors influencing meltwater temperature proves that percentage glacierisation has no impact on stream temperature.

1. Introduction

1.1 Background to study area

Meltwater temperature is influenced by climatic change, through air temperature and radiation with stream characteristics making water susceptible to changes downstream. Stream temperature is a key indicator of source of flow to a river channel in high mountain areas (Bolton, 2013). Meltwater draining from Findelengletscher and Gornergletscher in the Swiss Alps allows two adjacent and contrasting glaciers to be compared. Meltwater temperature and discharge are measured 1.57 km away from the glacier terminus at Gornera with the comparison glacier of Findelenbach being measured over 0.9km away from the glacier terminus (Collins, 1979). Figure 1 shows the two sites where the meltwater in the Gornera and Findelenbach is gauged, the number 1 indicates the gauging station for Gornera and the number 4 shows where the minisonde (mini data loggers) is placed. The smaller glacier of Findelenbach in 1973 was 7.8km long and by 2010 there had been a retreat of around half a km (Collins, 2008). The glacier feeds the Findelenbach stream, which will be where the temperature is measured; since the Little Ice Age the glacier has retreated by 2.5km showing the impact of the warming earth and rising air temperature. The comparison Gornergletscher is the second largest in the Alps with a length of 14km long almost double the size of Findelenbach and approximately 1.5km wide (Google Earth, 2014) . Comparing the two glaciers will lead to a further understanding of glaciers of different sizes and their water temperature differences, with Findelengletscher and Gornergletscher being adjacent the air temperature at the two glaciers will demonstrate patterns of variability. Examining relationships between air temperature, discharge, percentage catchment, length of stream and volume determines how these factors are contributing to water temperature. Stream length of channel to gauging station are interlinked as the water moves downstream as energy is gathered through transit. Motivation for the study is the percentage glacierisation retreating and making the distance travelled to gauging station longer and therefore allowing

more energy to be added to water temperature for warming and proving climatic change is influencing meltwater and meltwater temperature.

Table 1. Catchment characteristics

	Percentage Glacierisation %	Distance between Glacier Terminus and Gauging station
Gornergletcher	82	1.57km
Findelengletcher	65	0.9km

Table 1 describes the characteristics of the glacier catchment, showing the distance travelled and relationships between the two as described. Findelenbach is the smaller of both meltwater streams but also has a much shorter transit time to allow warming to occur. Gornera's discharge and velocity reduces transit time because of the mass of water travelling downstream and the wide deep river channel speeds up movement downstream, whereas Findelenbach has a lower discharge and velocity. Observational views of the two differing meltwater streams were taken while collecting data in Zermatt.

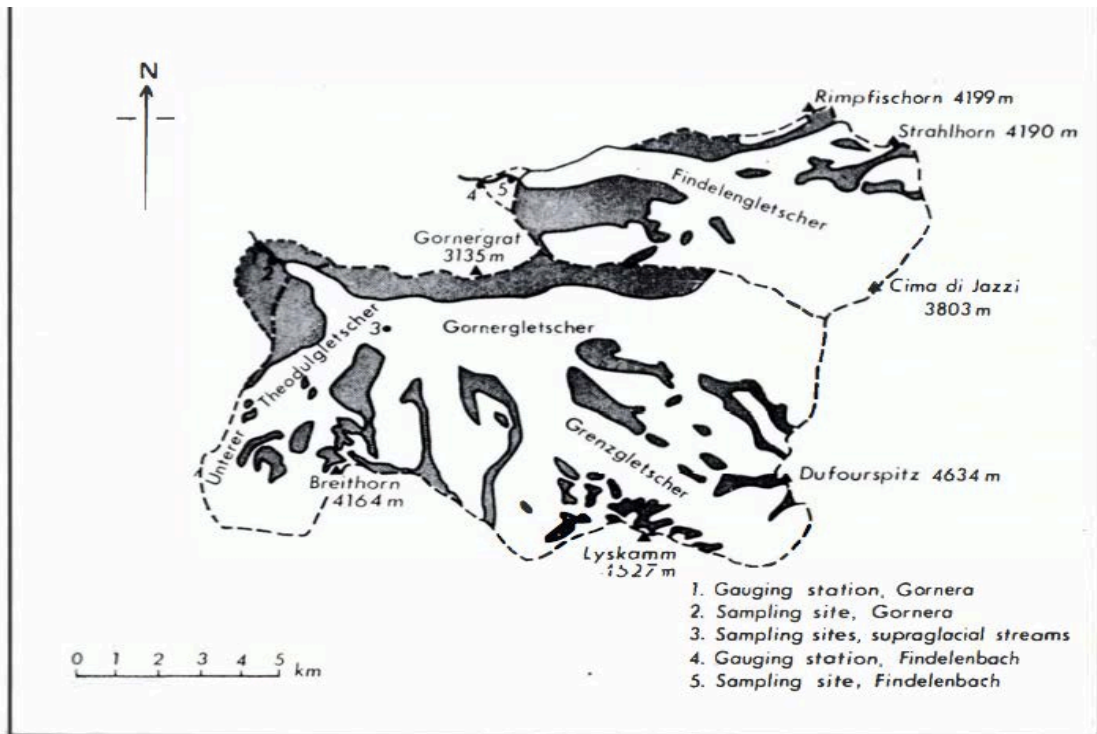


Figure 1. Map showing the catchments of Findelengletscher and Gornergletscher glaciers and the sites where the data were collected.
(Collins 1979)

1.2 Study Area

Zermatt, Switzerland, is a town that lies at the bottom of the Matterhorn, which is on the border of Switzerland and Italy; in the Swiss Alps. Zermatt and the surrounding glaciers are shown in Figure 1. Research in the area has been conducted over many years, which allows further in-depth studies to be taken within the area. Data which was collected over the years by researchers such as Collins (1979-2009), gives new researchers the chance to compare water temperature of Gornera and Findelenbach with new data found in the field and shows the fluctuations over a longer period of the study period. The more data available allows more accurate conclusions specifically when it comes to the variations in water temperature as comparisons lead to a better insight into differing factors driving the factors influencing water temperature. Findelengletscher and Gornergletscher are

adjacent meaning that they will respond to the same climatic condition, the patterns of variability of air temperature will be similar. The two glaciers that will be compared for the study will be Gorner and Findelen; the two differ in size and also the streams differ in depth and width. There are many contributing factors that influence stream temperature, with air temperature and stream size being the major factors. Stream temperatures are strongly correlated with climate (Morrill et al. 2005; Mohseni et al. 1999), and long-term data analysis has shown that stream temperatures have already increased as air temperatures have risen in recent decades (Hari et al. 2006).

1.3 Hypotheses

This thesis examines how stream characteristics and melt stream characteristics differ between two contrasting glacier with distance downstream from glacier termini and the influences of these variables on meltwater temperature. As the water moves downstream there is an increase in meltwater temperature and the rate of warming whilst travelling downstream.

1. Bigger glaciers add more meltwater in the stream making it colder in July and September. Meltwater temperature will be colder than that of a smaller glacier stream as there is a bigger volume of water to be heated.
2. The smaller the meltwater stream, the warmer the stream because less energy is required to warm the water.
3. Climate change in general leads to a major change in the temperature of the meltwater stream. The warming of the Earth has led to an overall rise in energy availability and minimum temperature in Gornera and Findelenbach.
4. Rising discharge over a monthly period does not necessarily lead to a decrease in minimum water temperature.

5. Daily weather variations have a major effect on the temperature and the warmer weather may not necessarily mean warmer meltwater.

1.4 Study period

The study period was conducted using data from 2007 as data was the most consistent and reliable collected. Comparing cool and warm daily periods, significant changes can be seen between the two periods and the difference climate change has made over the years looked at by other studies like Collins (1973-2009) and will be seen comparing other studies and literature that can be used to show the rises in air temperature and the difference between the warm and cold periods within selected months. The main body of work will be conducted over the months of August and September with some comparisons to early work to see the changes over a longer time period and highlight the changes in meltwater temperature. Studies of glacier meltwater temperature have been conducted over many years and the availability of literature will allow a comparison of datasets collected and the conclusions that are put forward. The conclusions that are put forward should be similar to the literature with more up to date data, due to consistent links with climatic change highlighting the changes in meltwater temperature. The data collected will be the verification that shows if the hypotheses are correct and will help to show recent trends in meltwater temperature that have not yet been looked into and further showing information on the subject area. The interesting part of the project is that a warm summer does not necessarily mean that the water will be warmer as there will be more water to heat up especially in the much larger glacier meltwater streams. Meltwater temperature variations between Findelengletscher and Gornergletscher will have consistent links with air temperature and will coincide with previous literature as rising air temperature is leading to increased melting.

2 Literature review

2.1 Energy Availability

Meltwater draining from the terminus of an Alpine glacier is heated as it flows across the proglacial area, and continues to warm with distance downstream. Available heat energy directly influences the warming of meltwater through solar radiation, the length of time over which energy exchanges occur, surface area of the stream and inversely on the volume of water to be heated. The distance between the glacier terminus and gauging station where the measurements are made determines the length of time available for heating to occur, and the velocity of the flow is also a determining factor. Higher volumes of meltwater increase velocity, which therefore reduces the time that the water is able to interact with the environment (Brown et al, 2006). As velocity of flow is discharge dependent, the larger the volume of flow, the more water there is to be heated and the shorter the time available. The more energy available for heating may not directly lead to warmer water as more energy creates more water, more water needs to be heated, but there is less time for heating to occur. Meltwater temperature is close to 1°C when released from the terminus and this creates an inverse relationship. When radiation levels are at their peak stream temperature remains low (Figure 2). As the glacier terminus recedes (percentage glacierisation), lengthening of the warming distance might increase the time in which heating occurs.

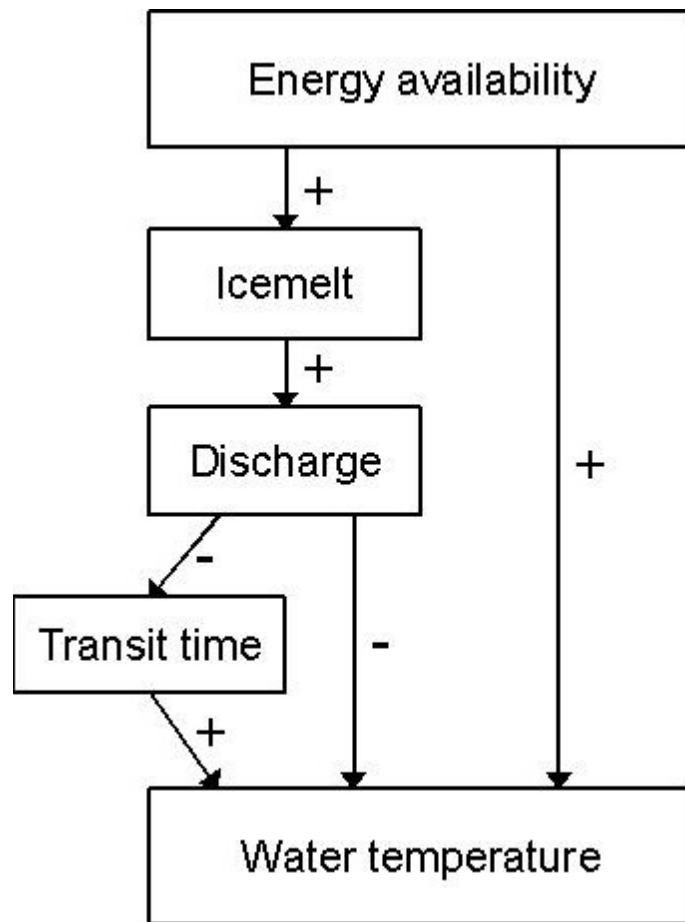


Figure 2. Schematic diagram showing the relationships between energy availability, glacier icemelt, discharge and water temperature in a river draining from an Alpine glacierised basin (Collins 2009)

Both Collins (2009) and Fellman et al (2013) selected streams draining basins with differing percentage glacierisation as the framework of experimental design for attempts to investigate temporal patterns of meltwater temperature over ablation seasons in rivers with various levels of discharge. Collins work is based in the Swiss Alps allowing extensive in-depth data to be analyzed within a relevant study area. Percentage glacierisation of basin forms a useful framework because it is a substitute or index measure of several of the variables involved. However, % cover of basin area by ice depends on the random location of gauging stations. A small glacier with a gauging/measurement station close to its terminus may have the same percentage glacierisation as a large glacier but with a gauging station a considerable distance away. The length of stream along

which heating can take place depends on the distance between measurement site and glacier terminus. Mean volume of meltwater flow depends on the area of ice available for energy exchange. Both of those variables are related to percentage glacierisation.

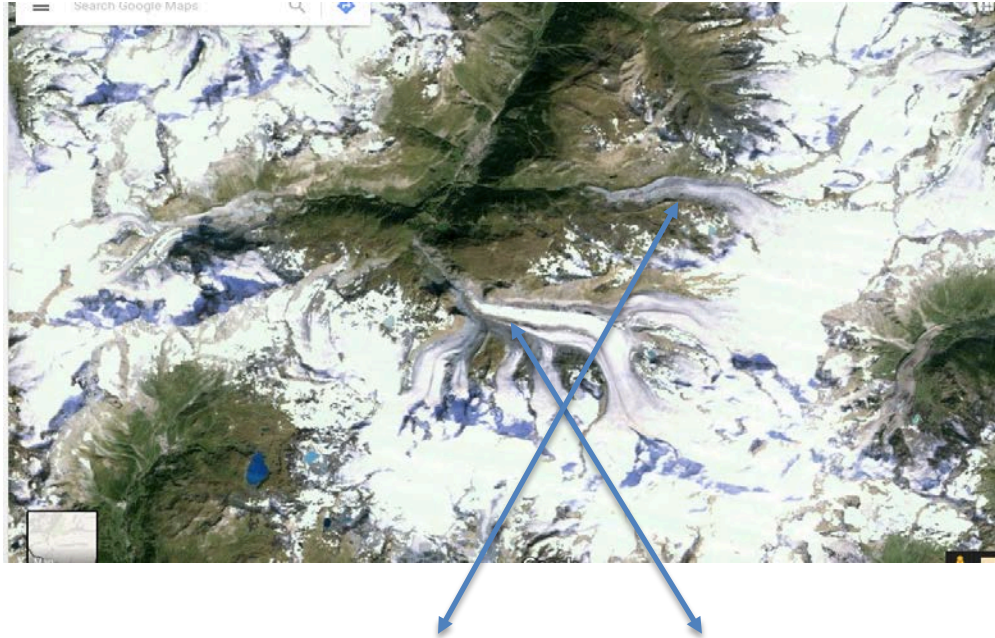


Figure 3. Study Area, Findelengletscher and Gornergletscher (Google Earth, 2014)

With the use of GIS glacier dimensions and recession can give a visual depiction on glacier size being put into place and highlight the hypothesis showing the glacier characteristics. Using data collected through the years by Collins and primary data collected in recent years the meltwater temperature can be used to show the effects weather changes are having on the glaciers. Climatic variations in high mountain areas are highlighted by the change of glaciers. They are sensitive indicators (Oerlemans 1994), and glacially fed streams are extremely sensitive to climate change. GIS will allow for greater analysis, showing the decline in percentage glacierisation throughout the study period and providing an extra dimension to the final results.

2.2 Determining factors

The determination of the importance of the glacierised area, distance of water travel and other defining factors influencing water temperature in meltwater streams is the aim to this project by seeing the relative importance between the two. An important issue is how basin size, glacierised area and meltstream length change with distance upstream from a measurement station, and hence how the balance between volume of flow and heating time varies with percentage glacierisation. Two glacier basins will be used near Zermatt Switzerland; Findelengletscher and Gornergletscher, both of which are situated near each other meaning air temperature will be the same but have different fluvial features giving an ideal comparison. Collins (2009) used other basins in the Alps with extensive temperature and discharge records allowing a wider range of investigation sites. Collins research showed that for different months throughout the year, for example March to May, water temperature warms in tandem with rising radiation. Increasing snowmelt runoff provides a greater volume of water to heat restraining the rise in water temperature. The rate of increase in water temperature is then enhanced as snowmelt wanes in June, reaching a maximum monthly mean of 10.2 °C in July in Switzerland (Collins 2007). Measurements will be recorded transitionally down the meltwater stream between the glacier terminus and the gauging station, which is supplemented through the introduction of mini loggers. Collins (2009) suggests that the characteristics of a glacial river water temperature only exist in large rivers close to the portals of the glaciers where the rivers drain.



Figure 4. Findelengletcher (Google Earth, 2014)

The impacts regarding water temperature can be compared between glaciers with different glacier size. Size of glacier indicates the impacts on water also the distance water travels to the gauging stations. Water temperature and glacier melt are highly seasonal. In spring lower discharges extend the transit times, small quantities of river water warm up in the increasing levels of radiation. In the summer the mass of water requires more energy to raise the temperature of the river, but there is a reduced transit time in which energy exchange can take place (Collins 2009). Seasonal impacts (warming) increase the melting and the more mass the glacier holds the more potential meltwater.

2.3 Glacier recession

Glacier recession is a factor in the increase of discharge with the added precipitation. The proof of glacier recession increasing discharge will be shown when glaciers ultimately disappear and flow will reduce. Precipitation will be the sole indicator of the discharge within the river system, with the amounts and variability defining the inputs to the river system. Runoff levels might be expected to increase before they indefinitely decrease (Barnett et al, 2005), but this may occur due to increased energy inputs, earlier disappearances of

reflective snow cover and exposure of lower albedo ice (Milner 2009). Within the future Moore et al (2009) theorise that as glaciers fall in mass and size the discharge will be lower leading to radiation and air temperature having a greater effect on warming and therefore, making the water temperature higher on average with falling discharge being the main contributing factor into water temperature rising as there is less meltwater to warm.

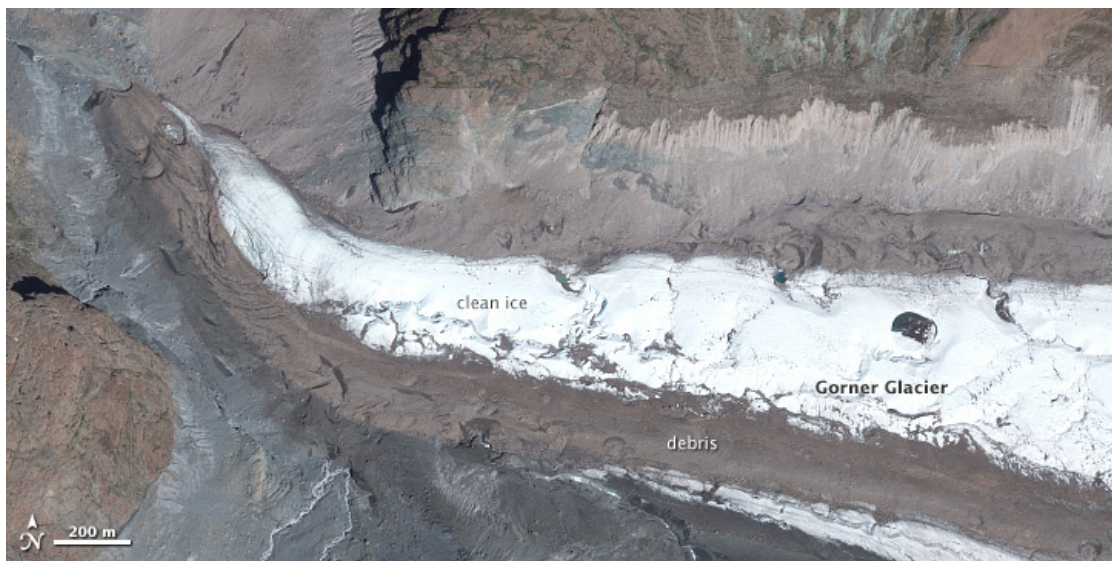


Figure 5. Gornergletscher (Google Earth, 2014)

The sooner and higher the transient snowline rises in the summer, the thicker the layer of ice melted, as larger area of ice is exposed to melt for longer; for example, warm summers and dry winters lead to a relatively low flow (Collins 2007) from the ice free area. Thermal energy influence over low glaciated areas is minimal compared to the contribution that it has on highly glacierized basins. In particular the ice created in the Swiss Alps throughout the Little Ice Age is declining rapidly as climatic fluctuations have led to a loss in mass and a reduced glacier size. Glaciers have a cooling effect on monthly mean temperatures in the summer months, (July – September) therefore there is a paradox in that when solar radiation and air temperature are high, stream water temperatures are often reduced. Mean monthly water temperatures are maintained at about the

same level in the summer months. With warmer summers the discharge levels will increase the melt; the added energy to the meltwater stream will be unable to warm because of the lack of available heat energy. Collins (1989), supports the theory by stating that in catchments with high percentage glacierization, discharge variation will reflect temporal variations in heat energy available for melt. As glacier recession occurs, a percentage of river flow in excess of that related to existing precipitation, a deglaciation discharge dividend is added to basin runoff from reduction of water stored as ice (Davenport 2013).

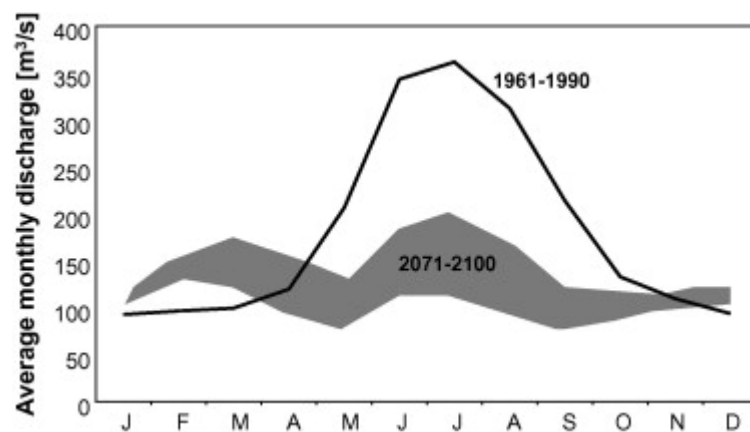


Figure 6. Changes in monthly discharge of the Rhone river close to its mouth in the Lake of Geneva, near Montreux, Switzerland, from current (1961–1990) to future (2071–2100, IPCC A2 emissions scenario). The gray shading gives the possible range of discharge, according to the timing and volume of snow-melt, estimates of glacier retreat, and shifts in seasonal precipitation. (Beniston, 2010)

2.4 Thermal energy

Glacierised environments are demonstrably one of the most vulnerable to climate change because of interconnections between atmospheric forcing, glacier mass-balance, stream flow, water quality and hydro geomorphology (physico-chemical habitat), and river ecology (McGregor et al., 1995; Smith et al., 2001). Brown et al (2007) states that the vulnerability of the area has

considerable effects on the stream temperature and the discharge because they are all so closely linked. Mohenski & Stefan (1999) argue that as discharge rises so does the stream temperature, which is not the case as the higher the discharge the more water has to be heated up on a diurnal period but over a monthly period amount of heat and radiation does increase the overall average of water temperature. When melt and discharge is at it highest in the day water temperature reduces but when the discharge is low in the day, (early morning and night) the extra energy from heat and radiation warms the smaller body of water but later acts as a driving force to cool the water adding more discharge to the system. There is therefore a paradox in that when solar radiation and air temperature are high, stream water temperatures are often reduced. Mean monthly water temperatures were maintained at about the same level between July and September, with the higher temperatures driving the meltwater temperature at low flow and then driving the melt to decrease the temperature therefore maintaining mean monthly water temperature.

Water temperatures in Alpine glacier fed streams will cool before warming as the deglaciation discharge dividend first increases runoff before subsequent decline (Bolton, 2013). Changing precipitation patterns and increasing air temperature since the Little Ice Age and especially the last century has led to the rate of glacier melt has been influenced. With increasing warmer weather melt of glaciers is much higher. Bolton (2013) highlights the predictability of runoff levels from glaciers as rises in air temperature link closely to water temperature, his study area has been intensely documented and researched over the last century. Swiss glaciers gained mass throughout the Little Ice Age but with increased warming throughout the last century have led to rapid decline with a loss in mass and a reduced glacier size as seen when at the data collection point, the valleys where the meltwater stream now runs through was evidently filled with ice in the past 100 years.

Glaciers are always trying to reach equilibrium with inputs and outputs, a constant in diurnal variations of glaciers. Temperature and albedo, at the

particular point in the day, lead to the amount of melt water that travels through the glacier. Transit from the production of the melt water at the top of the glacier usually takes about 12 hours to reach the portal that measures the discharge of glaciers. Glacial melt waters are not the only attribute of glaciers that are measured; the mass balance of glaciers is looked at especially at a time of climate change in the world. The mass balance of a glacier is defined as the difference between gains and losses measured over a specified time period, usually one year (Benn & Evans, 1998). The accumulation is the addition of snow and the ablation is the melting of ice while the overall mass balance is the accumulation minus the ablation. Glaciers are very complex and the processes that occur link in with each other, the mass balance of a glacier is its gains and losses and its losses that have been studied by most notably Collins. Current global warming shows that mass balance is negative and many glaciers are retreating at a fast rate, the climate is warm and dry which is why the glaciers are retreating as shown in Figure 9. The form of the daily hydrograph is influenced by the shape of the glacier, the area of bare ice exposed to melting and by the topology and dimensions of the drainage pathways making up the sub glacial hydrological network (Collins 1995).

2.5 Vulnerability

Climate change poses a considerable change to the water temperature of high latitude melt water streams (Brown et al, 2007); the effects are already beginning to show and global warming has had a major impact on areas such as Zermatt in Switzerland. With warming climate conditions, the glacier loses mass from ice melt, which in turn leads to a greater volume of glacier meltwater into the system. This means that at some point smaller glaciers will disappear during warmer periods including current climate in areas such as Switzerland (Sigurðsson & Williams, 2008 William & Ferrigno 2012). A number of contributing factors lead to the temperature fluctuating over annual, seasonal and diurnal time periods; the temperature is related to the changes in inputs and outputs into the stream, radiation and air temperature and also the size of the stream (Malard et al 2001).

The latter plays a big contribution since the larger the surface area and the lower the stream depth, allows radiation to penetrate down and warm the water. The opposite to this is a stream which is narrow and deep meaning the radiation and heat is unable to penetrate down and the water will not be as warm (Webb & Walling, 1993). Teti (2004) also supports with Webb & Walling and says that shallower streams are more sensitive to smaller changes within air temperature which lead to a increases or decreases in temperature depending on the time of year. Glacier mass is slowly decreasing and has been for the last century. Switzerland has been affected just like many others. Researchers study in this area because of the many glaciers in close proximity (Dyurgerov & Meier, 2000). The glaciers retreat means that water will be exposed to radiation for longer, meaning that the water could be getting warmer. The maximum water temperature for European glacier meltwater rivers is $<2^{\circ}\text{C}$ (Brown et al, 2007); the study of two contrasting glaciers with different contributions and affecting factors in adjacent area which is going to be the basis of a study, using other literature allows conclusions to be drawn when showing variations of water temperature in an Alpine meltwater stream from Findelengletscher and Gornergletscher.

2.6 Inputs and Outputs

The upstream temperature depends upon the geology, climate and discharges of the river (Mohseni & Stefan, 1999). The removal and addition of heat into the stream for both glaciers has a number of contributing factors for example evaporation, short and long wave radiation and reflection (Brown, 2005). The retreat of glaciers has lead to more exposure for longer for the water, and the patterns of glacial retreat will influence the timing and magnitude of the peak ice melt, duration and the amount of snow cover (Brown et al, 2005). The correlation between the climate change and water temperature are very strong (Mohseni et al, 1999), long term average of the area and stream temperature link together with a very small lag between them as it takes time for the river to warm. The

sensitivity of the areas is one of the reasons why Mohseni can very quickly and easily come to this conclusion because glacierised areas are one of the most vulnerable to climate change in every aspect and the correlations are easy to see (Smith et al, 2001). Studies show that temperature within Switzerland has increased by 0.57°C over the decade from the early 1900s (Hari 2006). If Mohseni is correct then the rise in water temperature should be around the same, especially if the river is wide and shallow. In Deas et al (2012) study of a cold water environment the average annual stream temperature warmed by approximately 1.6°C for each 2°C rise in average annual air temperatures, and varied from approximately 1.2–1.9°C over different elevations. Research links closely with Mohseni study by showing the rise of temperature followed by the rise of air temperature. The longevity of studies in this particular area help show the correlation between the two and can show the rise over decades instead of years, giving more accurate data leading to better data analysis (Webb & Nobilis 2007). Within a glacial system the sources of water contribute to the overall water temperature, which within a mountain region are precipitation, snowmelt and groundwater (Cassie, 2006). With receding glaciers it is thought that in the future air temperature will not influence temperature as much and precipitation will determine the temperature (Milner, 2009). Even though air temperature is the driving factor Milner shows that less water entering the system from melting will lead to precipitation inputs influencing the temperature downstream. Newer studies will have to be conducted to prove this in the future because of the ever changing climate and its influences on glaciers.

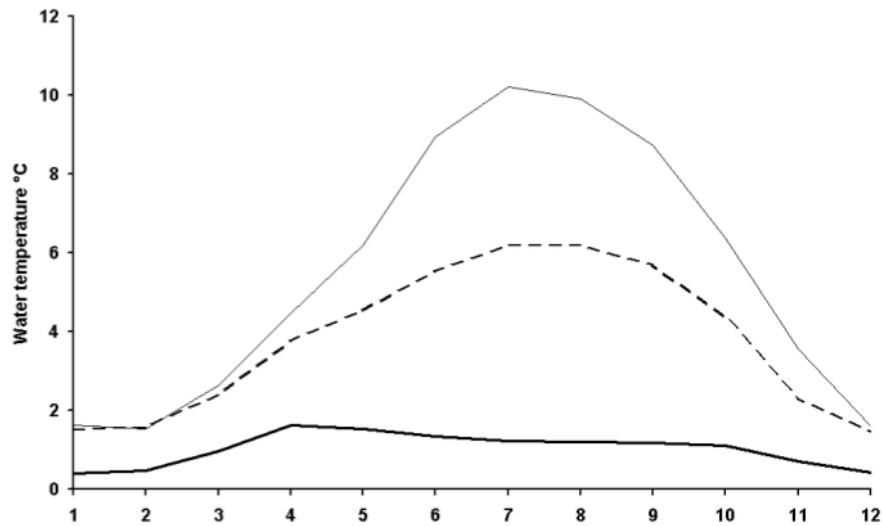


Figure 7. Mean monthly temperatures of Collins stream study in December (Collins, 2009)

2.7 Climate change

Seasonal change leads to increases and decreases in temperature, for example summer months where discharge is high because of the melting power and albedo effect. The assumption that the warmest summer months will mean that water will be at its warming is incorrect. As icemelt discharge increased, water temperature increases and mean monthly temperature is maintained at about the same level between July and September (Collins, 2009). The high discharge leads to the river rising slowly because with the higher discharge brings higher water temperature (on a monthly average) and therefore warming the water in the winter months of Collins study as flow is reduced and colder air temperature radiation is able to warm the low flow within the river system. It is thought that with air temperature rises that bring discharge rises means that water temperature will also increase while flow is low. Findelenbach is the shallower meltwater stream with a much higher temperature and the wide, shallow stream allows the water to be warmed. The ecological processes of the rivers are shown by understanding the processes

driving water temperature and the knowledge of the summer meltwater temperature, (June – September) is much greater than winter because of high snow and accessibility in such remote areas (Brown et al, 2007). Collecting data within winter months in remote environments where snowfall is high is difficult as accessibility is low due to safety, especially with the meltwater streams that are not as large and significant to the Swiss government. The stream flow over a yearly period is influenced by snowmelt in the spring, glacier melting in the summer and freezing conditions in autumn and winter (Malard et al, 2000). The very sensitive environment is influenced by different factors over a different seasonal period showing the instability of the area and meaning the most research is conducted when snowmelt and glacier melting is occurring. Within winter months the accessibility of the study area and reliability of results is much more difficult to collect because of sustained snowfall within the area.

2.8 Conclusion

Overall the warming of the earth has lead to the retreat in glaciers, with this comes the extension of the stream due to the retreat of the glacier. The stream is exposed to solar radiation between the glacier terminus and probes, resulting in higher temperatures (Richards, 2012). Figure 2 shows the inputs and outputs that lead to the temperature of the water, and different seasons and the cooling of the earth have an effect from the top of the schematic diagram to the bottom, which is the temperature. Field observations and analysis have shown that discharge or flow depth that significantly affected the river water temperature increase in discharge which caused a reduction in summer river temperature under given weather conditions (Gu 1998). The temperature of a glacier fed stream varies depending on a number of different factors, the comparison of two glaciers within the given area, with different size streams allow the comparisons to be made and accurate results and conclusion could be made. Many factors influence meltwater temperature, through the warm year

radiation was high in Switzerland and with high temperatures discharge were increasingly higher than previous years. Research shows that as discharge rises meltwater is cooler and the driving force of air temperature is factor that is measured can be statistically compared knowing its impacts on meltwater temperature. Observational views when research was conducted allows data to be put along side the characteristics of the meltwater stream including depth and width.

3 Methods

3.1 Aims

The objectives of this project are as follow

1. To analyze the relative temperature difference between two contrasting glacier meltwater streams.
2. To assess the heating patterns as meltwater flows across the proglacial area.
3. To determine whether meltwater continues to warm with distance travelled downstream.
4. To link heat energy from solar radiation to the warming and the effect it has on differing meltwater streams surface areas.
5. To demonstrate that the length of time it takes water to travel downstream, is inversely related to the volume of water that can be heated.
6. To evaluate the influence of key variables on stream temperature in two Alpine glacier systems.

Once all the aims are investigated and the development of meltwater temperature through time travelling downstream is determined the comparison between the two differing streams can be linked and show the relationship between stream characteristics, catchment size and melt water temperature. The process of examining the aims was undertaken by using secondary data via David Collins and primary data collected by researcher on individual visits through recent years. Differing air temperatures in certain years can show the relationship between air temperature and meltwater temperature.

3.2 Data Collection

To conduct the methods comparing relative difference in water between two contrasting glacier meltwater streams has to be shown through recording data in the field and transferred into excel to be critically analyzed. The methods undertaken in the field allowed the temperature and discharge to be taken hourly from Findelengletcher and Gornergletcher. Many studies use hourly data to conduct their experiments leading to more accurate results in this area of study because diurnal patterns show the changes to glaciers over a daily period (Brown et al, 2006). The data sets are collected by different mechanisms; Gornera has much more interest from the Swiss Government, as the discharge is much higher and the energy created from the meltwater counts for making over 50% of Swiss electricity. Data from Gornera is collected at the gauging station and the data is taken in raw forms from Grand Dixence, S.A., the servicing of gauging stations and maintaining reliable data due to shifting channel cross sections, restricted access and adverse water (Brown, 2006). The data collection period was small as the selected months had the most recorded data and the data collected needed to be consistent to show the contrast between the two glaciers. Gornera is different to Findelenbach because its doesn't fully take its natural course as the channel is funneled in to the gauging stations and the water is kept within the built up walls of the funnel, funneling means that the water is deeper due to the more compact area and there are no channel variation shifts. The servicing is kept up to date also because of the major use of water for electricity. The data from Findelenbach is collected by a Minisonde and the discharge is measured in $\text{m}^3 \text{ s}^{-1}$. The Minisonde is set up in the same position every year meaning that from month to month the data can be kept as accurate as possible when comparing years. The University of Salford collects the data at Findelenbach and then data is then used by the students instead of retrieving the data from the Swiss Government for use. The data for Findelenbach is easier to collect because of its accessibility straight from the University.

When conducting the research the expected and predicted allowed for hypothesis to be created and from the data (the observed) can be collected and manipulated. Once the data is collected in its raw form the data is put into graphs to allow easier interpretation and a visual depiction of numbers allowing statistical analysis.

3.3 Measurements

The water temperature and discharge were collected to show the characteristics between the two glaciers meltwater streams and the rises and falls showing how the variations in water temperature differ between the two adjacent glaciers. The two glaciers differ in size and are in the same climatic region, which also makes them good comparison glaciers. The heat transfers within a river system is very complex with radiation and other contributing factors, (Hondzo & Stefan 1994 & Silliman et al, 1995), but putting the glaciers in the same climatic region allows the data to not be influenced by different climate conditions. The data for both temperature and discharge from both sites was measured to an appropriate level of accuracy to be compared, backed up by the fact that the Swiss government use it for data. To overcome the unreadable data especially in 2007 at Gornera where the data was not read (e.g. outliers, where results are extreme compared to others and could not be correct) or there were some results were clearly incorrect; “gardening” is used when the data is in its raw form and is left out of the graphs, the data is deleted before manipulation. Data may not be collected as minisondes run on batteries which may run out, snow and water level change can lead to the data not being readable, for example if the water level drops below the data logger the temperature cannot be recorded. The unreadable data is estimated to be similar to the other data collected; where there are small sections of unreadable data the graphs made are not affected and are irrelevant because it is only a small number of results.

3.4 Geographical Information Systems

Using ArcMap and with the use of a digital terrain model allows images to be overlaid from the Randolph Glacier Inventory, (a global inventory of glacier outlines) from ArcMap manipulation of the data creates contour lines and slope angles using the 3d analyst and spatial analyst giving a visual of the glacier size and area and catchment size influencing water temperature. Downloading the DTEM (Digital Elevation Terrain Models) from Earth Explorer was the most efficient and effective way for the task at hand. With these simple steps the original digital terrain model layers can be extracted and used to show the data withheld within individual layers.

The first step allows the data to be manipulated in the correct format

1. Tools- Extensions- 3D Analyst and Spatial Analyst.

Further research showed that the image downloaded was only part of the image needed, adding another map was needed for sufficient research to take place. As the study consists of the comparison of two glaciers, the new map incorporated both glaciers within the same image. Going back to Earth Explorer and adding the correct coordinates the additional images were downloaded. Simply adding both images into ArcMap put them side by side and correctly created the necessary basic starter image. Creating a clearer image is the next step, this will highlight the ice area clearly using the mosaic view.

2. Toolbox- Raster- Raster Datasets- Mosaic to new

The third Step allows the toolbars to appear to create the contour lines

3. View- Toolbars- 3D and Spatial Analyst

Once the 3 steps have taken place then you are able to use the click down box to add the contour lines

4. 3D Analyst- Surface Analysis-Contour

To convert the data into raster from the original map is useful because it shows elevation bands through colour making the image much clearer. Ice can be seen and the elevation decrease is clear to see, also the route of the glacier fed stream and runoff can be seen from the conversion.

5. Spatial Analyst-Convert-Features to Raster

Raster data is ideal for mathematical modeling and quantitative analysis, with raster data the percentage glacierisation is easier to see and exposes different colours of different layers.

7. Spatial Analyst-Hydrology-Fill Tool

Creating a watershed layer gives a contrasting highlighted area, showing the different sizes of the comparison glaciers. The data downloaded from Earth Explorer doesn't clearly indicate the areas of interest, by using the following steps the glaciated area is easily seen.

8. Input Layer/Output Layer : Flow Direction : Accumulation

9. Spatial Analyst- Raster Calculator- Flow > 5000

10. Arc Catalogue- Shapefile- Snap pour point

Once these steps have taken place the coordinates of the data collection point must be placed on the map, simply by hovering over the area on Google Maps and adding them to Arc Map.

11. Start Editor- add coordinates into editor- Click target

12. Watershed Tool- Input: Flow direction

: Pourpoint

-Output: Watershed

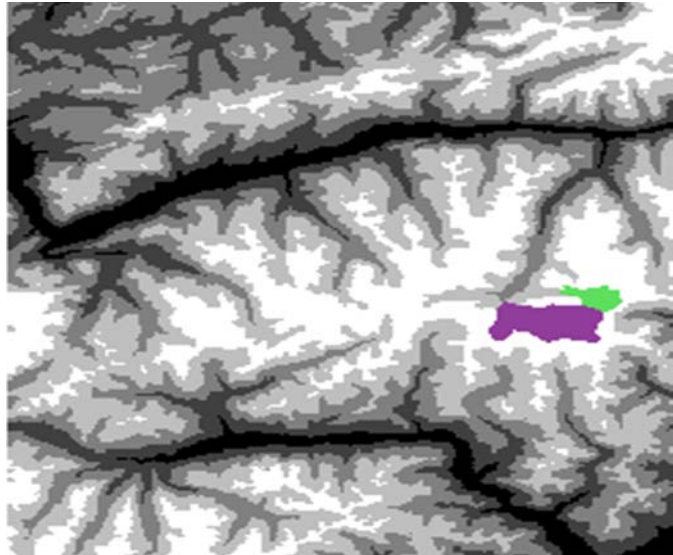


Figure 8. Digital Elevation model with highlighted watershed areas for the two areas of study. Gornergletscher (Purple) & Findelengletscher (Green). (Earth Explorer 2015 & Arc Map, 2015)

From the image created via ArcMap the two contrasting glacier catchments are easy to see, Gornergletscher is the dominating glacier. With a greater catchment area the more meltwater collected is much higher leading to the cooler temperature of the Gornera. Findelengletscher has a much smaller catchment area leading to the smaller discharges coming from the glacier and the surrounding area. From the image generated it is clear to see why discharges are much higher and the glacier catchment size is much higher in Gornera compared to Findelenbach as the area is bigger more meltwater is drawn into the system. Further in-depth research can highlight glacier snout recession like shown in Figure 9. Recession year to year and the short time between 2005 and 2010 highlights the impacts of global warming on glacial systems with a clear decline in glacier length and width.

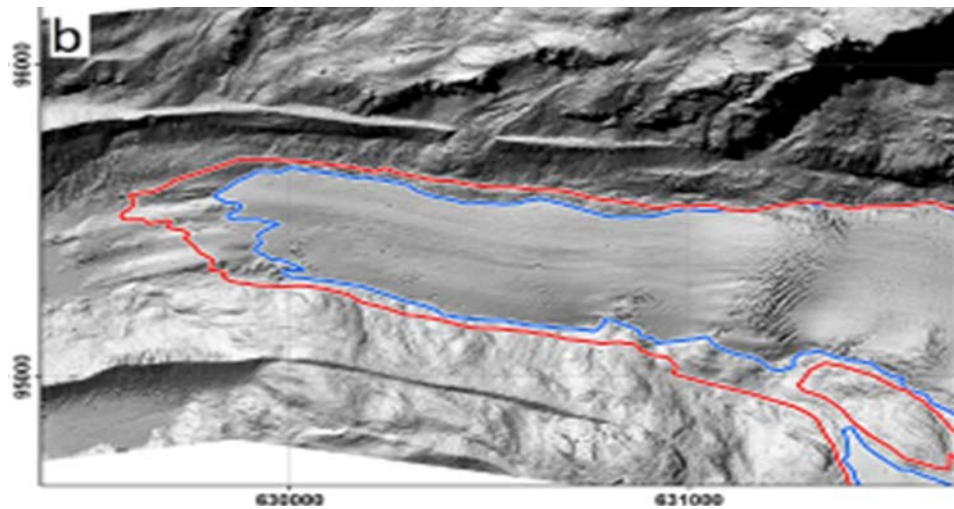


Figure 9. Decrease in glacier length and width between 2005 Findelengletscher (Red) and 2010 (Blue) (Joerg & Zemp, 2014)

Geographical information systems provide a visual depiction of the area where the study was undertaken, the assessing of changes in glaciers area, thickness, and volume have a long tradition in glaciology with high quality topographic mapping reaching back to the late nineteenth century (Finsterwalder 1987; Mercanton, 1916). The red band in figure 9 shows the glacier tongue of Findelengletscher in 2005 and the blue in 2010 increased global warming has led to a retreat over around 200m over the 5-year period. Percentage glacierisation of specific areas can be highlighted to show the extent of ice within areas of interest, Figure 10 show the area of Findelengletcher.

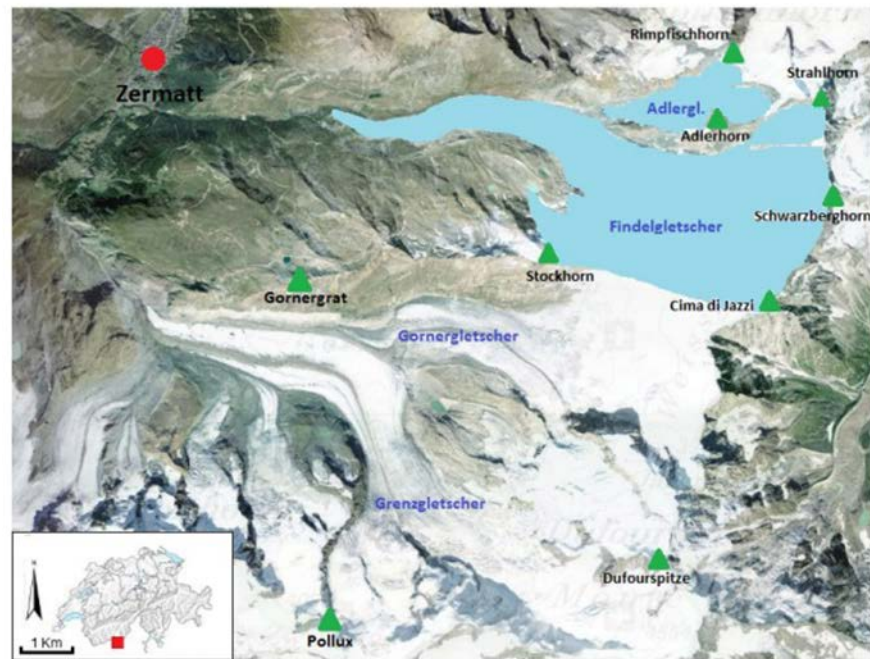


Figure 10 Highlighted Glacier boundaries Findelengletscher (Arrigo, 2012)

4. Results

Graphs give a visual depiction presenting the data collected through a series of scatter and hysteresis loops which can be analyzed. Comparing individual days against each other gives an insight of daily variations between the two glacier meltwater streams shows how each react to warmer and cooler days. Also comparing meltwater temperature and discharges throughout the monthly periods showing the overall flux between the two. Differing sizes between the glaciers will be the factor that temperature will be compared against along with the other influential factors. Figure 10 shows the contrasting sizes in watersheds, Gornera has a much bigger catchment, which will lead to bigger discharges. Findelenbach's catchment area around 3 times smaller than Gorner, which could lead to the assumption that the discharge is 3 times bigger leading to much cooler meltwater temperature than Findelenbach.

4.1 Monthly trends

Figure 11 shows discharge is very constant with a fall off at the end of the month with air temperature (Deci Julian day 270) falling below freezing the likelihood of snow is very high on the glacier. With the snow on the glacier, the reduced runoff and air temperature lead to less water getting into the system and therefore decreasing discharge. As the reflectivity of snow is 80% meaning that only a small portion is melted. As the water discharge is decreased radiation and air temperature increases the meltwater table, which is shown in the latter half of the graph. The time of year where discharge is limited allows for higher stream temperatures, unlike the perceptions that warmer weather in summer month's means meltwater temperature is higher.

As the Swiss Government uses meltwater from Gornera for electricity results are much more reliable and closely monitored leading to a consistent set of results compared to Findelenbach, this is shown by the results in Figure 12 compared to

Figure 11. The data collected at Findelenbach is measured by the minisonde where Gornera is measured at a much bigger gauging station. Although results from Gornera are much more accurate throughout the years the data collected by the minisonde at Findelenbach is valuable as the comparison between the two is key to showing the differing water temperature between two glacier meltwater streams. Discharge follows air temperature with a small lag as expected; as the meltwater travels downstream the lag will be after the warmest part of the day. Deci Julian day 235, discharge is at its lowest also resulting in water temperature being at its highest around that time period. Air temperature falls below freezing at the start of the graph, meaning the likelihood of snow is high, with snow on the ground data collection stalled and no temperature was recorded. Rises in discharge after the low air temperature could be a result of increased runoff of meltwater via the albedo effect. The albedo effect is the amount of the sun's energy that is reflected back into space.

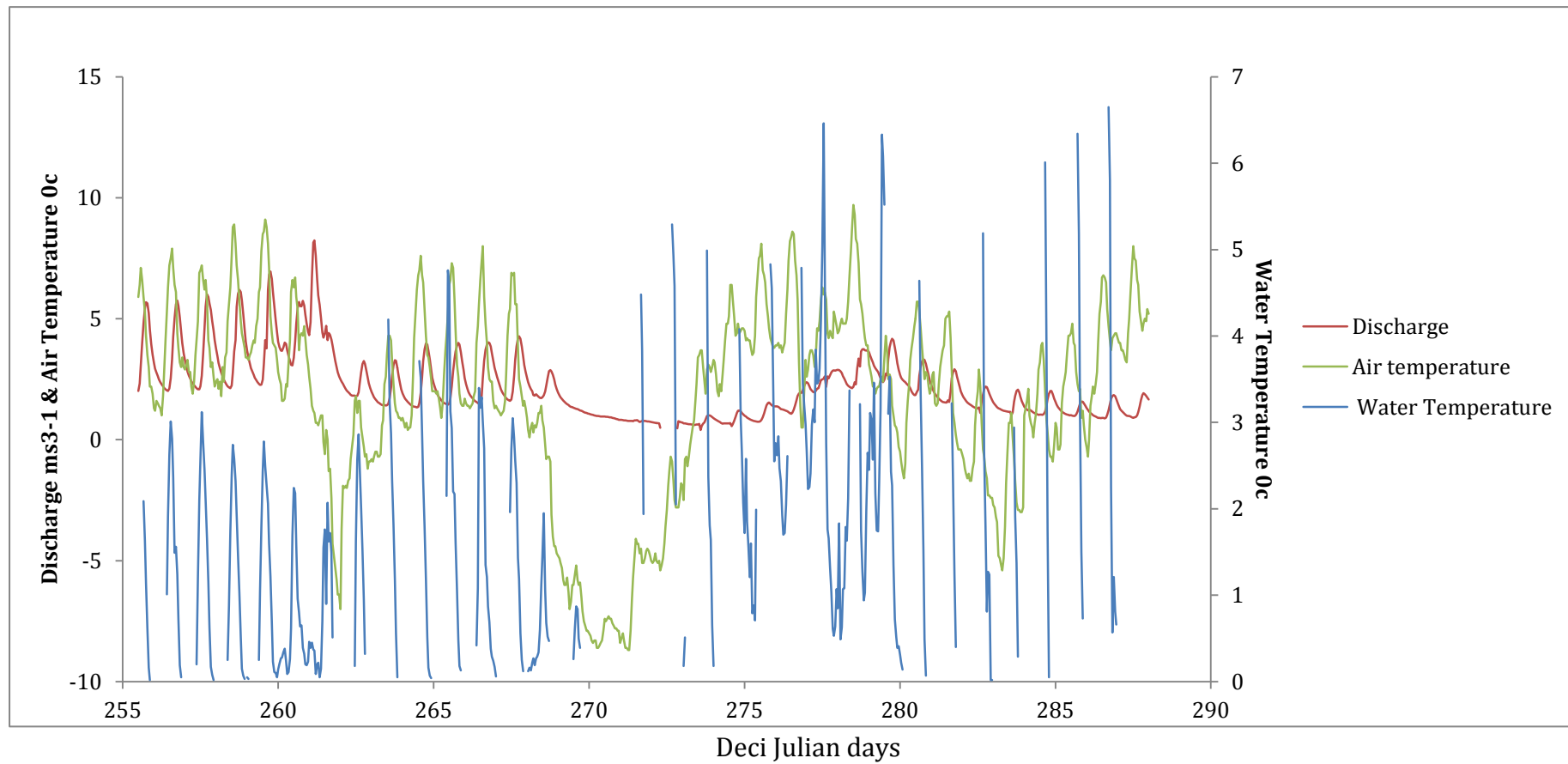
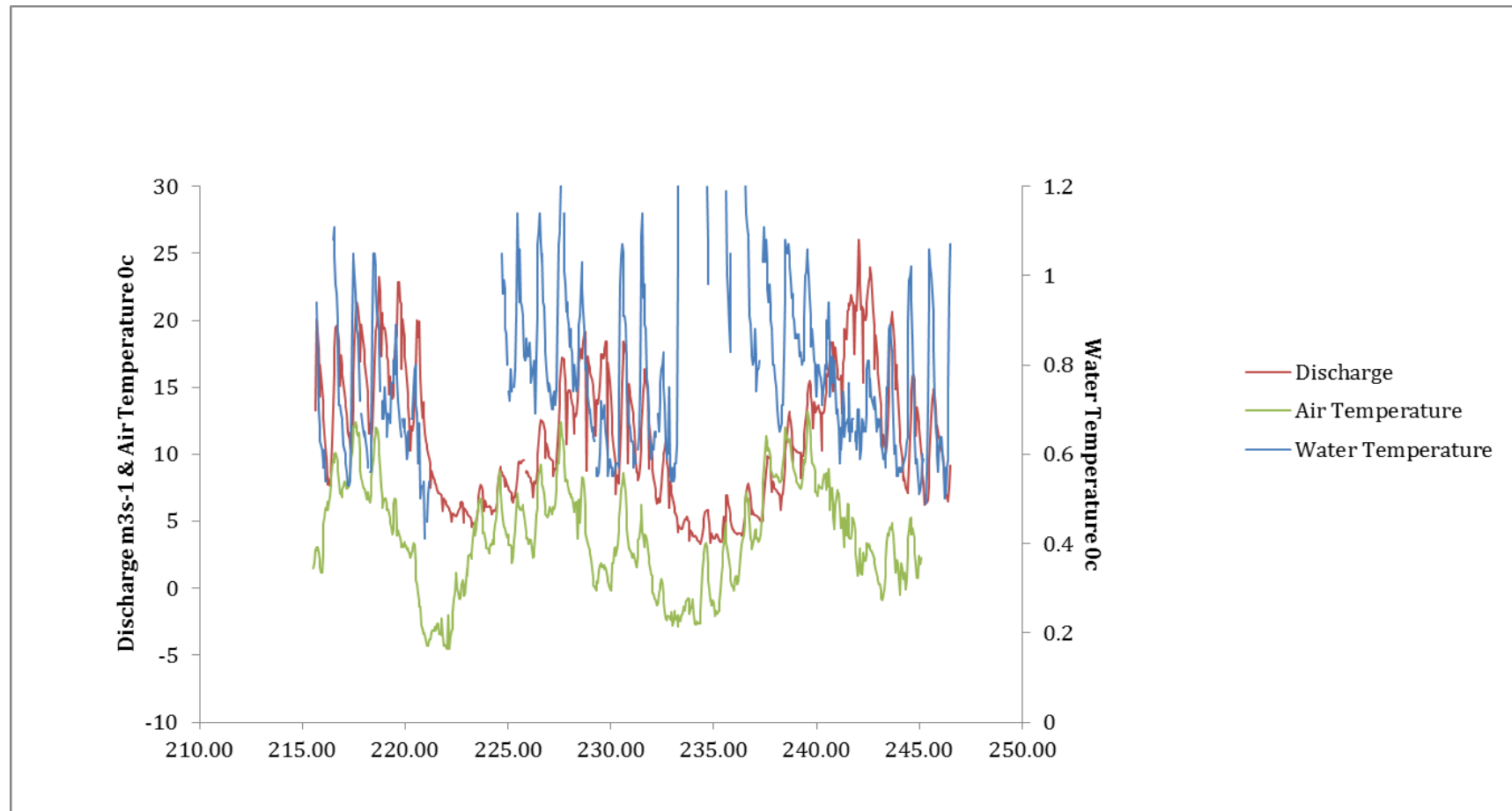


Figure 11. Findelenbach 12/9/07, 12:00:00 to 15/10/07, 00:00:00



Deci Julian Days
Figure 12. Gornera 03/08/07, 13:00:01 to 03/09/07, 12:01:00

Water temperature rises up with the air temperature. In figure 13 water and air temperature starting from a temperature of 7°C, with the drop in temperature as the peak has already occurred in the day as only half a days results were recorded. Air temperature rises with warming water, Gornera short transit time means meltwater doesn't have time to warm, radiation is minimal at particular times in the day as steep valley sides restrict direct sunlight. Snow and ice melt created by increasing radiation leads to increasing discharges, these higher discharges are lagged because of transit time through the glacier. As seen in figure 14 the discharge doesn't take long to reach its peak discharge because of the short transit time to the gauging station. The highest discharge of $9\text{m}^3\text{s}^{-1}$ means water is unable to be heated because discharge is so high. The peak temperature of 1°C in figure 13, proves the higher the discharge over a diurnal day the lower the temperature. The comparison graph (Figure 14) for Findelengletscher peaks at 2.84°C because it is susceptible to more warming due profile of the Findelbach. The discharge is clearly much lower in the Findelbach because of glacier size; Figures 13 & 14 show clear differences in meltwater temperature and discharges from the two different size glaciers and in turn different volume streams. As stated above the temperature in this specific case is around three times bigger in the smaller stream of the Findelbach.

4.2 Individual diurnal days and hysteresis loops

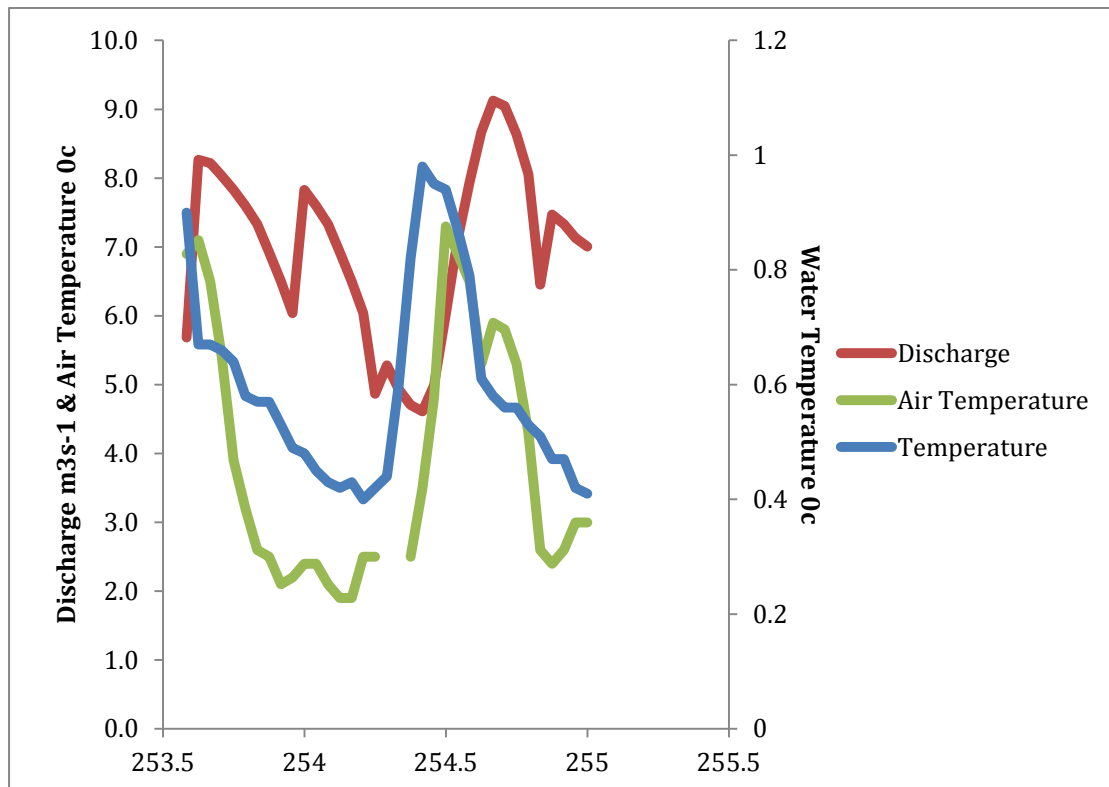


Figure 13. Gornera 10/9/07, 14:00:00 to 12/9/07, 2:00:00

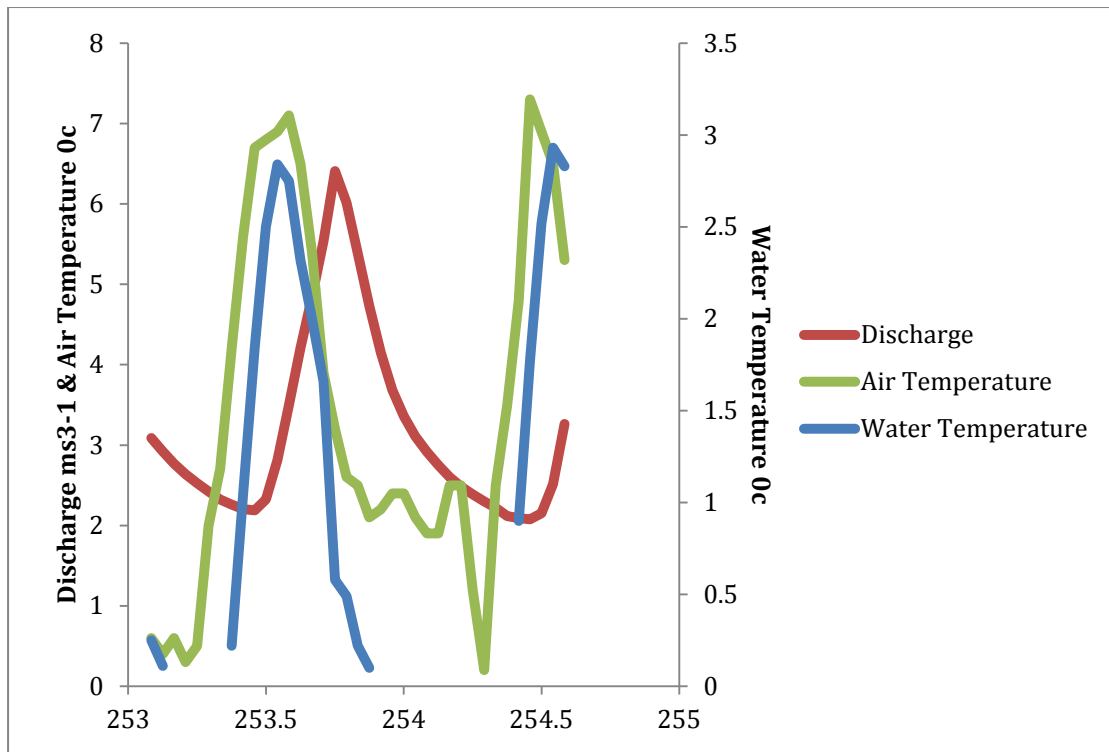


Figure 14. Findelenbach 10/9/07, 14:00:00 to 11/9/07 14:00:00 , comparison to the small section of readable data from Gornera.

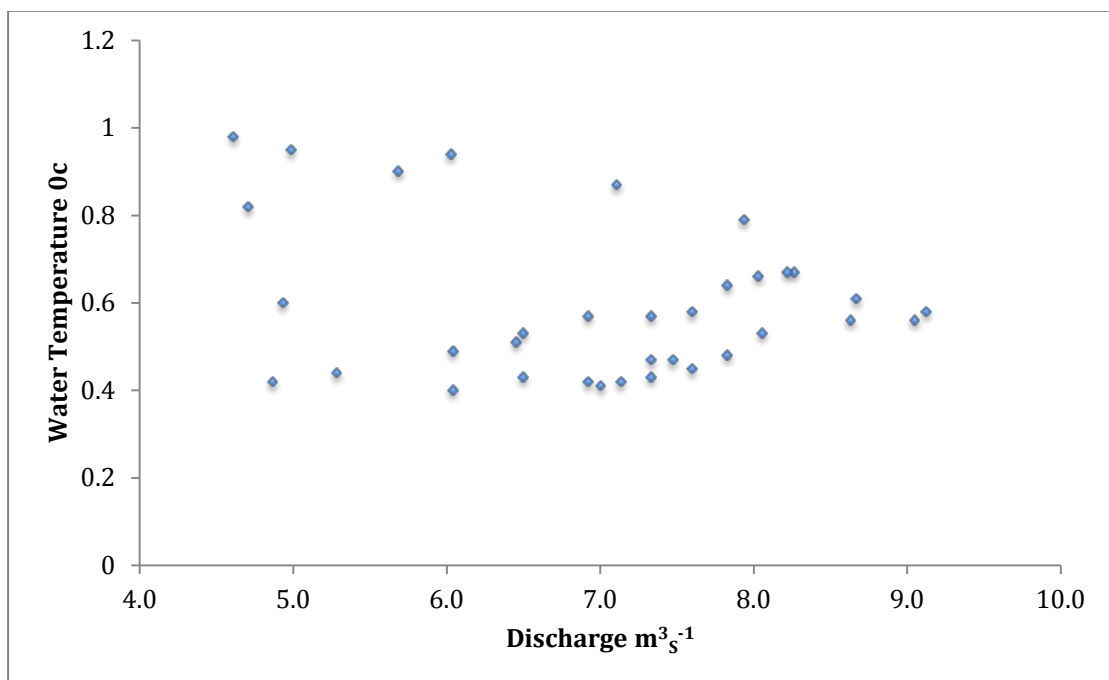


Figure 15. Discharge in relation to Water Temperature, Gornera 10/9/07, 14:00:00 to 12/9/07, 2:00:00.

Small rises in minimum temperature as discharge rises are shown in both Figures 15 & 16 with the highest temperatures being at the lowest discharges. The small rise in minimum temperature with discharge throughout the monthly period shows that when air temperature increases it leads to higher discharge, the extra heat and radiation has a small effect on the water temperature. With the lowest discharges comes the highest water temperatures and the triangle shape that is created shows the decline of maximum meltwater temperatures as the meltwater rises. Figure 16 shows a much steeper decline showing that Findelenbach is much more susceptible to change from outside influences. Gornera's slower decline highlights bigger discharges not being influenced as quickly by factors such as radiation due to the larger glacier meltwater stream. Higher discharges in the Findelenbach stream are most likely to be the result of heavy rainfall in the area, impacting both meltwater streams. Differences in meltwater temperatures are clear to see from Figures 15 and 16 which the latter showing much warmer meltwater over a consistent period. Minimum discharges in Gornera are bigger than average discharge in the Findelenbach emphasizing the difference in stream size and capacity.

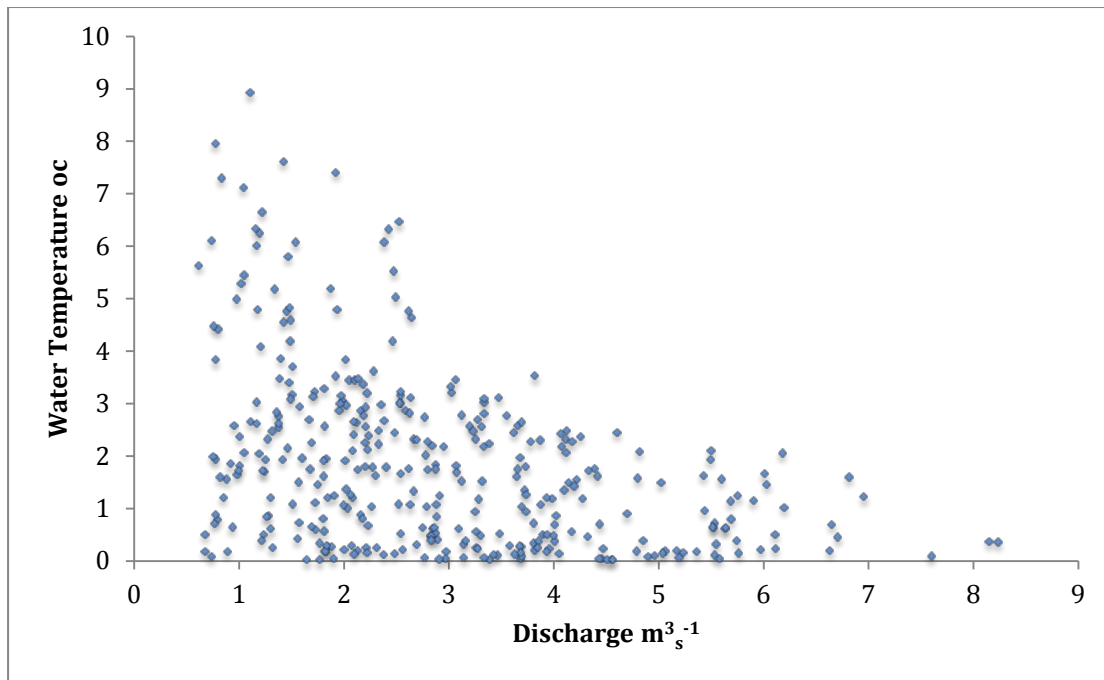


Figure 16. Discharge in relation to water temperature, Findelenbach
12/9/07, 12:00:00 to 15/10/07, 00:00:00

The hysteresis loops in figure 17 show the critical timing when the discharge reaches its maximum and where the graphs curve over to lead to more discharge like a diluting effect. Hysteresis loops move in a clockwise movement as the temperature rises and discharge follows after the lag. As temperature rises and while discharge is at its lowest the critical point builds so when discharge peaks and temperature starts to fall at Findelenbach in figure 18, this is when discharge reaches $3 \text{ m}^3\text{s}^{-1}$ meltwater temperature falls to create the loop. Leading to a temperature decrease and the flag shape that the loop makes shows the diurnal critical points. Findelenbach has a much smoother loop. Gornera has a much higher discharge and the rises in temperature are much less. The more abrupt fall in Gornera compared to Findelenbach displays the larger discharge having a much greater effect on the water temperature.

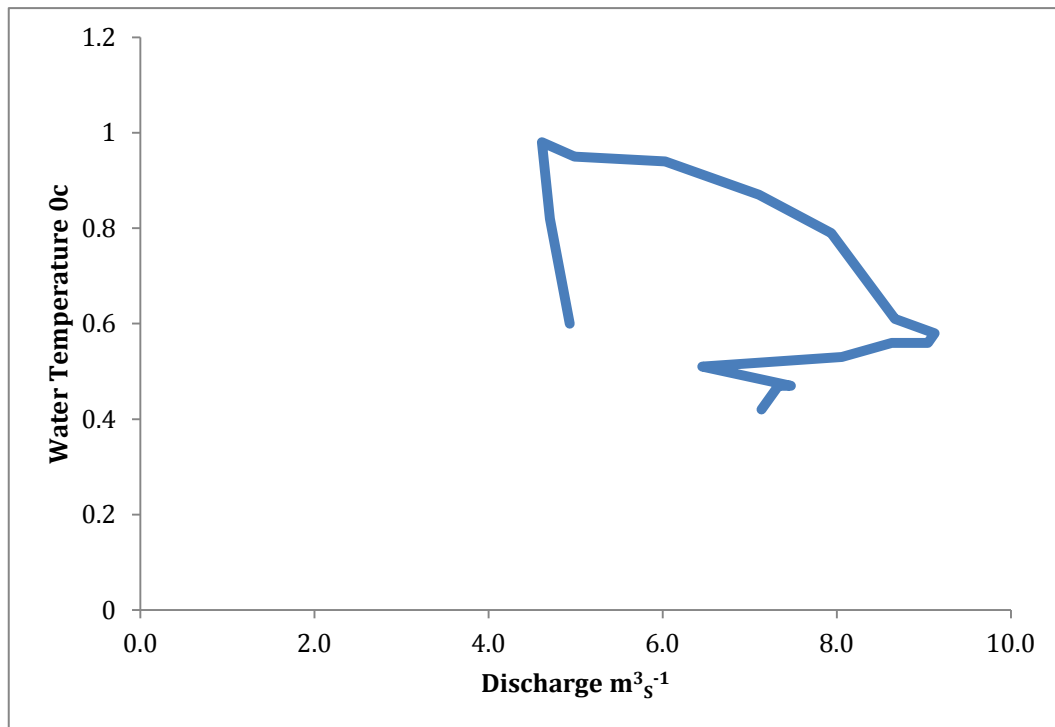


Figure 17. Gornera. Hysteresis loop showing the critical points in rises and falls within the day 11/9/07

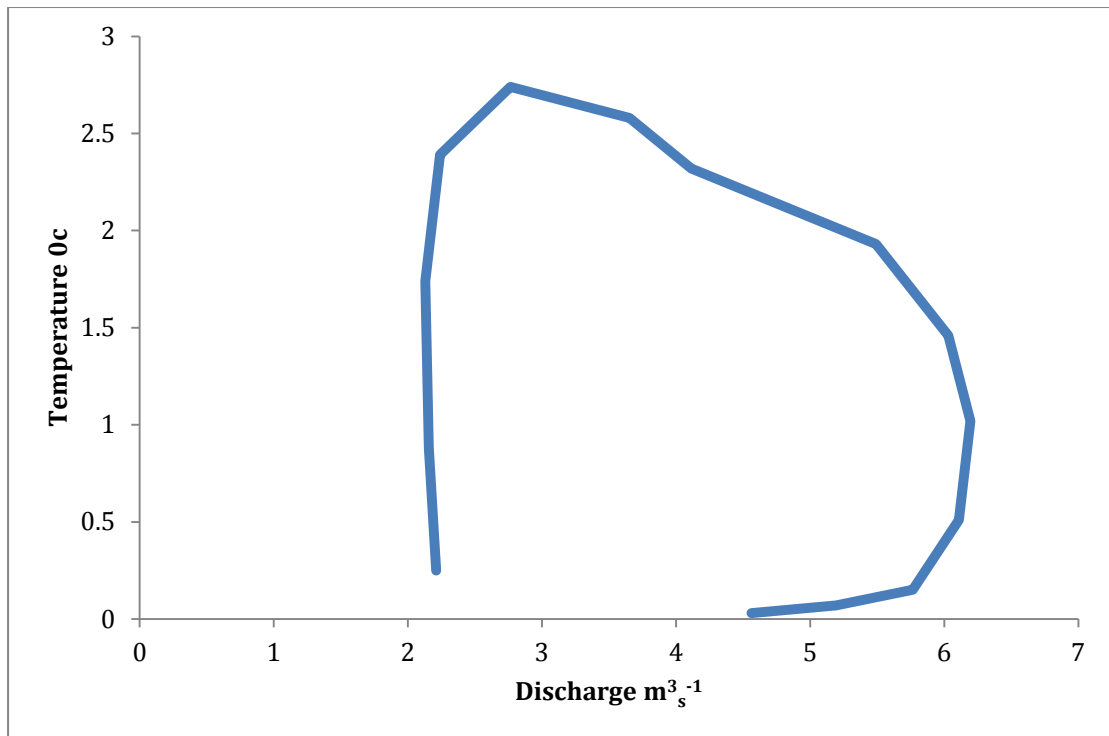


Figure 18. Findelenbach, 15/9/07

Warm days are reflected by meltwater temperature and discharge; water temperature follows air temperature closely in Figure 19. Discharge peaks late afternoon as there is a lag between the air temperature melting and the water passing through the system and to the gauging station or minisonde.

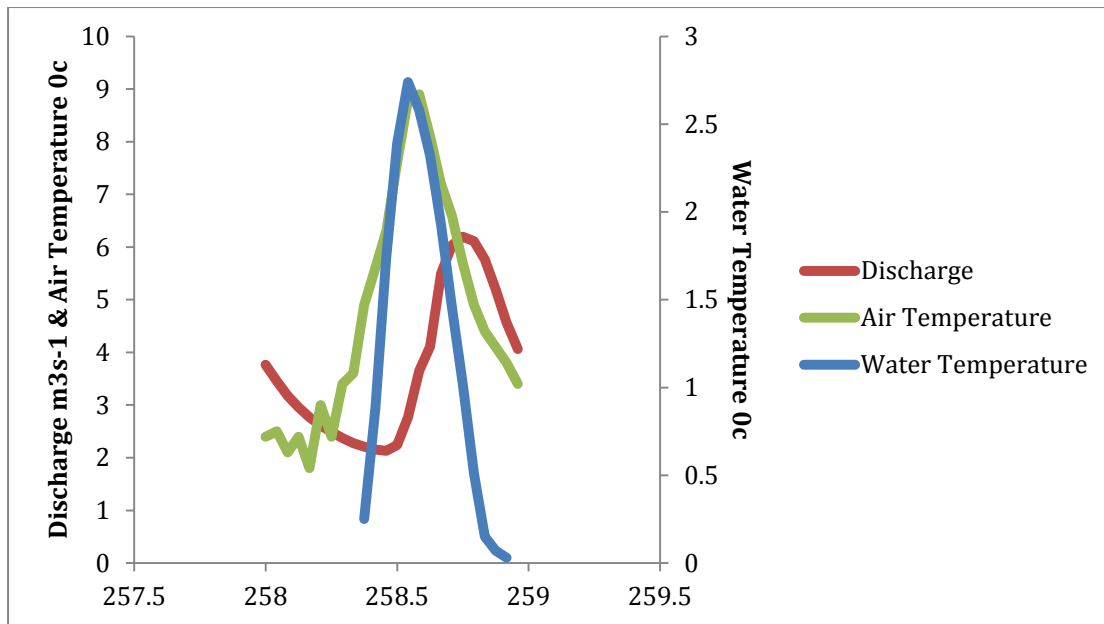


Figure 19. Gornera daily rises and falls in Discharge, Air and Water Temperature on a Warm Day 15/9/07.

Rising air temperature leads to more radiation and more heating power. Extreme cold temperatures shown in Figure 20 and 21 lead to a period of snowfall with temperature falling throughout the day. Discharge is high because of melting and direct snowfall entering into the system, snowfall won't have fully settled and become fully reflective at this point. In the upcoming days the reflective impact snow has will restrict discharge.

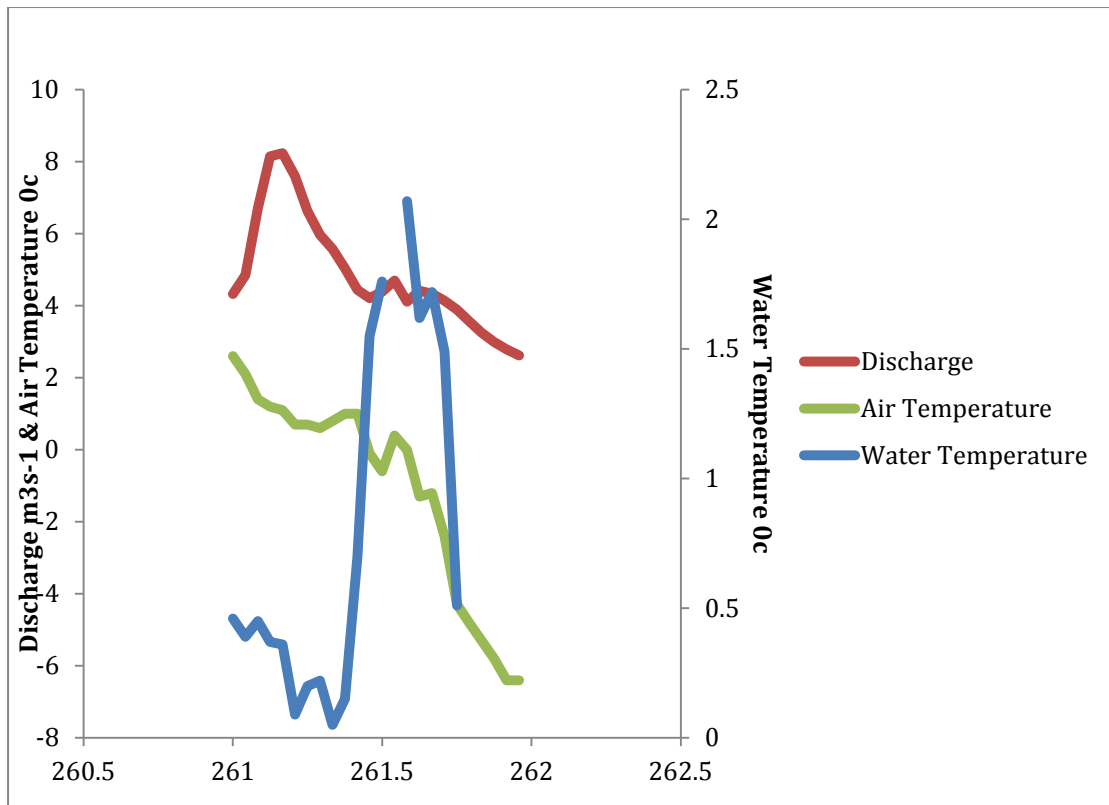


Figure 20. Findelenbach . daily rises and falls in Discharge, Air and Water Temperature on a cold day 18/9/07.

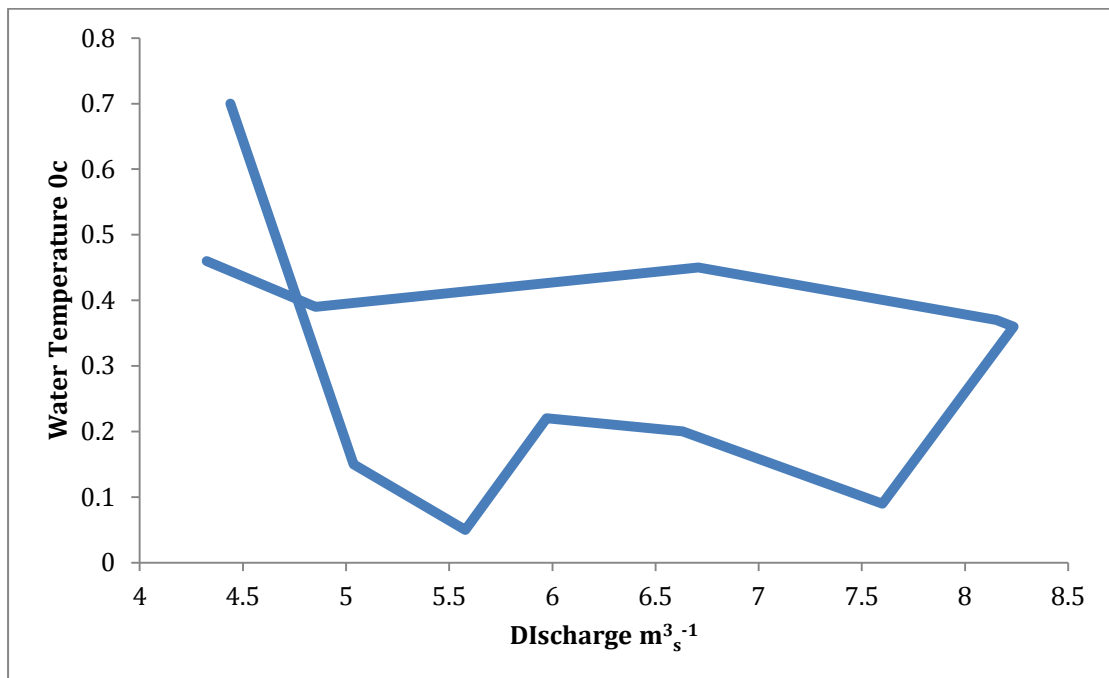


Figure 21. Cool day of 18/9/07 at Findelenbach.

Figure 22 shows that the values of results are positive, with a small rise in minimum water temperature when discharge is between 2 and 9 m³s⁻¹. As first thought higher discharges would cancel out the warmer weather used to create such discharge but Figure 22 shows that with higher discharges there is a small rise in minimum water temperature. Higher readings are when discharge is at its lowest leading to less water to warm and more time to heat less water, still all the power of heating but much less water. Extreme high discharges won't allow warmer meltwater temperature as seen from the gathering of results near the bottom of the graph, outlying results are less frequent as discharge increases which is shown by the triangular shape of the graph. In comparison Figure 23 is a very clustered set of results with not many gaps in the centre, with much more clustered together than September, with slightly higher temperatures and lower discharge compared to September. There is a clear cut off point for temperature and the lowest results are very close together and only a couple of results fall below the average minimum temperature.

4.3 Relationship between discharge and temperature

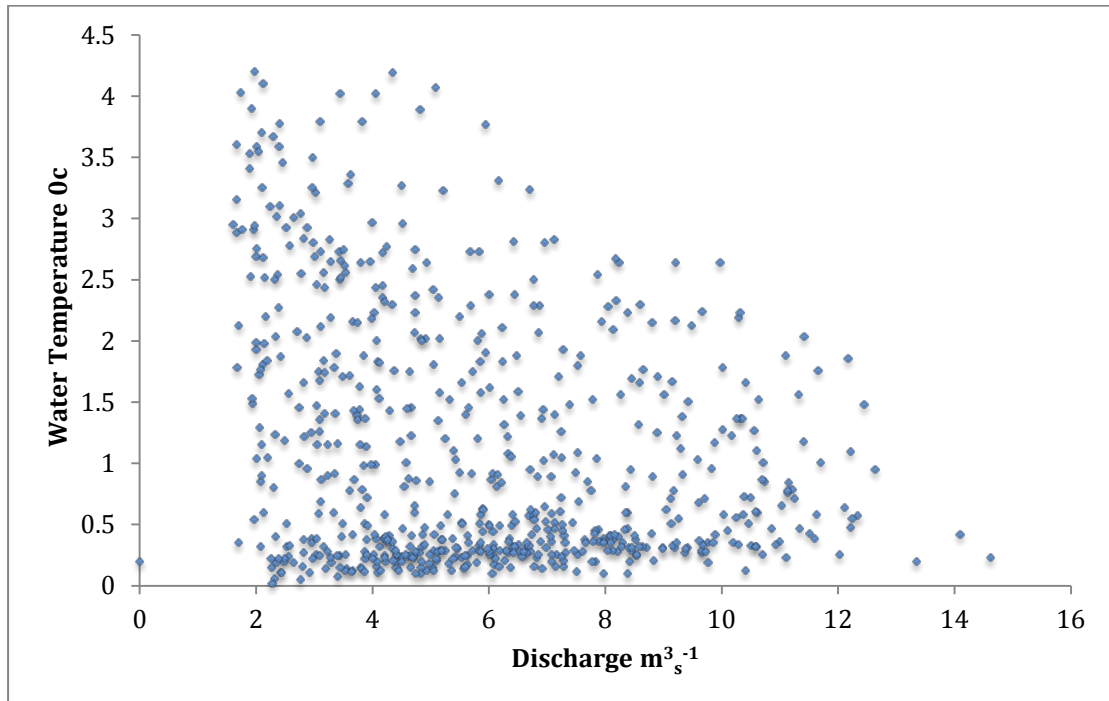


Figure 22. Discharge in relation to temperature at Findelenbach 05/8/07, 13:00:00 to 12/9/07 10:00:00

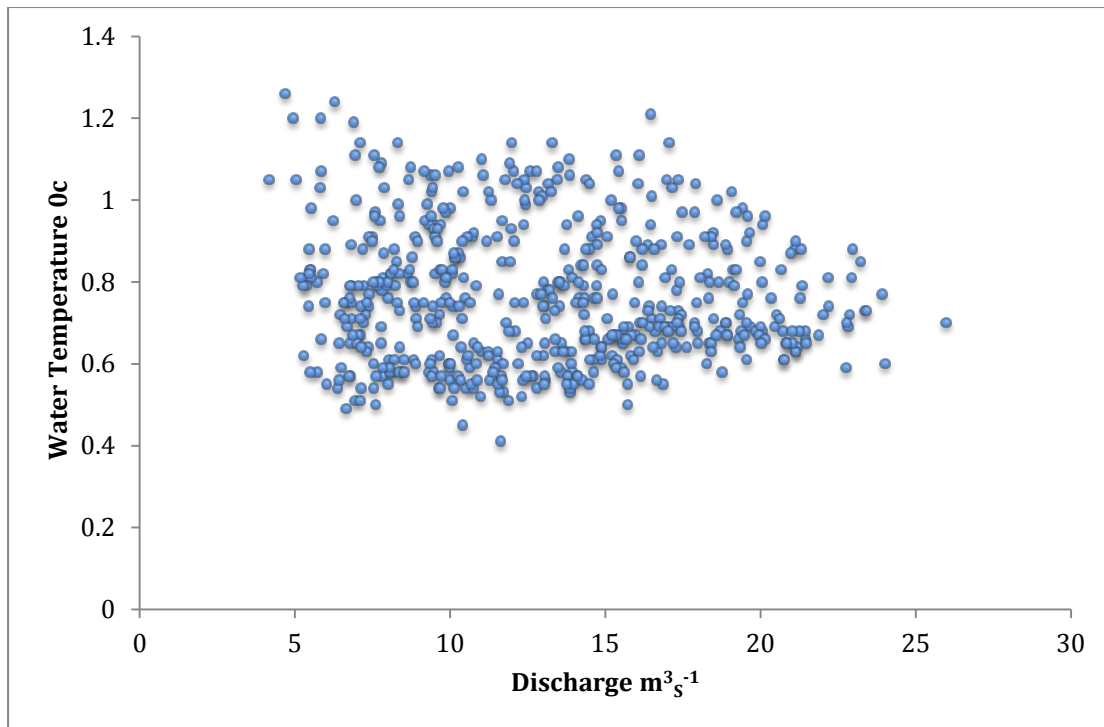


Figure 23. Discharge in relation to temperature at Gornera 03/08/07, 13:00:01 to 03/09/07, 12:01:00

Warm days such as figure 24 (not the warmest but warmer day) show temperature reach 7°C. There is a quick rise in air temperature followed by water temperature in Gornera. Discharge reaches the maximum before peak air temperature in Gronera; the peak in water temperature is after the peak in air temperature unlike at Gornera. Findelenbach reaches its daily peak in meltwater temperature as it is more susceptible to change with its shallow wide stream characteristics. Curvature created by discharge in Figure 24 is typical of a lagged discharge with an “S” shaped curve. Discharge stays a constant with small rises in temperature after air temperature peaks. Findelenbach does the same with air temperature rising and water rising quickly as it is a smaller glacier and not as much melting occurs hence why the meltwater stream is smaller.

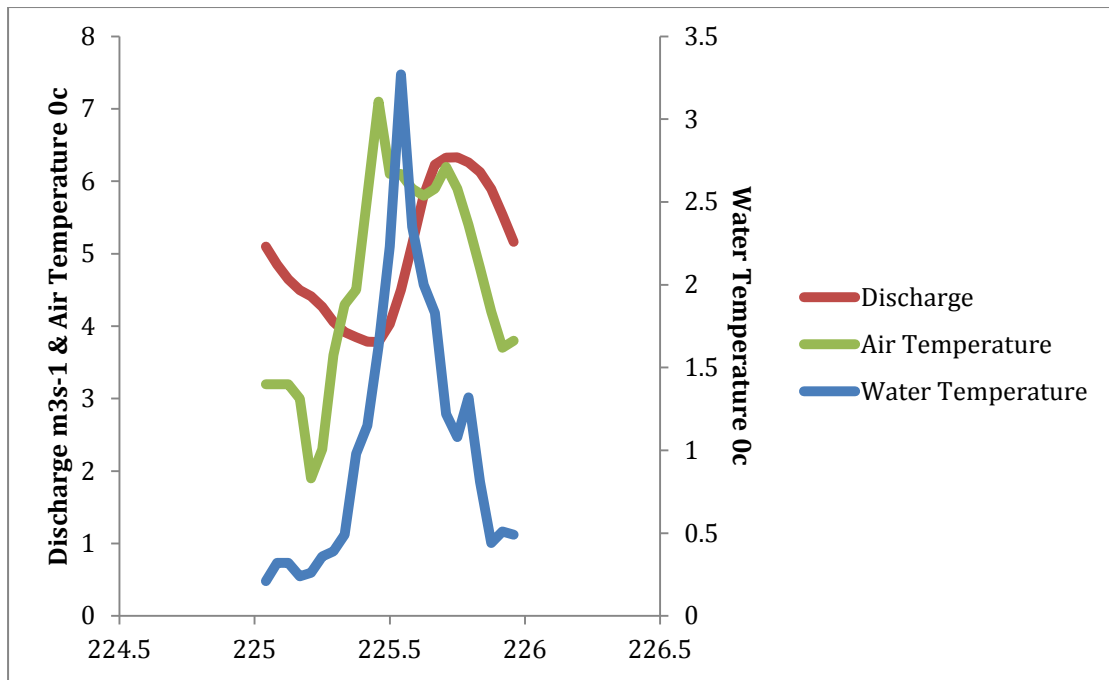


Figure 24. Warm day from Findelenbach from 13/8/07

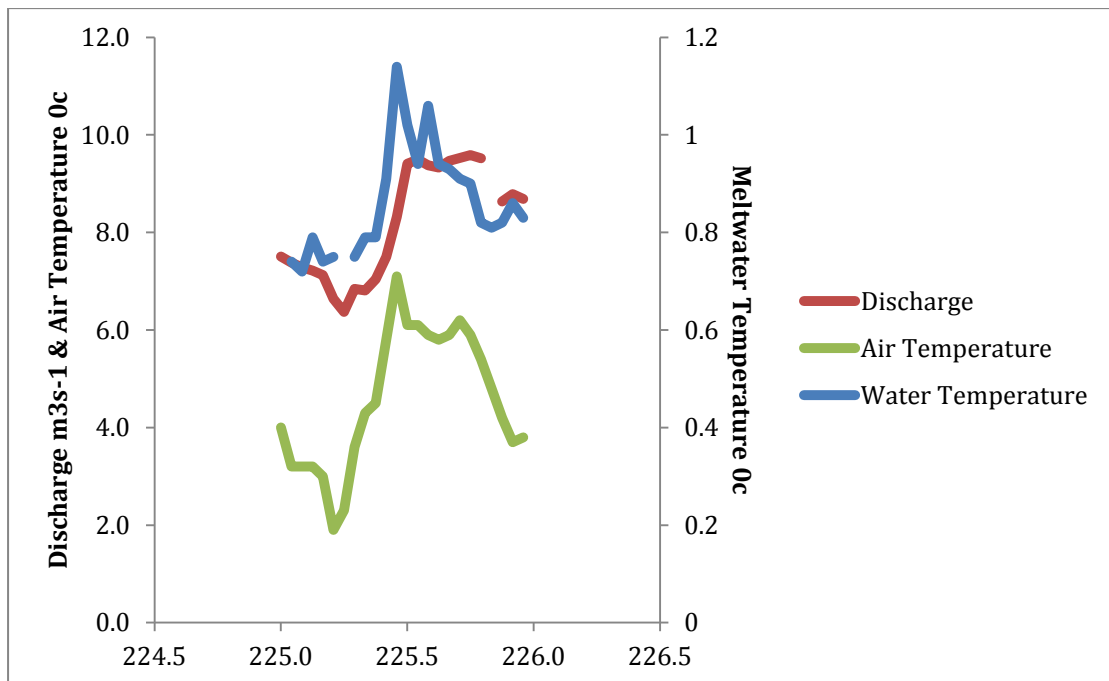


Figure 25. Warm Day Gornera on the 13/8/07

Hysteresis loops at both sites show the critical points where discharge starts to rise and temperature starts to fall. At Findelenbach the critical point is at 3.2°C and 4.5 m³ s⁻¹, the lag in meltwater reaching the gauging station because water that is melted has to travel through the glacier

before being collected. Critical point at Gornera is at 1.1°C and 8.3 m³s⁻¹, showing that discharges are much higher but with much lower temperatures.

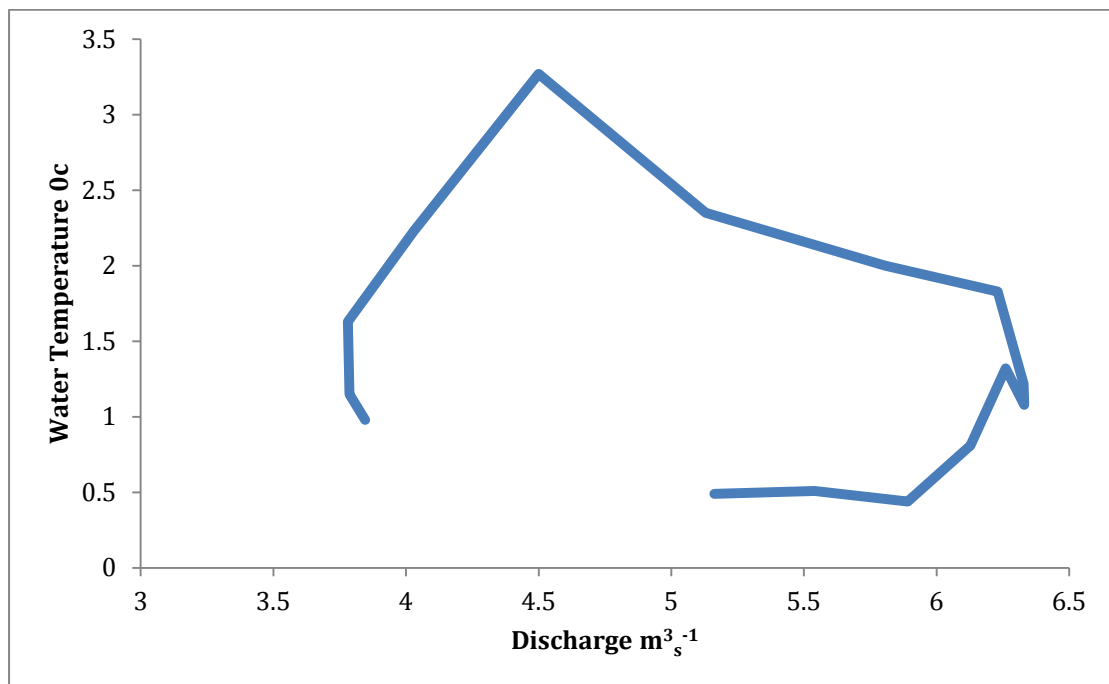


Figure 26. Findelenbach, 13/8/07

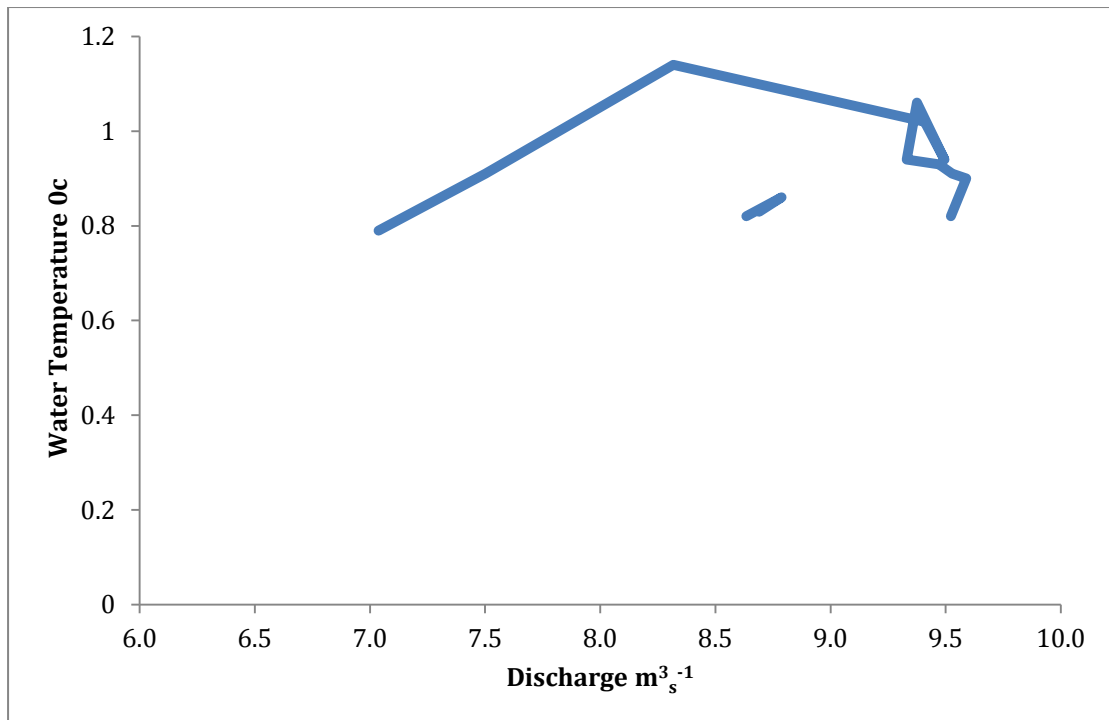


Figure 27. Gornera 13/8/07

Data loss throughout the day can lead to half days of results. Figure 28 is the afternoon of Findelenbach, discharge rises through as the lagged meltwater reaches the minisonde while air temperature and water temperature fall throughout the afternoon. Figure 29 the hysteresis loop for such data highlights the afternoon and the smooth curve shows the clear relationship between the two. Loss of data is unfortunate on this particular day as it shows the hypothesis to be correct.

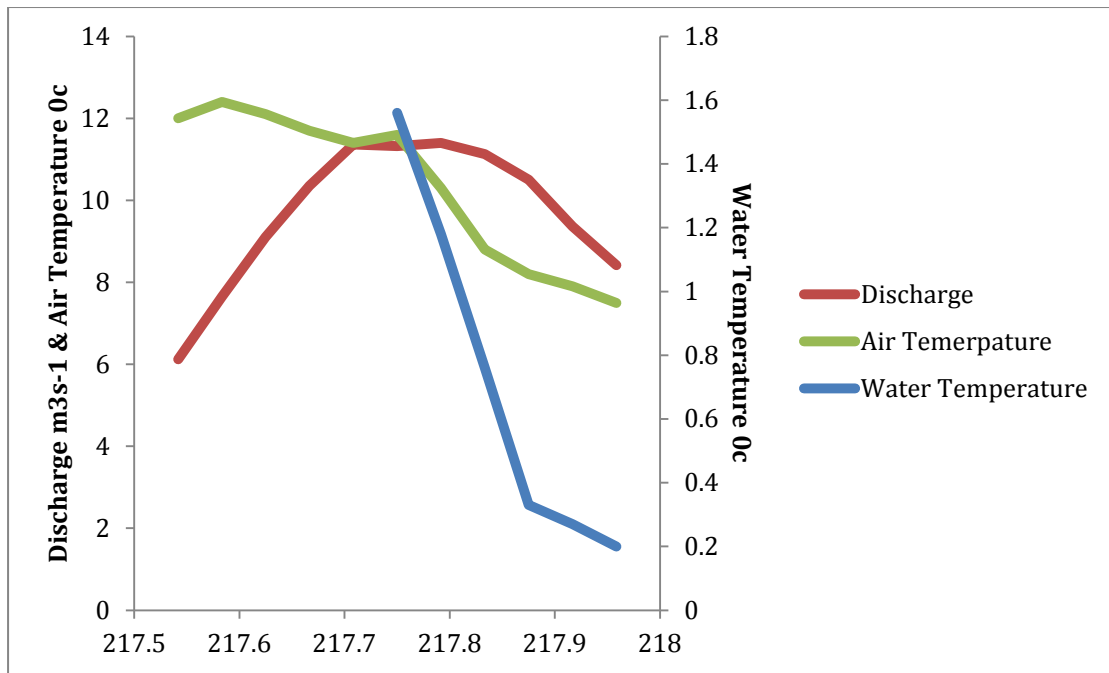


Figure 28. Findelenbach, Warm day with decreasing temperature throughout the half day 5/8/07

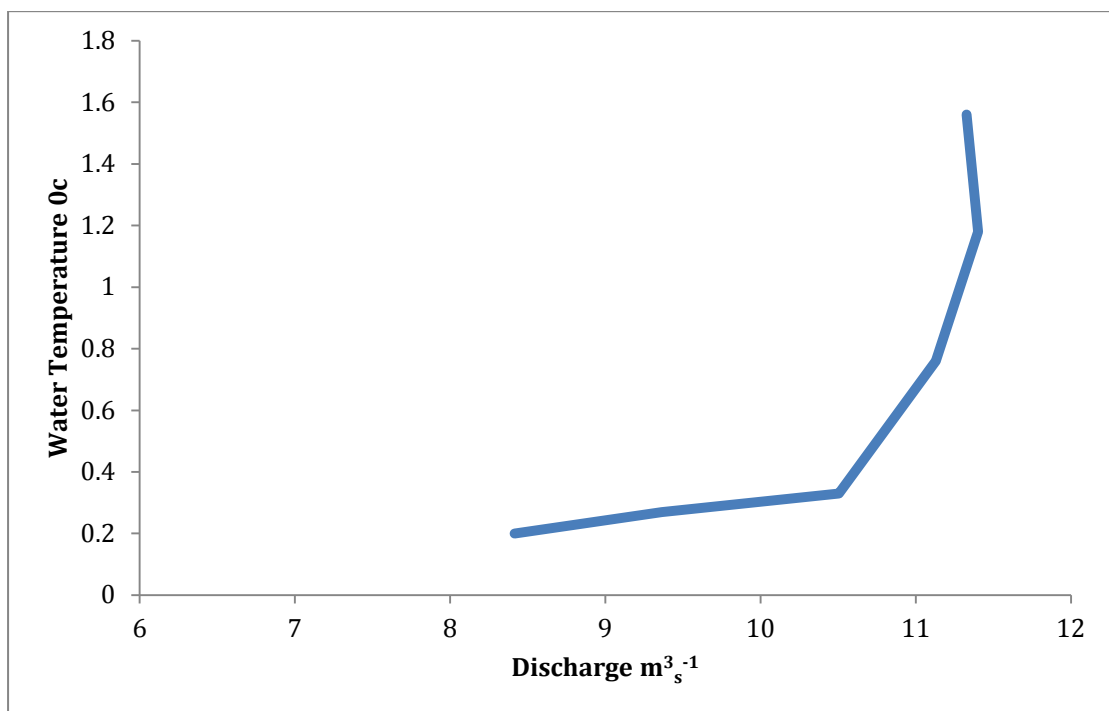


Figure 29. Findelenbach 5/8/07

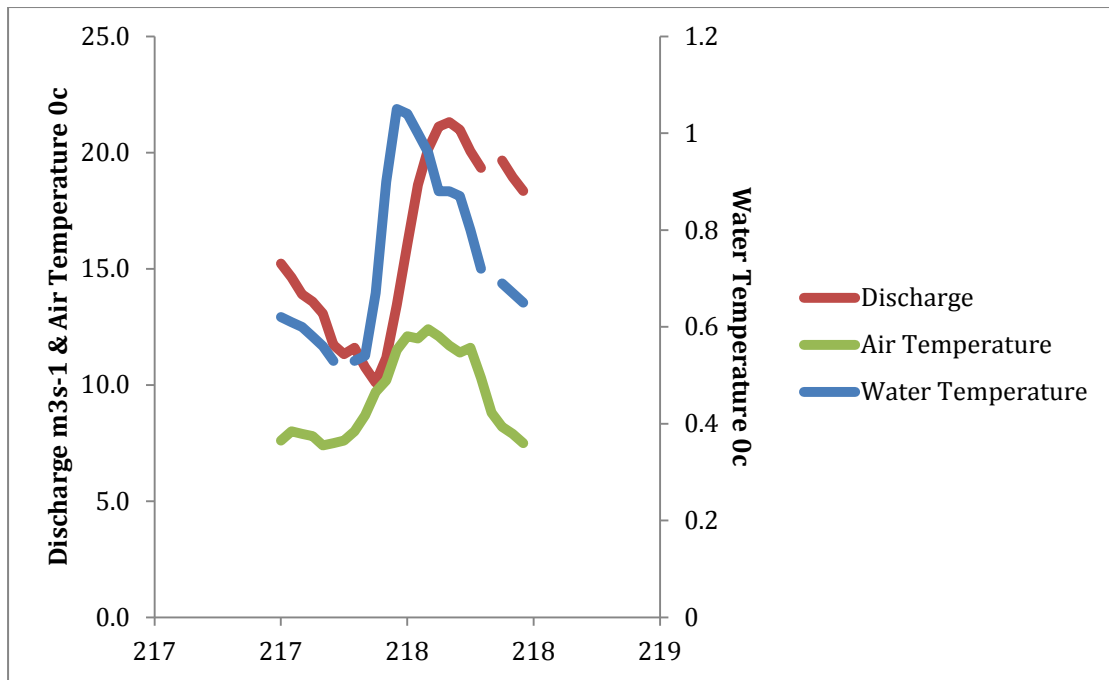


Figure 30. Gornera, Warm day 5/8/07

Water temperature rises with air temperature, with the lag of discharge as expected and shown in previous Figures. Figure 30 particular warm day brings high discharge, which results in low water temperature for the day. A relationship between water temperature and discharge on the warm day in Figure 30 is reflected within the consistent loop and flag shape created in the hysteresis loop in Figure 31.

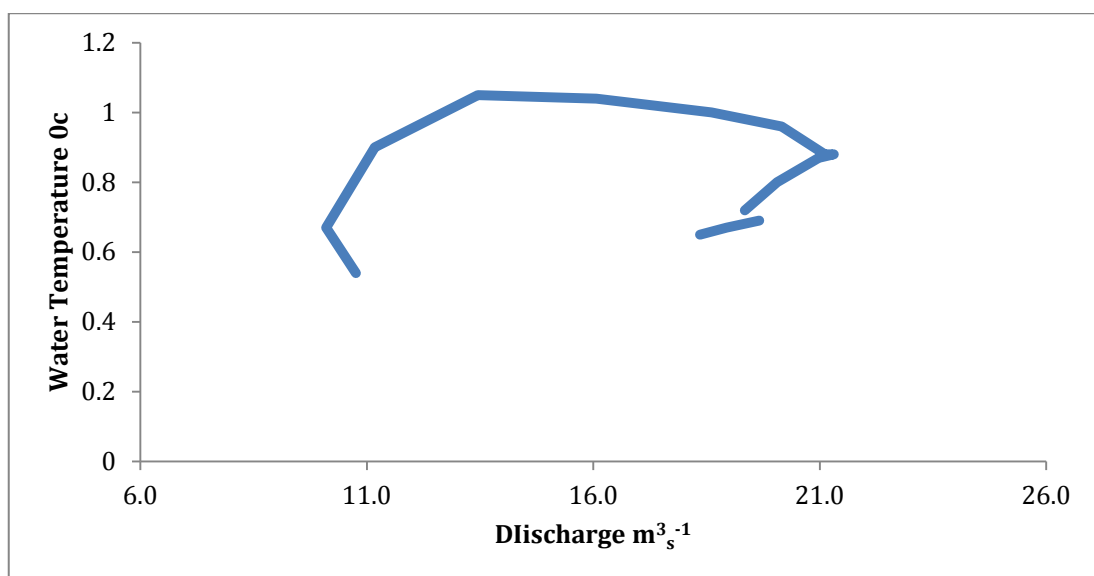


Figure 31. Gornera 5/8/07

Different days have different outcomes; cold days limit discharge but also limit heating, leading to radiation being increasingly more influential on such days, radiation could be the leading factor in the glacier system and melting and heating meltwater. Percentage glacierisation could have a minuscule impact and leaning more to glacier size and shown by the Figures and air temperature radiation and stream characteristics are the driving force. Figure 32, shows limited heating due to the lack of air temperature resulting in minimal discharge throughout the day. A comparison day for Figure 32 is figure 33, which shows high discharges and low water temperatures. Due to cold weather water temperature has fluctuations and rises with air temperature. Discharge carries on rising. Discharges carries on rising to its peak, which prevents water temperature from rising, further leading to a decrease in temperature. When air temperature is low water temperature maps closely to discharge as shown in figure 33.

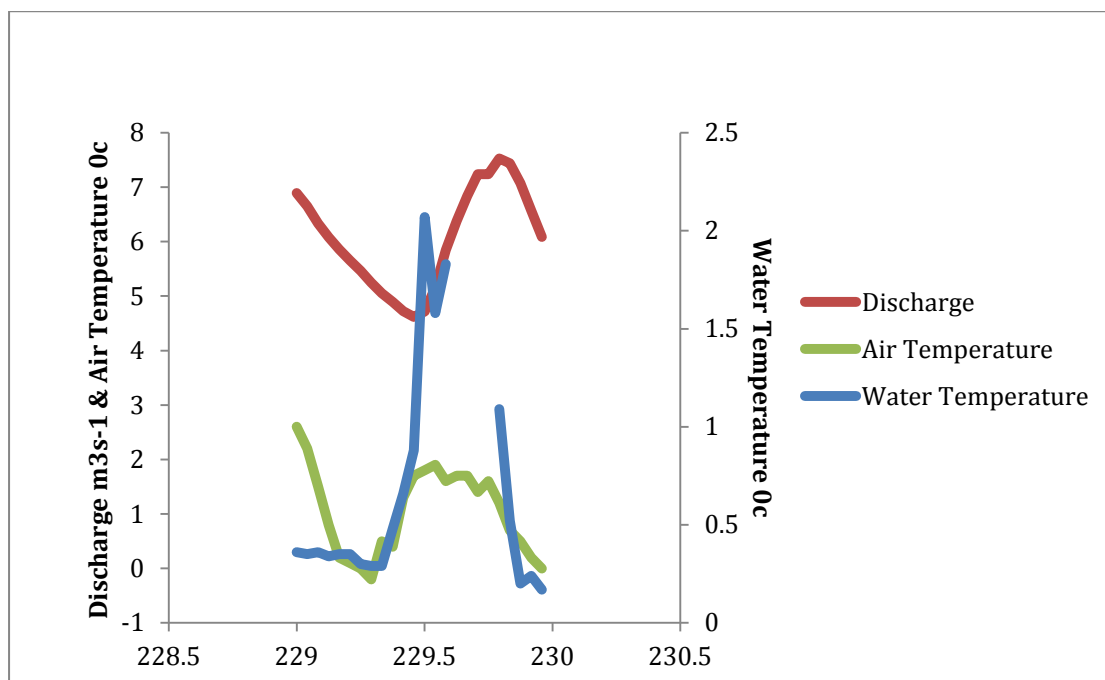


Figure 32. Findelenbach, Cool day 17/8/07

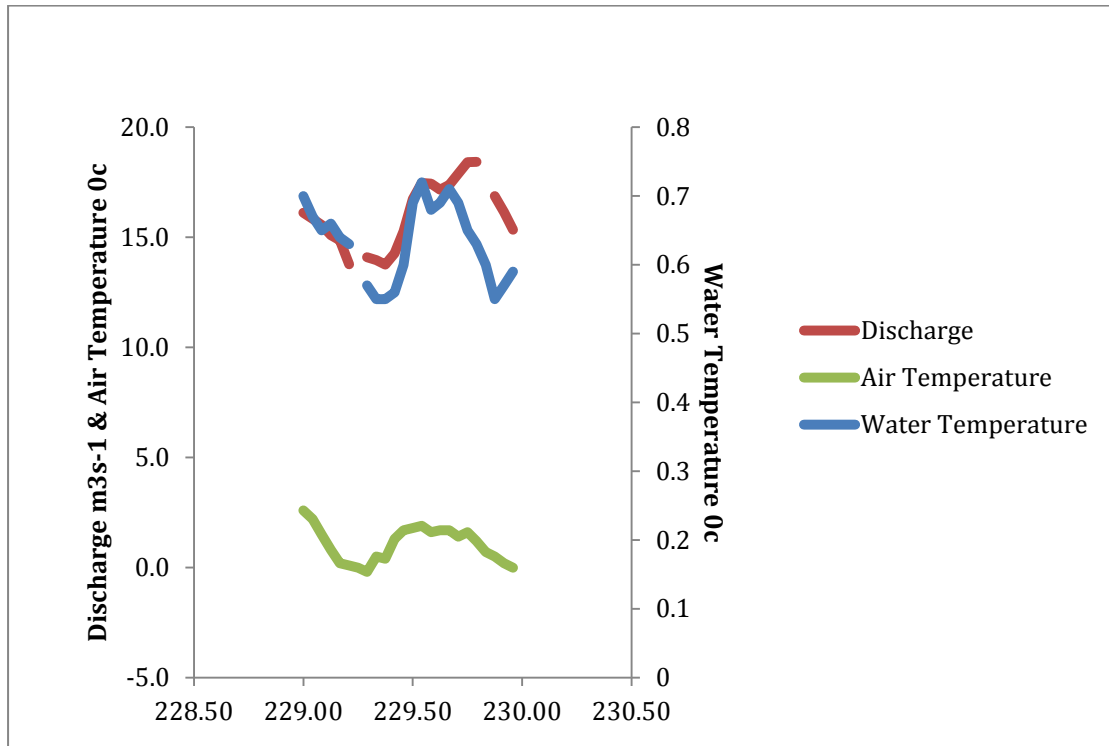


Figure 33. Gornera, Cool day 17/8/07

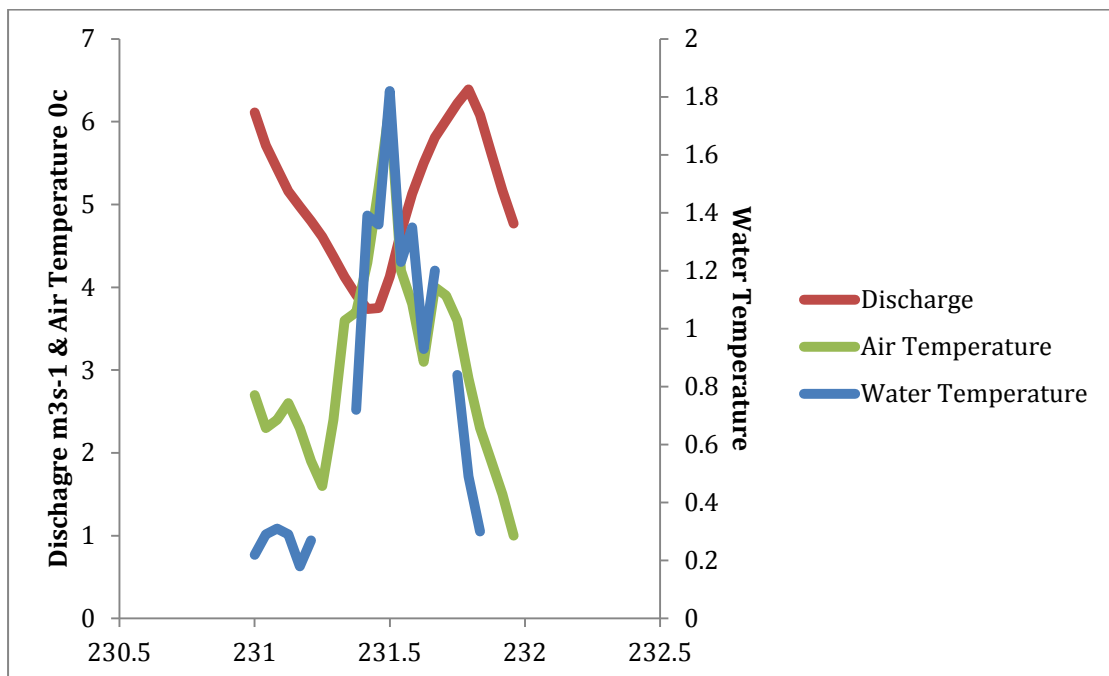


Figure 34. Findelenbach, Cool day 19/8/07

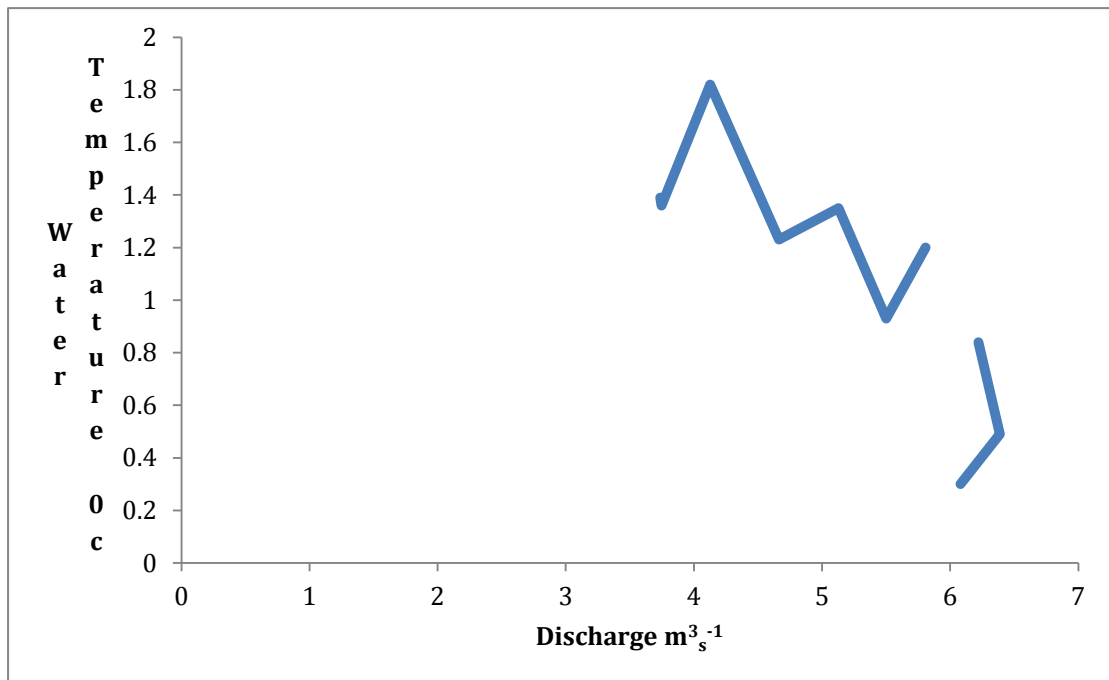


Figure 35. Findelenbach, Cool day 19/8/07

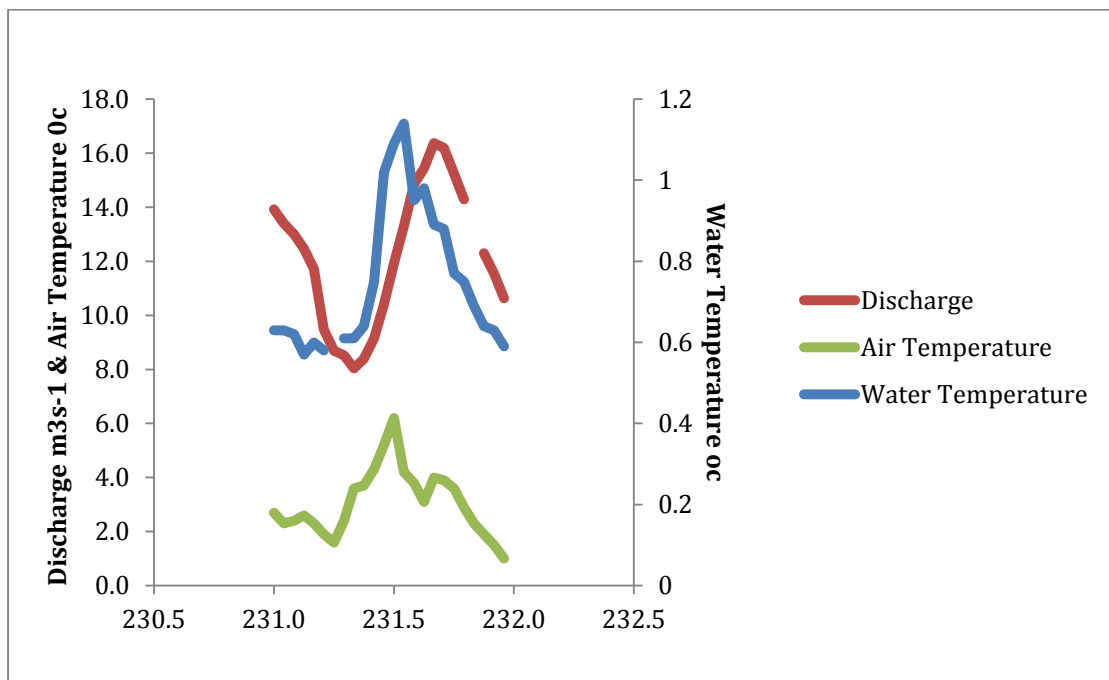


Figure 36. Gornera, Cool day 19/8/07

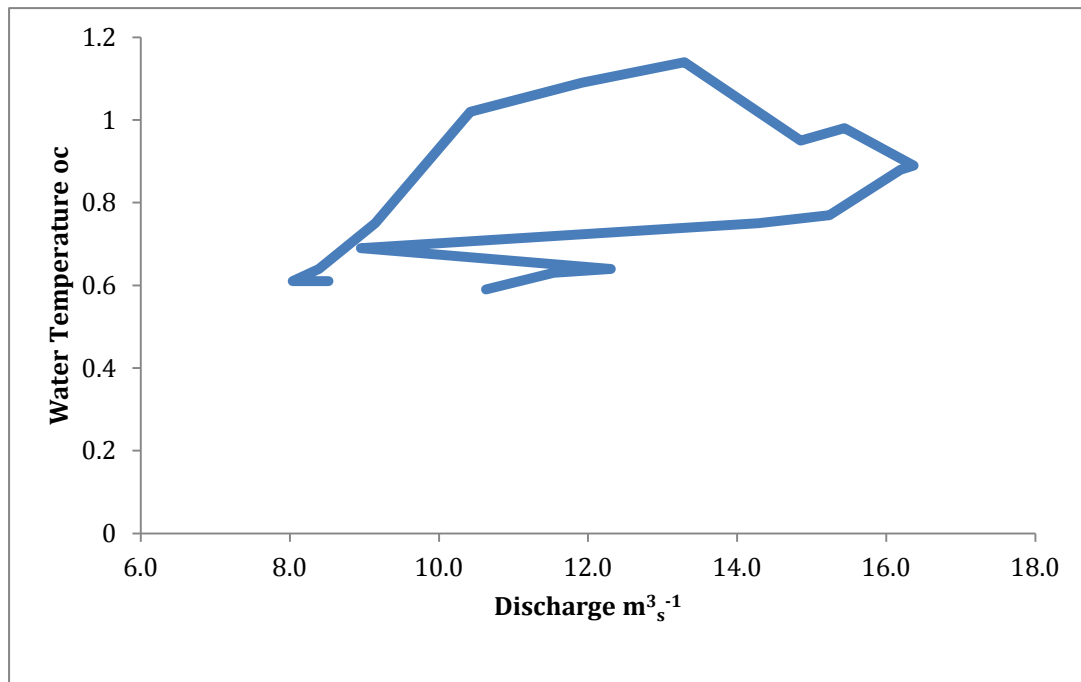


Figure 37. Gornera, Cool day 19/8/07

Figures 34 and 36 are clear indications that discharge is higher in Gornera than Findelenbach, Figure 34 shows that when air temperature is at its highest water temperature is at its lowest. Discharge is the driving force that dilutes meltwater and cools meltwater. Figure 37 supports figure 36 showing the diluting effect discharge has on meltwater, figure 35 has minimal data and is hard to read when discharge started diluting the meltwater and reducing the temperature.

4.4 Monthly comparisons of discharge

Stream characteristics and the impacts it has on water temperature are underlined in Figure 38, with Findelenbach's wide and shallow stream being much more susceptible to change. Temperature ranges in Findelenbach were much greater than at Gornera with not only the highest temperature but also the lowest. Figure 38 shows that glacier size and stream characteristics ensure that water temperature fluctuations are greater at Findelenbach. Gornera characteristics are the opposite to Findelenbach and the narrow and deep stream doesn't respond to change in outlying influences. Peaking water temperatures in both comparison glacier meltwater streams are very similar demonstrating that the factors that influence meltwater temperature are alike showing that air temperature and radiation are key contributing factors.

With temperature and discharge of glacier meltwater being closely linked Figure 38 should closely link with Figure 39. Discharge in Gornera also is closely followed by discharge in Findelenbach the rises and falls are closely linked showing that once again outside influences like radiation and temperature influence impact on discharge. Gornera is consistently higher showing the bigger glacier with bigger catchment area creates more melt. Highs in discharge at Deci Julian day 243 are shown in both days with limited discharge throughout the period before the rising discharge. The familiarity between both meltwater temperature and discharge in the two contrasting glaciers goes some way to proving the hypothesis, showing the links between two contrasting glaciers are affected in the same way.

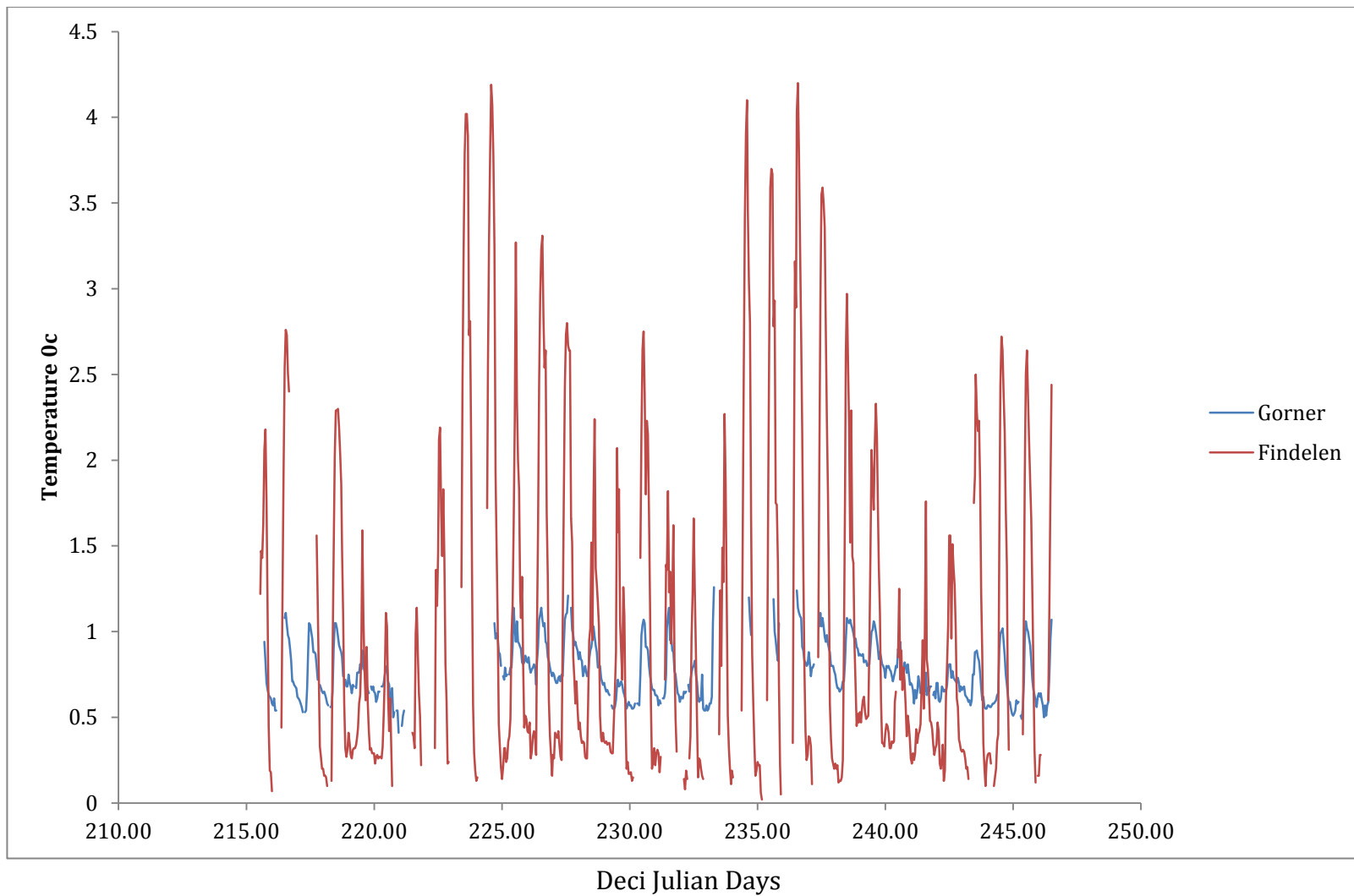


Figure 38. Comparison of Water Temperature. 3/08/07, 13:01:00 to 3/9/07, 12:01:00

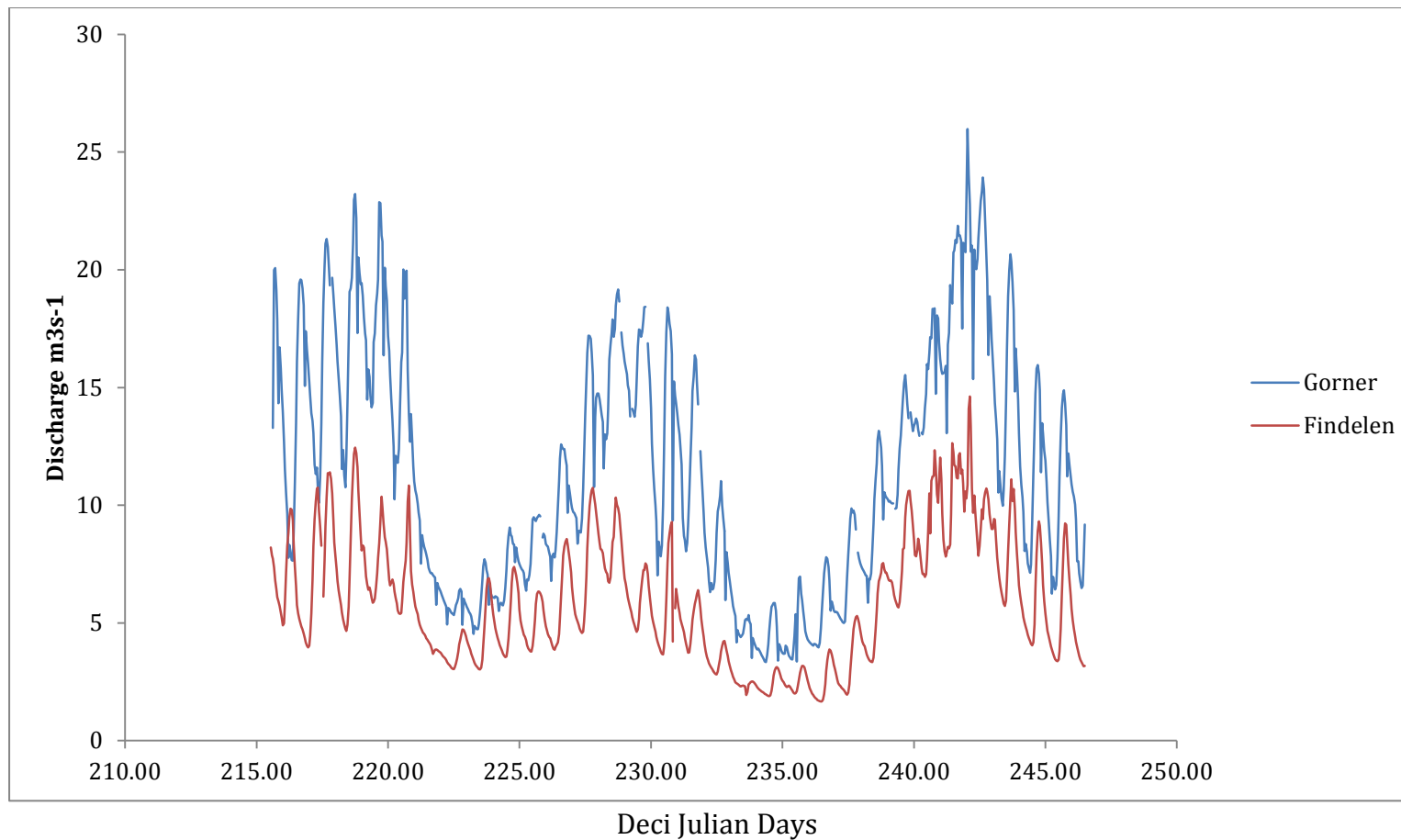


Figure 39. Comparison of Discharge, 3/8/07, 13:01:00 to 3/9/07, 12:01:00

Variations in water temperature are clear to see from figure 38 and support the hypothesis that the smaller river will be warmer for longer periods of time than Gornera, the water temperature of Gornera is more constant than Findelenbach, showing that the meltwater stream is much more vulnerable to changes in temperature and radiation than the bigger meltwater stream of Gornera. In Findelenbach river channel stability is low this is shown by the flux in discharges and temperatures strongly influenced by intense solar heating (Robinson & Matthaei, 2007). Figure 39 uses the discharge from both discharge data sets from August; what the graph shows is that as the water rises in one there is a rise in the other. The two patterns follow almost identically with them rising and falling at the same time through the monthly period. It also shows where the cold and warm periods occurred with the cold periods limiting discharge and the warm periods with high radiation showing the discharge rise. When snow is on the ground in the two cold periods the graph shows that Gornera's discharge is not much higher than Findelenbach's discharge showing that snowfall has a major impact on the discharge and melting power of the sun. When at their peaks the discharge for Gornera is much higher because of the area being melted. Glacial systems are linked closely together, meaning that what happens in the winter months before the summer has a greater effect on the summer discharge. Rothlisberger and Lang (1987) support that seasonal discharge pattern with summer peak flows is due to the compensating effect of winter precipitation storage in the solid phase followed by release as summer melt.

4.5 Diurnal comparison graphs

From the daily graphs (Figures 40 to 45) the two highest lines on the graph are the discharge from Gornera (Gorner as shown on graph) and the water temperature of Findelenbach (Findelen as shown on graph). With the same air temperature at both locations due to the small distance between the two glaciers the similarity in glaciers features will be highlighted and

temperature will be a constant factor on both glacial systems. Figure 40 shows that with higher discharges lead to lower meltwater temperatures and lower discharges lead to higher meltwater temperatures. Cold periods limit discharge and also limit warming of meltwater; warmer periods over a diurnal period lead to higher discharge cancelling out the higher water temperature at the end of the day, but in the morning water temperatures can reach their peaks. In the morning, warming and radiation allow the low discharges to be heated. The results put forward go somewhat into supporting the hypothesis and the data and evidence from other papers will also support the results. Discharge at Gornera is a constant at the top of the graph, with Findelenbach's meltwater temperature starting at the bottom and rising throughout the day reaching its peak. Previous Figures 38 and 39 show the discharge rises and falls at the same time, this is highlighted within the individual days in the following Figures; most clearly shown in figure 43. An individual comparison day with all data gives a graphical image showing how water temperature reacts with air temperature and discharge throughout a diurnal day. Discharge in Findelenbach shows a very consistent movement throughout the day with the sideways 'S' shape constant throughout the comparison graphs, showing the wide shallow stream makes the same changes to Gornera only to greater or lesser extents whatever air temperature may be. Gornera also follows the pattern, limited discharge in the morning is due to minimal melting throughout the night and with warming and albedo come the higher discharges, also taking into account the time it takes the glacier melt to reach the terminus and then reach the gauging station or minisonde.

Comparing water temperature in the Figures shows that Findelenbach has a steep rise and a steep fall compared to Gornera. Where Gornera is flat and has a much smaller rise in supporting that larger streams with narrow and deep stream characteristics don't respond to air temperature and radiation. Whereas when temperature rises and radiation is at a high Findelenbach sharply rises to its peak. Stream characteristics remain an influential factor on determining meltwater temperature after exiting the glacier terminus. Percentage

glacierisation is looking less of a contributing factor than the other stated throughout the results section, other features influence meltwater temperature.

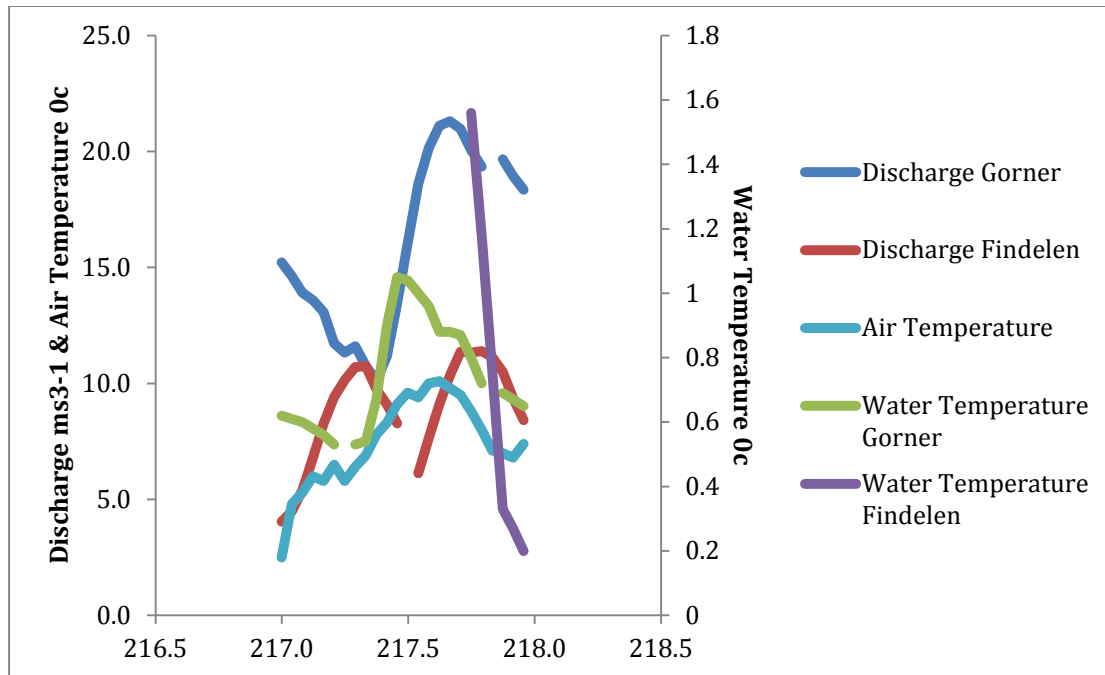


Figure 40. Comparison of all the data Warm Day 5/8/07

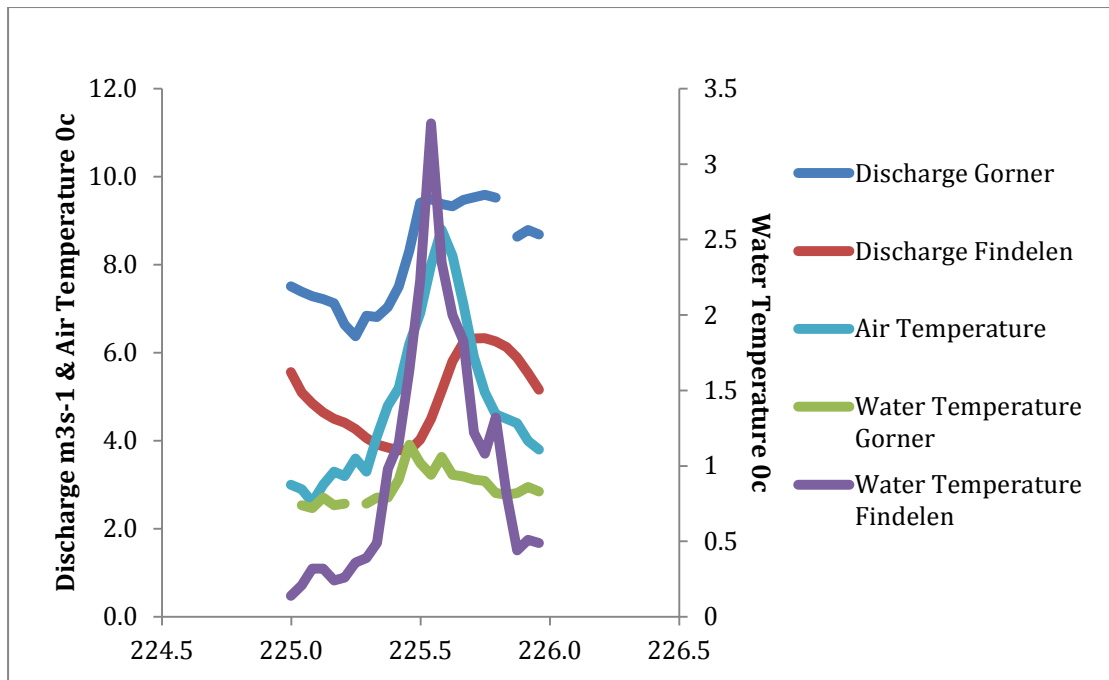


Figure 41. Warm Day Comparison 13/8/07

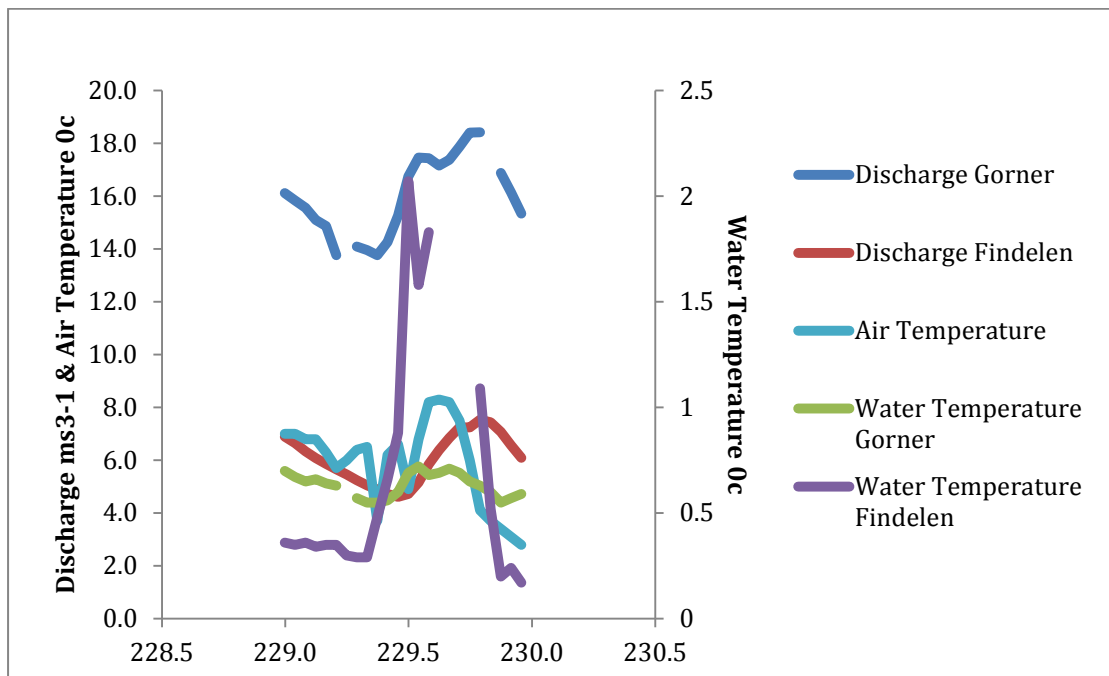


Figure 42. Cool day Comparison 17/8/07

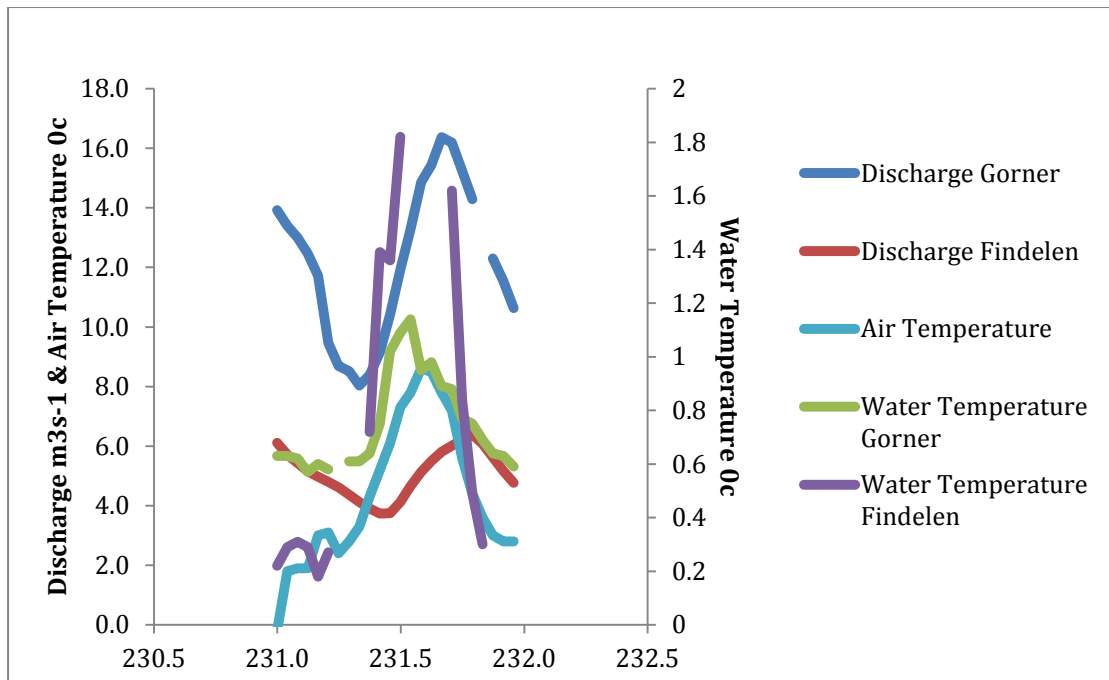


Figure 43. Cool day Comparison 19/8/07

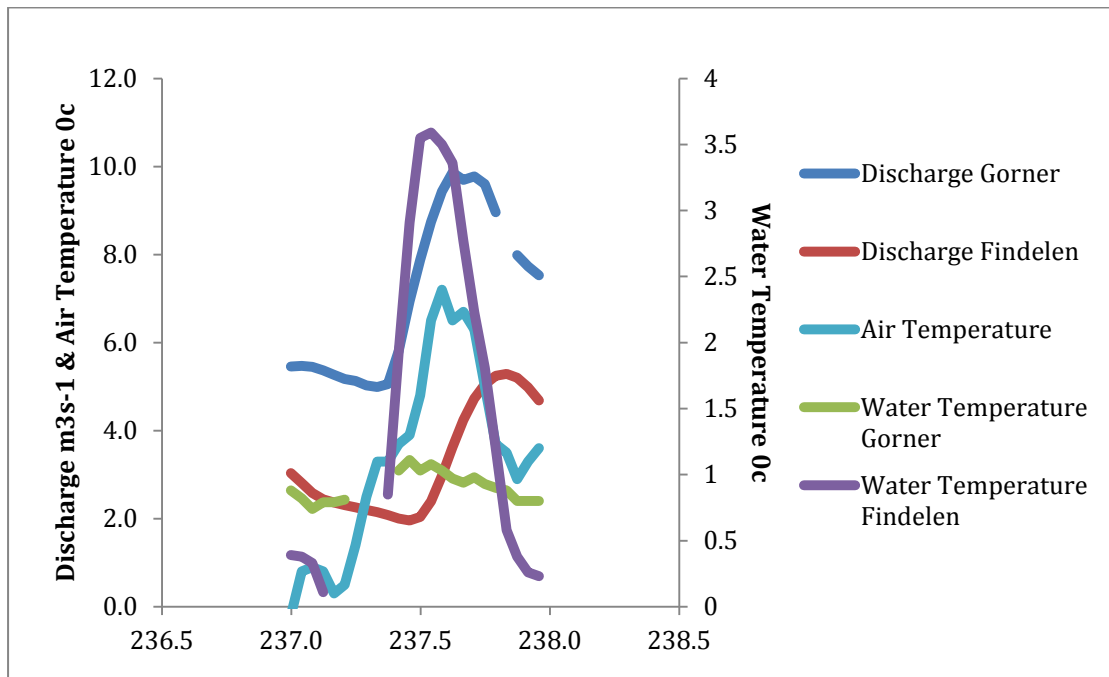


Figure 44. Cool day comparison 25/8/07

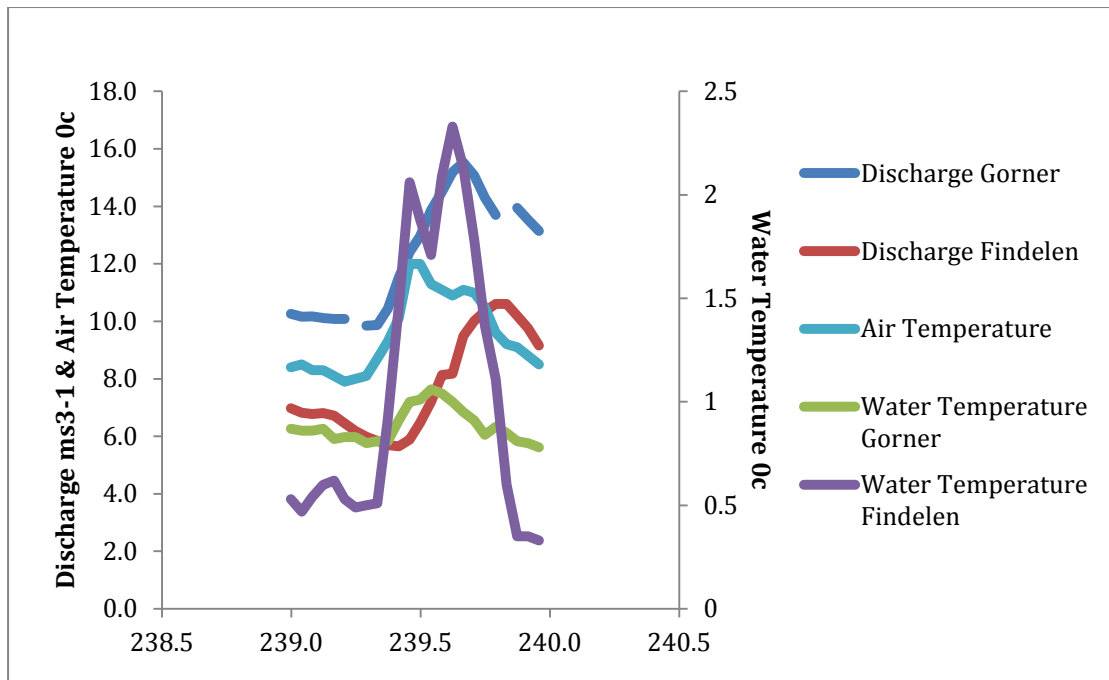


Figure 45. Warm day comparison 27/8/07

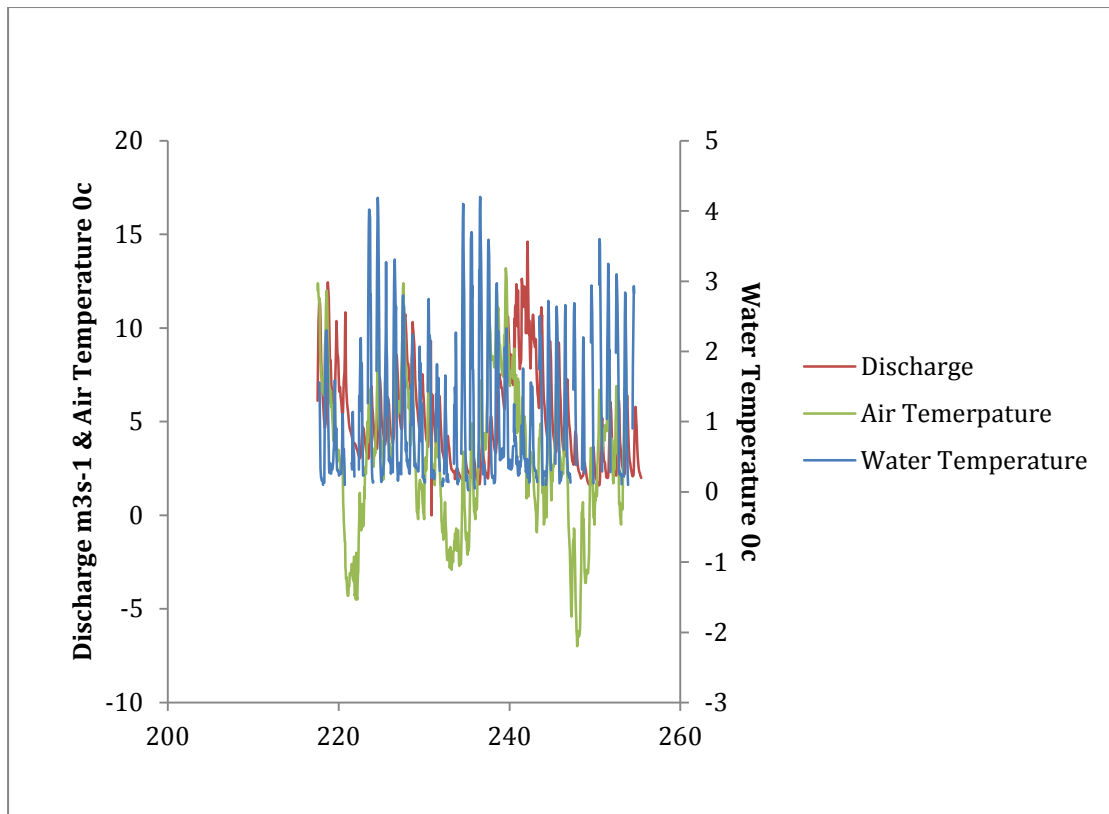


Figure 46. Findelenbach 05/8/07, 13:00:00 to 12/9/07 10:00:00.

Results overall have shown that the hypotheses are supported and predicted outcomes are coming together and have been proved by the data. One incorrect hypothesis has occurred as it was thought that over a daily period the warm weather wouldn't warm meltwater. The rise in water temperature but the warmer weather overall leads to a rise in discharge and a rise in minimum temperature as shown in Figures 22 and 23. Warm weather has the morning period to warm meltwater before lagged discharge cools the water down. The higher discharge that the rising air temperature brings does not mean that water temperature decreases on average; it actually does the opposite and rises slowly.

5. Discussion

5.1 Air temperature

Air temperature is the biggest contributing factor directly influencing the temperature of the meltwater stream and discharge, with strong links between the two contrasting meltwater streams. The warming earth has shown with evidence of previous studies and results that stream temperatures have already increased as air temperature has risen in recent decades. With the two glaciers being in the same climatic region of Zermatt the air temperature will be very similar. Glacier size is the difference between the two study glaciers; studies conducted by Brown (2003) on thermal variability prove why Zermatt, Findelengletscher and Gornergletscher and the close proximity of the two remove the factor of air temperature because it should be constant in both areas. In the French Pyrenees air and water temperature correlate, (Brown et al 2003) the air and water temperature will also correlate in the Swiss Alps. Moving away from the air temperature the other major factors that influence the temperature between the two are the characteristics of the stream and the different sizes of glaciers. One of the other most salient features of glacier fed streams is marked diurnal and annual discharge variations (Rothlisberger & Lang, 1987). Results from the study show that when discharge is at its peak, temperature is at its lowest whatever the time of year in a diurnal period. Peaks in discharge for the time of year means that there is not enough heat to heat the water. Water temperature follows the air temperature as radiation and heat rise through the day with the discharge lagged because the meltwater has to travel through the glacier. Once the water has travelled through the glacier discharge then rises at the gauging station. Transit time through the glaciers means that meltwater has time to heat up before the discharge rises.

5.2 Comparison Studies

Hood (2013) examines how air temperature and watershed land cover, especially glacier coverage, relate to stream temperature across the seasonal glacier meltwater hydrograph using similar months to the study period. Hood concludes that percentage glacierisation is crucial to meltwater warming downstream. Overall, our findings and others (Morrill et al., 2005; Isaak et al., 2010) indicate that watershed landcover may be more influential than atmospheric temperature for predicting stream temperatures in the region, particularly in higher elevation watersheds (Hood, 2013). Whereas other studies such as Collins (2009) suggest that distance from terminus is much more important. Short water residence times in the relatively small watersheds together with the cool and cloudy maritime climate in the region likely restrict the accumulation of heat via air–water exchange throughout the watershed network (Collins, 2009). Transit time through glacial systems when exiting glacial terminus to point of measurement defines warming downstream. Two similar size glaciers with larger a longer transit time will lead to the bigger glacier having warmer meltwater. Percentage glacierisation isn't a shaping factor for meltwater temperature as suggested by Hood, not only transit time but additionally stream temperature is strongly correlated with climate (Morrill et al. 2005; Mohseni et al., 1999). Enough evidence was collected through the study to show that catchment area and catchment characteristics influence water temperature and percentage glacierisation holds not statistical analysis to suggest otherwise. Supporting Collins theory Richards (2012) showed glacier retreat will increase the length of proglacial stream exposed to solar radiation between the glacier terminus and probes, resulting in higher temperatures. Warming consists of outside impacts not the glacier itself, as the glacier is melted and creating stream discharges of differing sizes but the driving effects melting eg, radiation and air temperature leading to transit time and stream characteristics being influential.

Studies such as Collins (2009) in Switzerland from 2003 to 2007 show that the stream with higher discharge, because of its basin area, glacier size and mean runoff had the lowest mean monthly water temperatures. Collins' study uses a different study area in Switzerland than the one conducted but shows the same results over a much longer period, when it comes to larger discharge streams being the lowest in temperature. With Gornera being the larger of the two streams the temperature of the stream is much lower for example in August 2007 the discharge was over $25 \text{ m}^3 \text{ s}^{-1}$ and temperature around 0.8°C . Subsequently as ice melt discharge increased, water temperature decreased and mean monthly temperature was maintained at about the same level between July and September (Collins, 2009). Increases in volumetric flow raises the heat capacity with high discharge shortening the distance between glacier portal and gauge. Collins paper links closely to the study being conducted with results corresponding with each other and similar conclusions being made, supporting that in Switzerland glaciers are influenced by air temperature and radiation in the same way. Comparable conclusions such as proof that relatively low discharges and extended transit times let small quantities of river water warm in the increasing levels of radiation. In warmer months the mass of ice-melt derived water emerging at $< 1.0^\circ\text{C}$ requires more energy to raise the temperature of the river, but there is reduced transit time in which energy exchange can take place. Collins also goes some way to showing that distance travelled is more important than percentage glacierisation.

Highly glacierised basins such as the Massa in Collins study suggests similar characteristics as Gornergletcher such as flow increase in May with a steep rise to maximum in July and August. Increasing radiation in spring is able to raise water temperature because of limited discharge. Rising radiation increases discharge derived from ice melt and in turn reducing water temperature. Water temperature is generally reduced as the proportion of snow and ice melt adds to total runoff. Meltwater has passed through the internal drainage system of the glacier which increases effects most apparent in meltwater streams such as the Massa and Gornera.

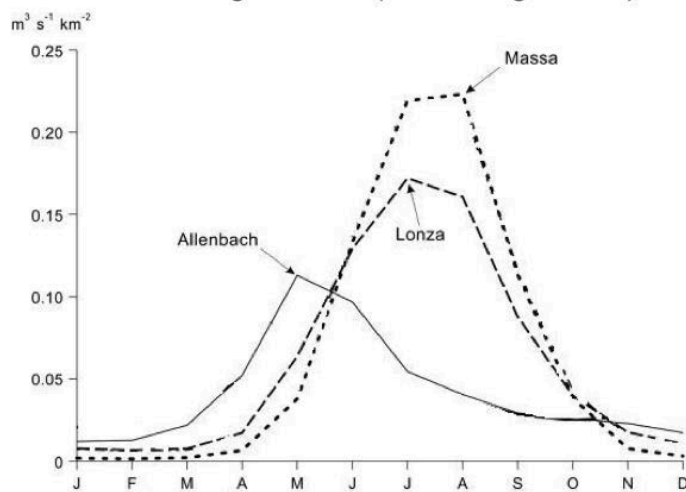


Figure 47. Mean monthly discharge for the 1956-2007 period (Collins, 2009)

Climate change does not have an instant impact on changes in water temperature but it is a progressive movement down and up through time. During the second warming cycle (1980s-2006), temperatures exceeded those experienced in the 1940s. However, mean discharge in the warmer 1990s-2000s failed to exceed that of the 1940s-50s (Collins, 2008). Rising discharge through the warm periods has led to a fall in stream water temperature. Collins (2008) explains that throughout the two recent warm periods there has been a reduction in discharge because of glacier recession and within the first warm period the glaciers would have had a greater mass balance. Climatic warming in the second warm period has lead to major glacier recession leading to less melting because of a smaller surface area to melt. Rising air temperatures have lead to the temperature of the rivers and streams in Switzerland responding coherently to regional climatic forcing at all altitudes. During the last quarter of the 20th century substantial stream warming occurred (Hari, 2006). Warming temperature in

the last century would seem to agree with this because the higher discharge is a result of warming of the earth so both are increasing. With rising air temperature more heat and energy is being put into the stream leading to more warming than within the diurnal cycle when the discharge reaches its peak, water temperature is at its lowest. Over a short period of time like a day higher discharge leads to lower temperatures, but over a long sustained period of climatic warming the stream temperature rises with the air temperature. Gu (1998) used analytical solutions and field observations to show that the meltwater temperature significantly affected discharge causing a reduction in summer meltwater temperature.

5.3 Discharge

Temperature of meltwater increases as air temperature rises meaning that there is more water needing more energy to heat. The two are driven by the same signal (air temperature) but in a different process, with volume of water working against the rise in temperature that climate change is bringing. Air and water temperature are opposing factors and with rises in air temperature and rises in discharge leads to a decrease in temperature; the two are working against each other meaning that one could cancel out the other especially discharge cancelling out the rise in meltwater temperature over a day. Where there is a glacier like in the study area there will always will be a rise in temperature because of rising overall air temperature and a small rise in discharge, air temperature and radiation will always melt some of the glacier and in turn will always warm up the water. The atmosphere supplies and removes mass and energy at the glacier surface, determining accumulation and ablation regimes, and ultimately glacier extent (Milner, 2009). In the summer months where the research was conducted the ablation is the key with melting occurring in cold summers. Warm years like 2003 show that the sooner and higher the transient snowline rises in the summer the more exposed the layer of ice

is, and the larger area of ice is exposed to melt for longer leading to a much higher discharge (Collins, 2009).

Evidence collected through the study shows that Lotter (2004) is incorrect, summer month discharges rise in figure 48 are shown with the mid-summer water temperature also rising. Overall higher discharges in summer months would show a decrease in meltwater temperature, with higher discharges in the summer the meltwater temperature will be overall lower than in months such as October where limited discharge increases the impact of air temperature and radiation with lower discharges especially in Findelenbach where the spread out characteristics of the stream are subject to the radiation penetrating the stream. Collins (2007) said that there is therefore a paradox in that when solar radiation and air temperature are high, stream water temperatures are often reduced (as referenced above). Mean monthly water temperatures were maintained at about the same level between July and September. Showing that the warmer weather increases discharge but is equalled out, when cooler temperatures and less stream water also balance out. Research undertaken in Alaska provides evidence that glaciers had a cooling effect on monthly mean stream temperature during the summer (July through September) with the equivalent to a decrease of 1.1°C for each 10% increase in glacier coverage (Fellman et al, 2013).

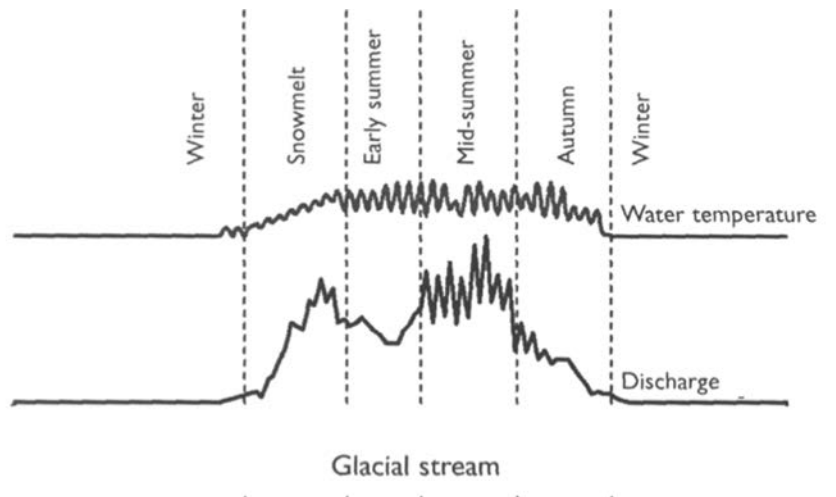


Figure 48. Differences between seasons based on typical changes in discharge and water temperature. (Lotter, 2004).

Higher temperatures produce more meltwater but cannot heat the added meltwater. Discharges within a monthly period show that there are very small rises in temperature when discharge rises, but over a daily period the rise in discharge leads to decrease in temperature. Rises in air temperature lead to higher radiation over the monthly period leading to a steady slow increase in water temperature. Within a daily period the radiation and air temperature warm up the water and within the diurnal period the discharge rises with a lag behind the water temperature and with the high discharge dilutes the water and it is unable to keep the warm temperatures. Within 2007, (cold year) this is the case but with the warm year of 2003 the discharges are even higher and the temperature is much colder (Webb et al 2003). Warmer weather and radiation leads to higher discharge. River water temperature is a resulting variable, which follows a diurnal cycle and a seasonal cycle, due to the net of heat inputs and outputs under specific hydrological (discharge, depth, and volume of groundwater exchange) and meteorological conditions (air temperature, solar radiation, wind and humidity) (Gu, 1998). Rising air temperature is

leading to glaciers to retreat with the length of the stream increasing as it moves backwards; this means that streams will be exposed to solar radiation for longer before the data is read, (Richards, 2012) leading to the conclusion that water temperature will be higher. Evidence of glacier retreat has not only been proved by graphs but also been provided by modeling in studies such as Collins (2009) and Hood (2013). In the case of the study which overall was a cold year, which means that the snow cover and radiation were lower than a warm year and the melting and discharge would have been much lower. In Collins (2009) study he concludes that the summer cooling in the Massa reflects the volume of low flow. With this experiment being conducted in the same year as the study this will be the same. Low flows within the summer months mean that over the monthly period meltwater stream will be much cooler in such a year, even with the low flows as increased snowmelt into the system will keep the water cool.

5.4 Precipitation

Precipitation shifts from snowfall to rainfall, and low flow conditions were two characteristics that drive water temperatures dynamics with climate warming (Deas, 2012). Periods of snowfall are having greater impacts on discharge as snow limits meltwater entering the system and making it rise through melting when temperature increases. Moore et al. (2009) argued that glacier retreat and reductions in late-summer flow should result in higher late-summer stream temperatures and identified a need for further process-based research to assist in predicting the magnitude of warming. Currently this could not happen because low summer flows are related to cool years, but in the future when small glaciers such as Findelenbach get smaller the lower discharge that will be created will lead to much higher water temperatures. Discharge of Findelenbach in the study is relatively low because of the cool period but with these low discharges there the air temperature is not enough to heat water up as suggested by Moore et al, with the highest temperature for August been 4.3°C. The study that was conducted shows that with temperature being so low, the theory put

forward by Moore might only be proved in the future when there is a much lower discharge. The study shows that the discharge is low but so is the water temperature with it only being a cold year. With the study being in a cold year the snow will stay on the glacier for longer and not leave the ice exposed, the sooner and higher the transient snowline rises in the early summer, the thicker the layer of ice melted as a larger area of ice is exposed to melt for longer (Collins, 2009).

5.5 Future

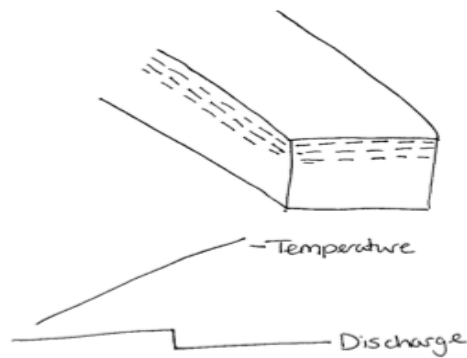


Figure 49. Gornera in the future. (Eyres, 2014)

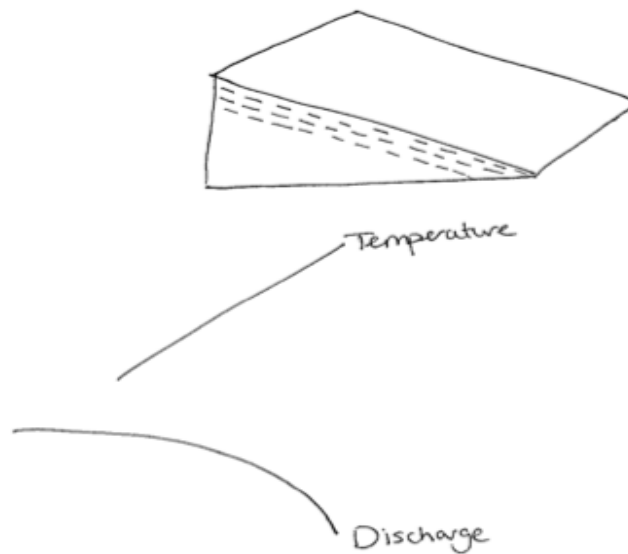


Figure 50. Findelenbach in the future (Eyres, 2014).

Figure 49 and 50 show the future for Gornera and Findelenbach, as seen in the result section discharge for Gornera is much higher than Findelenbach and the gap between the two will carry on increasing because of glacier size. Gornergletscher will lose only the top layers of ice but the sheer mass of ice will still be there in the near future. Gornergletscher is like a brick lay on its side and the layers keep coming off as air temperature rises, with layers being taken off the discharge will stay constant until the glacier has fully gone and then the discharge will fall off when the glacier has totally gone. In comparison Findelenbach will lose layers and will shrink because of the size and shape of the glacier; layers that will be taken off will shrink the glacier in size and mass. It is suggested that as glaciers recede with a warming climate, stream flow will decrease (Barnett et al., 2005), but this may not happen immediately. Instead, an initial increase in meltwater generation may occur due to increased energy inputs, earlier disappearance of reflective snow cover and exposure of lower albedo ice (Milner, 2009). As air temperature carries on rising the discharge will rise

and fall like is shown in figure 50. Figure 49 shows that the discharge will drop at Gornera but it will drop off suddenly because of the sheets and layers of ice that are being melted off. Smaller glaciers like Findelengletscher will disappear in the future with the bigger glaciers like Gornergletscher the mass of the glacier will take much longer to melt (William, 2012). Larger glaciers such as Gornergletscher produce more discharge and have a greater influence on the surrounding area like for example being used for electricity. Bigger glaciers create more discharge, which is why they are used for such purposes. The cool year of 2007 in the study has limited discharge leading to the temperature of the meltwater being much warmer in the particular year. Within the future Moore et al (2009) theorise that as glaciers fall in mass and size the discharge will be lower leading to radiation and air temperature having a greater effect on warming and therefore, making the water temperature higher on average with falling discharge being the main contributing factor in to water temperature rising. As the results showed at this particular moment in time as discharge rises so does the minimum monthly temperature, this may only be very slightly but the rise is still there, although on average the temperature is lower. As glacier recession occurs, a percentage of river flow in excess of that related to existing precipitation, a deglaciation discharge dividend is added to basin runoff from reduction of water stored as ice (Collins, 2008). Earlier Collins work shows that precipitation is more of a variable than air temperature and considerably modifies runoff through the interaction effect in the glacierised area of a basin (Collins, 1990). Collins explains that glaciers such as Findelengletscher will reduce and allow longer transit time therefore leading to warmer meltwater. Meltwater transit time is key to warming, glacier size is irrelevant in water warming the longer the transit time the higher meltwater temperature will rise.

5.6 Individual months

Within the month of August the discharge is limited within three specific periods of time when the air temperature drops below 0°C, with discharge

being limited. Daily graphs show that the temperature is higher on a daily basis, especially in specific days where radiation is high and intense heating is occurring. Gornera's water temperature peaks when air temperature is at its lowest and discharge is limited as shown in figure 16; discharge could be limited by snowfall, water temperature peaks at 1.2°C. Deas (2012) showed that in his experiment that stream temperature increases were driven by the start of the low flow period because the thermal mass of water was reduced and was able to heat up quicker and reach higher temperatures. As the experiment was conducted in the late summer/early winter months it is after the highest summer melting has occurred and the temperature is decreasing into the winter months, meaning that discharge will be lower with lower temperature and the warming of meltwater will be less effected in comparison to the summer months. Deas, results also show that for every rise in air temperature of 2°C water temperature increased by 1.6°C. This specific calculation cannot be conducted in the experiment but it goes to support that with rising air temperature and higher discharge this brings, the water temperature does rise. The period of September that was recorded for both meltwater streams was a relatively warm period for the time of year with Findelenbach's discharge reaching $6.5 \text{ m}^3 \text{ s}^{-1}$ with Gornera reaching $9.1 \text{ m}^3 \text{ s}^{-1}$. With water temperatures being respectively 3°C and 1°C the high discharges over the day have lead to low temperatures when at its peak. When discharges are at their highest the water temperature is at it's lowest; figure 19 from the results section shows this clearly. Air temperature is followed closely by the water temperature with its rise and fall. When discharge starts to rise water temperature falls and while discharge is at its peak water temperature is at its lowest within the day. Weather it is a warm or cold day the rises in discharge will lead to the water temperature being at its lowest.

5.7 Radiation

As 2007 was overall classed as a cold year the snow will take longer to melt and will lead to the discharge being lower. Peaks in discharge will be later in the summer, rather than a warm year where snow would be melted earlier and the peaks would be in the early summer months where melting power is at its maximum. The sooner and higher the transient snowline rises in early summer, the thicker the layer of ice melted as a larger area of ice is exposed to melt for longer (Collins, 2009). Seasonal discharge patterns are created by the following seasonal temperatures, the storage stage within winter months in what is known as the solid stage followed by the release stage as summer meltwater (Rothlisberger and Lang, 1987). Discharge and air temperature and radiation are the most important contributing factors into water temperature all leading to the resulting temperature at the reading point. Discharge is the only factor that can be managed by humans to alter water temperature (Gu, 1998). With the filtering system put in at Gornera gauging system this could have a very small effect on the water temperature as the water is filtered into a narrow deep area not allowing for heating to occur, where the minisonde at Findelenbach is situated the data has not been influenced by humans. Even though the data may be altered by a small amount by this factor, the stream and the glacier is much bigger meaning that the water temperature will be lower at Gornera rather than Findelenbach. Within both images of Figure 51 and 52 the apparatus that is used to read the data is shown.



Figure 51. Findelenbach and data collection point . (Eyres, 2012)



Figure 52. Gornera Gauging station (Google Maps, 2014)

As shown in the hysteresis loops critical points within daily periods are key to showing when discharge in cold and warm periods affects water. Daily maximum water temperature in a diurnal cycle is an important indicator of a water body's response to weather during a diurnal period (Gu, 1998). Hysteresis in the results section show that on warmer days water rises to a greater height because of air temperature, radiation and when heating occurs. On warm days hysteresis loops that are supposed to be made is less jagged and is more rounded, unlike the cool days which have much more of an up and down set of results for example Figure 21 a cool day and Figure 18 a warm day show differences between the two. Links between discharge and temperature show that they are closely linked due to the hysteresis loops showing that temperature rises early within the day when discharge is low and then when discharge rises temperature falls, meaning discharge is a function of water temperature. When flow is large, it leads to rises in heat capacity of the river (Collins, 2009). When flow is larger in river such as Findelenbach and Gornera the water temperature will be lower. Both discharge and water temperature have an effect on each other; air temperatures leads to the rise in temperature but air temperature also leads to a higher discharge because of melting. With rising discharge there is not enough energy to warm the waters over the daily period shown in the hysteresis loops as the discharge rises at mid afternoon the temperature falls, the temperature will never rise in mid afternoon as the discharge rises, water temperature decreases. In contrast over monthly period the water temperature will rise with discharge as discussed earlier.

5.8 Overall comparisons

Both water temperature and discharge cancel out each other through energy inputs, if air temperature is high then the higher the discharge so there is not enough energy to warm up the rising daily discharges. When air temperature is cold the discharge is less because there is not enough

melting power and there is not enough energy to melt the small discharge, as air temperature is low. Radiation is key as that penetrates down into the water; radiation can penetrate the water surface area as it is much greater and less volume in the Findelenbach meaning that the water will warm. Figure 51 shows the wide, shallow meltwater stream from Findelengletscher within a warm day with high radiation would warm the small stream to high temperatures. Solar radiation and air was by far the most influential factor and a change from clear skies to overcast impacted the warming of the water and the discharge rises (Collins, 1975). In 1975 when Collins looked into sub-glacial hydrology of the same two glaciers, the reduction in radiation lead to the reduction on the height of the daily peak on Gornera. With cloud cover reducing englacial flow contributions to total flow, over a set period of time within the study. Transit time from the glacier snout to the gauging station allows radiation to warm the moving water; the longer the distance to travel the more time to warm the water. The distance from the snout at Gornera to the gauging station is approximately 1 mile, the distance between the snout and minisonde at Findelenbach is approximately 0.9 km. Meltwater temperature in Gornera should be a slightly warmer due to transit time. In the case of Findelenbach the transit time contributes minimally and if the were equidistance the water at Findelenbach would be much warmer. With the higher discharge brings reduced transit time in which energy exchange can take place (Collins, 2009). Higher discharge at Gornera all year round means that there is much less time to warming to occur, with higher discharges comes higher velocity. Within summer months the discharge is much higher meaning that the transit time is even less. August and September is a transitional period and the discharge and temperature is not higher or low. Within cold days transit time will be longer leading to the influence of more time for radiation and air temperature to heat up the stream. Warm days have more radiation and higher air temperature for the water to warm up but have a quicker transit time. Influence of transit time due to warm or cold days creating more or less discharge means that the influence transit time has, is not that influential within the individual

glaciers and their temperature because warm days have energy but not the power and cool days have time to heat but not the energy. Little heat gained in short distances between glacier portal and gauge like Findelenbach especially in September and October as falling radiation is offset by greatly reduced discharge. The time of year when water will be at its warmest due to high radiation and relatively low discharge will be spring. The cool over all year of 2007 means that the air temperature and radiation is lower with longer transit time, cool year means that water will not have the energy to warm meltwater, the study supports this with the higher air temperature leading to higher discharge leading to less transit time. With length from the glacier snout and the portal from both study glaciers means that if the water were measured at the same distance of 1.57 km the water at Findelenbach would be warmer, and if the meltwater was measured at 0.9 km away from Gornera it would be colder. With the shallower stream of Findelenbach being more sensitive to heat inputs than deeper streams (Quilty & Moore, 2007). As shown in figure 53 radiation and its effects on streams, the open valley of Findelenbach lies in the very open and is not affected by such things as trees or cliff faces. If the glacier meltwater stream travelled through a gorge like part of Gornera it has less time from radiation interact with meltwater. Thermal energy influence over low glaciated areas is minimal compared to the contribution that it has on highly glacierized basins, as both glaciers are highly glaciated thermal energy creates more melt. Although thermal energy in the higher glaciated glacier of Gornergletscher creates more melt leading to on average less warming, with the bigger body of water unable to be warmed with also reduced transit time. Heat capacity of water still shows that with bigger body of water there is still a small rise in the minimum discharge as shown in Figure 23.

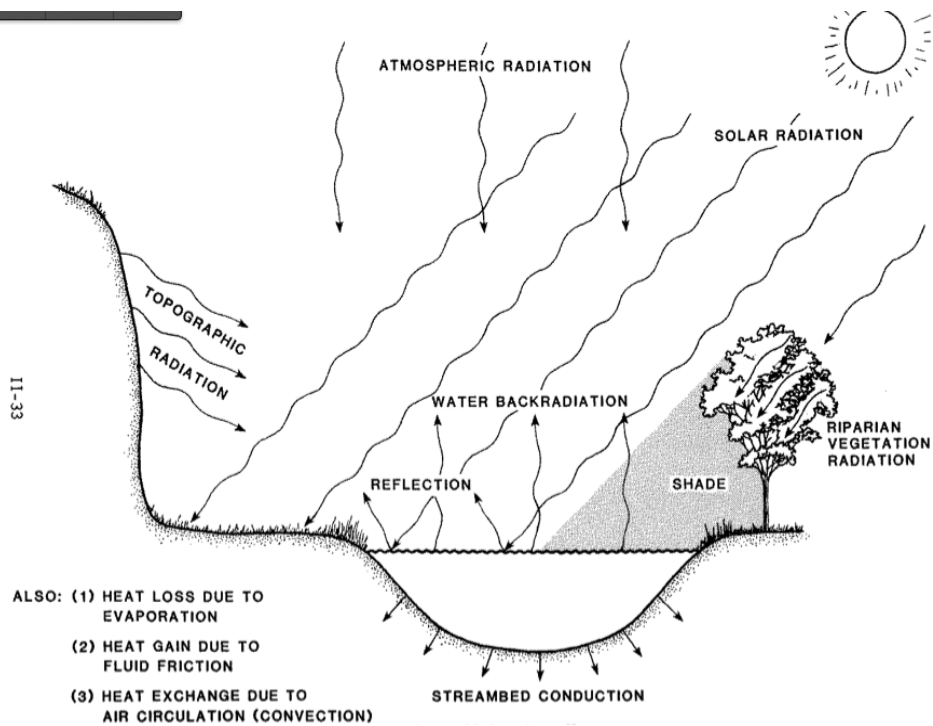


Figure 53. Radiation impacts (Theurer et al, 1984).

6.Conclusion

Meltwater temperature is influenced by many different contributing factors, with rising air temperature leading to rising discharge it is easy to come to the conclusion that meltwater gets cooler; this may occur over a diurnal period but over a monthly period the minimum water temperature rises with discharge due to air temperature rises. Throughout a yearly period increase will also occur, within the future when glaciers no longer have as much mass, the decrease in meltwater will lead to much warmer waters. Within the much bigger glacier of Gornergletscher the meltwater temperature is much cooler because of the amount of melt and the size of the glacier meltwater stream, the comparison glacier stream of Findelengletscher which is much smaller in mass has a wide shallow stream which leads to the increase in water temperature, not just over a diurnal period but all year round. Deep water of Gornera means that radiation is unable to warm the water because of its narrow and deep so limited surface area over which radiation can be exchanged. Overall climatic warming has lead to a rise in water temperature, with air temperature overall rising, the water temperature will carry on increasing.

Within the study period of 2007, which was overall a cold year, the air temperature was lower which lead to lower discharges and lower water temperature. Energy that it is required to heat the lower discharges is not there within cool days selected for the study; within warm days higher temperature do not have the energy to warm the bigger discharges. Higher water temperature within warm days occur before the lagged discharge reaches the meltwater stream, which is why overall the temperature rise over the specific months in the results section. Temperature reaches a maximum when meltwater is low and then when the lagged meltwater catches up because of glacier transit time, the water dilutes the temperature leading to the water to cool down. Key issues that are raised is that with the rising air temperature; rising discharge indicate that water

would be cooler but over a monthly period the minimum average water temperature rises due to air temperature rises.

Different time periods have different results with the future holding different prospects to the high sensitivity glacial system. Water temperature is positively related to air temperature and negatively associated with river flow/ thermal capacity (Webb, 2003; Brown et al 2006a; Brown and Hannah, 2008). With climate warming and glacier recession, stream flow is expected to decline in the long term. Thus, it may be hypothesised that water temperature will increase due to (1) an increase in atmospheric energy receipt with warmer air temperature (although radiation may be reduced by increased cloudiness) (2) a decline in the relative contribution of cold meltwater versus warmer groundwater, and (3) the reduced thermal capacity of river with lower flow (Milner et al 2009). With data generated within the study it not only supports the hypothesis put forward at the start of the study but backs up Milner hypothesis, not just in the long term but within the hot and cold days and monthly periods from the cool year of 2007. One thing that is known for certain is that climatic warming will decrease glacier size in the future and smaller glaciers will disappear in the near future.

River flow will solely reflect precipitation as the deglaciation discharge dividend declines and glaciers cease to exist. In catchments with high percentage glacierisation, discharge variation will reflect temporal variations in heat energy available for melt (Collins, 1989). Increased ice melt leading to increased discharge also enlarges the volume of water exposed to heating alongside reducing transit time from the glacier portal as velocity increases. These negative links lead to lower water temperatures even at times of high energy availability for reduced transit time in which for energy to exchange can take place. Volumetric flow of Gornergletcher even with the longer transit time than Findelengletcher shows that stream characteristics impact warming as heat capacity is raised quickly in Findelenbach. Limited time for warming from snout to data collection point is key to warming of the two glacier fed stream with one

being longer than the other. Summer months further reduce transit time in which energy exchange can take place, shown by August results being all round cooler. Transit time where meltwater can interact with outside influences such as radiation is much more significant than percentage glacierisation. Discharge and velocity combine with distance travelled to reduce transit time, if velocity and discharge are higher the shorter the travel time. Discharge isn't related to percentage glacierisation but the size of the glacier. Distance doesn't vary with percentage glacierisation, instead bigger catchment with smaller glacier has a longer distance to travel, also a elongated catchment with a big glacier can be have a long distance to travel.

Alpine meltwater temperature draining from terminus of an Alpine glacier is heated as it flows across the pro-glacial area and continues to warm with distance downstream. Air temperature drives melting with radiation increasing discharge but also warming meltwater. Surface area of Gornera and Findelenbach differ highlighting stream characteristics including length of time which time which energy exchange can take place which links inversely the volume of water to be heated. Gornera produces higher discharges producing cooler waters, with stream characteristics like Gornera does not allow much warming to occur. Findelenbach's lower discharge and wide shallow stream allow warming to occur even though the distance travelled is much less than Gornera, higher discharges increase stream velocity. It has been proven through research and backed up by results that percentage glacierisation doesn't influence meltwater as it moves downstream; stream characteristics and energy inputs influence warming.

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