Title: Meltwater temperature in streams draining Alpine glaciers

Keywords: River temperature; glacier hydrology; climate change; glacierisation; thermal regime; Findelenbach

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Abstract

Water temperature is of considerable importance with respect to lotic habitats. Water temperature influences physical, chemical and biological conditions within river environments and is, therefore, a key determiner of the health of a river. Climate change is significantly impacting lotic environments, through changes to hydrology, biodiversity and species distribution. Effects of climate change are greatest at high elevation and biota in and around glacier-fed rivers is likely, therefore, to be at great risk. How climate change influences the hydrology will have great impact on river water temperature and glacier-fed rivers in Alpine environments are extremely sensitive to climatic change. This paper assesses five rivers: Four glacier-fed rivers (36.9 - 82% percentage glacierisation) located in the Swiss Alps, and one located in an ice-free catchment in the Bernese Oberland,

Switzerland. The aim was to assess the impact of basin characteristics on river water temperature. A distinct paradoxical relationship was identified whereby water temperature in some glacier-fed rivers was reduced during the time of highest incoming shortwave radiation receipts and high air temperature. Whether a summer cooling effect presented itself in all glacier-fed rivers within this study was researched. The key findings were that the identified summer cooling effect was not present in all rivers, despite percentage glacierisation. Percentage glacier cover has often been reported as they key determiner of water temperature in such rivers. More important was the stream dimensions, notably stream surface area. Understanding the controlling factors that influence water temperature of glacier-fed rivers will help river managers and planners in knowing how climate change will impact fisheries downstream of glaciers over the coming decades. This may allow plans to be introduced to try and mitigate warmer water temperature that will result, in some glacier-fed rivers, as the climate warms.

1. Introduction

Water temperature is recognised as one of the most crucial river quality variables (Arismendi et al., 2012; Fellman et al., 2014; Hood & Berner, 2009) and has been referred to as a rivers master variable (Hannah et al., 2008; Hannah & Garner, 2015). This is because the temperature of river water influences physical and biological conditions (Robinson et al., 2001), and chemical processes within a river system (Blaen et al., 2013; Dickson et al., 2012; Woltemade and Hawkins, 2016). River temperature is, therefore, a vital determiner of the health of lotic environments. For these reasons water temperature is a crucial river variable that concerns scientists and river managers with respect to fisheries. Chemical processes including dissolved oxygen levels and the nutrient cycle within these systems are influenced by small changes in water temperature (Caissie, 2006; Mohseni et al., 2003). Species distribution, metabolism and growth rates, and food production are directly influenced by water temperature in river systems (Hannah and Garner, 2015; Milner and Petts, 1994; Milner et al., 2010). The generally low temperature of glacier-fed rivers is said to be one of the key filters preventing widespread aquatic life (Hari et al., 2006; Khamis et al., 2014; Robinson et al., 2001).

Water temperature of a river is controlled by both atmospheric energy fluxes and hydrological fluxes (Leach and Moore, 2011; Webb and Nobilis, 2007). There is also significant temporal and spatial variation in water temperature (Fellman et al., 2014). At any given point in space and time on a river, factors that determine water temperature are segregated on micro-, meso-, and macro-scale (Kurlyk et al., 2015). Those on the micro-scale include riparian shading and channel geometry (Garner et al., 2014; Hannah et al., 2008; Johnson, 2004; Malcolm et al., 2008). Meso-scale factors consist of basin hydrology and local climatic factors (Moore, 2006), and macro-scale influences include altitude and latitude (Cadbury et al., 2008). Combination of these factors drive the complex energy transfer in river systems (Figure 1) Heat exchanges occur by short-wave radiation (solar radiation), long-wave radiation (atmospheric downward radiation less emitted radiation), friction between water surface and streambed/banks, and evaporation, as well as heat exchange between the air and water (Johnson et al., 2014; Mohseni and Stefan, 1999). The net heat budget (Q_n) can be calculated using the equation:

$$Q_n = Q_{sw} + Q_{lw} + Q_e + Q_h + Q_f$$

where Q_{sw} is heat exchange due to incoming short-wave radiation, Q_{lw} is the net longwave radiation (atmospheric and emitted), Q_e is latent heat of vaporization, Q_h is sensible heat, and Q_f is frictional heat at the river bed and bank (Caissie,2006; Web et al., 2008; Fellman et al., 2014; Hannah & Garner, 2015).

The cryosphere is a sensitive indicator of climate change. Glaciers cover around 10% of the earth's surface and store 75% of the world's fresh water supplies (Fellman et al., 2014). Fluctuations in the cryosphere follows cyclical changes, and since the end of the Little Ice Age (~1860). The Little Ice Age is the period when the earth experienced its last cooling phase, following on from the Medieval Warming Period (Matthews & Briffa, 2005). Since the Little Ice Age, European glaciers have been in a state of general retreat.

Figure 1. Schematic diagram showing the heat and hydrological fluxes controlling river temperature of an Alpine stream

Atmospheric temperatures during the last three decades have been warmer than any decade since 1850 (Stocker et al., 2013), and many studies have demonstrated the rapid retreat of mountain glaciers in the majority of the earth's regions. There have been many studies modelling how glacier-fed rivers will respond to global warming and glacier retreat. As glaciers retreat, initially there will be an increase in discharge as more meltwater is produced. Eventually, however, the volume of remaining glacier ice will not be able to sustain these higher discharges, and river flow will decline as the glacier retreats further. This initial increase in discharge for rivers sourced from glaciers is termed the deglaciation discharge dividend (Collins, 2006).

Changes to river hydrology in mountain regions, as glaciers retreat, pose implications for river water temperature. Collins, (2009), Hood and Berner, (2009), and Fellman et al., (2014) have assessed the impact of stream hydrology on water temperature in glacier-fed regions. Such work analyses the percentage glaciation of the river catchment and analyses how this impacts stream temperature. These studies, however, analyse streams in highly glaciated catchments at high latitudes (Hood & Berner, 2009; Fellman et al., 2014) and narrow, fast flowing glacier-fed rivers (Collins, 2009).

Atmospheric factors (e.g., net radiation) is thought to be the most important factor driving stream temperature in rivers, attributing to more than 90% of a rivers energy budget (Webb et al, 2008). It is thought that, in mid-latitude high elevations regions atmospheric factors could account for an even higher constituent of a rivers heat budget. Hydrological factors influence on water temperature is also accentuated in such regions, as mountain glaciers considerably moderate riverflow. Over 90% of discharge in some Swiss glacier-fed rivers occurs in the months April-October, with very small or even negligible discharge in the winter months. This has implications for the temperature of glacier-fed rivers, with an almost paradoxical (Arismendi et al., 2012; Collins, 2009) or a moderating (Moore, 2006) effect occurring. Water temperature in such rivers peak early, in the spring, and is cooler during the summer months. In the current warming climate, water temperature will be positively influenced by atmospheric and environmental conditions, however this is also expected to, initially, increase riverflow, and this increase in riverflow will negatively drive water temperature (Collins, 2009).

1.1. Aims and Objectives

The principal aim of this study was to analyse water temperature of four glacier-fed streams and one non-glacier-fed stream in the Swiss Alps with basin glacier coverage, for the glacier-fed rivers, ranging from 36.9% to 83.7%. The specific objectives of this study were:

1. Develop understanding of river water temperature in rivers draining large Alpine glaciers in mid-latitude regions, developing on recent work in similar fields (e.g., Brown et al., 2006; Brown and Hannah, 2008; Cadbury et al., 2008; Collins, 2009; Hood & Berner 2009; Fellman et al., 2014).
2. Examine the influence of percentage glacierisation on meltwater temperature
3. Use multiple linear regression to determine the major influence on meltwater temperature from a range of basin and river properties, alongside the hydro-meteorological factors: Solar radiation, precipitation and riverflow.

Previous studies have assessed the water temperature of glacier-fed rivers in either catchments with litter glacier-cover (Brown et al., 2006), areas of different climatic conditions (Hood & Berner, 2009; Cadbury et al., 2008; Chikita et al., 2010; Blaen et al., 2013; Fellman et al., 2014) and that encompass a smaller range of glacier-fed river in terms of their hydromorphology (Collins, 2009). Therefore, this study will expand understanding of river temperature in a variety of high mountain glacier-fed rivers using regression models (after Fellman et al., 2014) to assess the relationship between climatic and basin factors, and river water temperature.

2. Method

2.1. Study Area

This study collated data from five catchments in the greater Upper Aare and Upper Rhône watersheds, in the Swiss Alps (Figure 2). The percentage glacier cover of basins in this study range from 0-83.7%.

Figure 2. Map of the five study basins located in the Upper Rhône and Upper Aare catchments, Switzerland.

The only river located in the greater Upper Aare catchment of Switzerland and used in this study is the Allenbach, which drains an ice-free catchment. Total area of the Allenbach catchment equates to 28.8 km^2. Discharge and water temperature are monitored as the stream flows through the village of Adelboden. Rossbach, Stigelbach, and the Gilsbach are the three tributaries to the Allenbach. The average elevation of the basin is 1856 m a.s.l. Discharge maxima happens in the spring and early summer, usually as early as April and as late as July. Measurements are recorded and provided by the Swiss Federal Department for the Environment, Transport, Energy and Communication's Bundesamt für Umwelt (BAFU).

Of the glacierised catchments, the Lonza is the least glacierised (36.5%) despite areal ice coverage being large, with total ice area equating to 77.8 km^2. Draining the Langgletscher, with several smaller contiguous glaciers, elevation ranges of the glaciated region of the Lonza basin range from 2450 to 3005 m a.s.l. with the basin upper-boundaries defined by the Mittaghorn, Grosshorn and Sattlehorn. The average elevation of the catchment is 2630 m a.s.l., and the river is monitored at a gauging station in Blatten, 8.9 km downstream of glacier.

The Massa is the largest catchment in this study (195 km^2), yet is the third most glacierised (65.9%). The main glacier in the basin is the Grosser Aletschgletcher (1760-4195 m a.s.l.) the river has been monitored year-round 2.4 km downstream of the glacier portal by BAFU since 2003.

Findelen is located close to the town of Zermatt and has been maintained by the Alpine Glacier Project (AGP) for the past 40 years. During this time the AGP has amassed one of the longest collection of Alpine glacier meltwater data in the world. Since 2003, with the introduction of automatic water quality loggers, water temperature has been monitored every summer field season close to a hydroelectric intake around 1 km from the glacier portal. Here, water from the Findelenbach is collected and contributes to the Grand Dixence hydroelectric power generation. Findelenbach accounts for only 5% of the greater Grand Dixence watershed. As a result, discharge is monitored year-round by the Grand Dixence S.A. power company, who kindly make the data available to the Alpine Glacier Project. The Findelen basin is 24.9 km^2 and is 73% glacierised.

Contiguous to the Findelen catchment, is the Gornera basin. The Gornera is the second largest catchment in this study, with an area measuring 82 km^2, and elevations ranging from 2005 to 4636 m a.s.l. Switzerland's second largest glacier, Gornergletscher, is the principal glacier in this basin, covering an area of 60 km^2 (Huss et al., 2007). The Gornera catchment (83.7% glacier covered) was the most glacier covered catchment of this study. Measurements are taken 1.5 km from the portal of Gornergletscher and, as with the Findelen catchment, discharge is measured and provided by the Grand Dixence S.A., at their hydroelectric intake. Stream temperature is recorded throughout the summer field season by the Alpine Glacier Project (AGP) researchers. An overview of the study basins is given in Table 1.

Table 1: Characteristics of the five study basins used in this study

2.2 Measurements

For the Massa, Lonza and Allenbach data were collected for the period of 1 January 2003 and 31 December 2016 by the Swiss Federal Department for the Environment, Transport, Energy and Communication's Bundesamt für Umwelt (BAFU). Water temperature and discharge measurements are taken hourly throughout the sampling period. At the AGP's Findelen and Gornera basins, both water temperature and discharge measurements were collected throughout the ablation season for the years 2003-2016, with precise dates depending on access to the field site each year. Stream temperature was recorded at the AGP's Gornera and Findelen basins with Hydrolab MS5 Minisondes with a temperature sensor (accurate to 0.10 °C, measuring at a resolution of 0.01 °C). Validation of Minisonde data was conducted in more recent years with the use of a secondary set of temperature data instruments. Since 2013, a set of Tiny Tag Aquatic 2 data loggers have been used alongside the Hydrolab MS5 Minisondes. Tests of the instrument's reliability, consistency and measurement stability can be conducted using the pair of instruments in tandem.

Data provided by BAFU were pre-processed prior to public availability. Data collected through the AGP also required pre-processing; for example, as no permanent fixture was available close to the Findelenbach, the data logger was situated on the river bank. However, due to weather anomalies and lower meltwater resulting in a fall in water level let to the temperature sensor rising above the water level. This data was therefore removed.

Furthermore, there were issues with minisonde battery life being reduced because of the environmental and water damage. Data provided from the Grande Dixence, also needed to be pre-processed, with data points removed from the dataset. This was required due to the de-gravelling process that is conducted by the hydroelectric power company. De-gravelling is a process where large volumes of water is flushed through the system to remove sediment that has built up due to the high suspended sediment present in glacier-fed rivers. As a result of de-gravelling, discharge readings would spike usually once during the early morning, and once in the evening during the summer months. A simple data processing script was developed to remove all spikes in discharge data before data analysis was undertaken. To find the associated errors within the collected data sets, analysis of the data was conducted using the R programming language (R Core Team, 2013). An R script was created that would assess each value within the data set and compare it to the previous and next datapoint. The indices of these values were printed and the datapoints were assessed manually to determine if they were correct or errors. Most of the errors occurred during degravelling processes that usually occurred at regularly spaced intervals easing the data correction process. In terms of sensors temporarily exiting the water, when river flows declined, a similar script was developed. This would simply look for values higher than the expected maximum data and remove datapoints that were within this range.

Solar radiation data was obtained by MeteoSwiss (Federal Office for Meteorology and Climatology, Switzerland). The closest long-term data available for this study were measurements made in the town of Zermatt (1608 m a.s.l). It is assumed that there is little variation in solar radiation across the study sites, and the solar radiation measured at Zermatt would be analogous to that across the region where the study was conducted. Similarly, precipitation values were obtained, through MeteoSwiss, for the Zermatt region.

This was used to indicate the influence of the preceding winters precipitation, in the form of snowfall, on the following summer riverflow and therefore water temperature. Both solar radiation and precipitation data was available year-round throughout the period, 1 January 2003 to 31 December 2016.

After Fellman et al (2014) multiple linear regression was employed to assess relationships between catchment variables, environmental variables and meltwater temperature characteristics. The hourly data samples were averaged over monthly periods to provide mean monthly water temperature at each river. It was required, therefore, that this analysis could only be conducted on months in which there were no gaps in the data set

For year to year comparison and presentation of water temperature and discharge, averages of 7-day measurements were taken. Maximum Weekly Water Temperature (MWAT) statistic was calculated. MWAT is a metric of water temperature, the seasonal maximum of 7-day average temperatures. This is a useful technique for comparing water temperature as it is said to smooth out the dataset and correlates well with various environmental and biological indices (Fellman et al., 2014). As a result of averaging over 7-day periods beginning on 1 January, 29 February during a leap year is the same day of the year as 1 March in a non-leap year (Day 60). An 8-day week therefore occurs at the end of the year during Week 52.

Stream and basin characteristics were calculated using a combination of analysis of ASTER imagery within ArcGIS alongside analysis of satellite imagery from Google Earth. River length was calculated alongside widths at 10 m intervals to calculate stream surface area. River width was calculated using imagery photographed in the summer months to ensure discharge was at high levels. Assessment of discharge data for the month in which satellite imagery was used, ensured that the river level corresponded to river levels during the months selected for cross-river analysis. Percentage glacierisation statistics were obtained from BAFU for the Massa, Lonza and Allenbach basins, and recent literature for the Findelenbach and Gornera.

3. Results

3.1. Solar radiation

Seasonal patterns of solar radiation followed typical cycle for a mid-latitude region of the globe. Measured solar radiation in Zermatt, rises to a peak in late June, close to the summer solstice, then begins to decline to a minimum in late December during the time of the winter solstice. 2003, 2009, 2012, and 2015 were the that witness highest average summer air temperature, measuring 19.9 °C, 18.7 °C, 18.7 °C and 19.2 °C respectively. This study demonstrated that these years of high summer air temperatures also witness high levels of spring solar radiation, however, years of greatest solar radiation do not necessarily correlate with highest average summer temperature. For example, the year of highest maximum solar radiation was 2013.

3.2. Precipitation

Measurements of precipitation for the Zermatt region were assessed for this study as they provide a surrogate measure indicating the extent of the winter snowpack in the preceding winter prior to each summer ablation season. Winter precipitation observations provide an interesting insight for glacier hydrology studies as the total and extent of winter snow will impact seasonal stream hydrology and therefore, temperature. Snowfall influences runoff regimes in glacier-fed river catchments (Collins, 2006). Discharge from glacier-fed river catchments will rise earlier or later in the season dependent on the extent of winter snow cover. The timing of high volumetric flow is important for water temperature studies, as this will affect the heating capacity of the river. Secondly, liquid precipitation throughout the ablation season will provide warmer runoff, increasing meltwater temperature in the glacier-fed river catchments. The driest year of the study period was 2003 where rainfall remained low throughout the calendar year (7-day total precipitation maximum = 25.9 mm). Following this dry year, the years 2004-2007 saw higher precipitation totals with maxima 7-day total occurring during 2007, 103.4 mm. For winter precipitation (P_{11-5}), herein defined as precipitation total for the period of 1 November – 31 May, the greatest winter precipitation total occurred during 2013-14 totalling 469.7 mm. Only in two other accumulation seasons did precipitation total greater than 400 mm, 2008-09 (422.4 mm) and 2012-13 (444.4 mm). The driest winter was that of 2003-04 where only 163.8 mm of precipitation fell. The only other year in which precipitation equated to less than 200 mm was 2010-11 when winter precipitation totalled 164.4 mm. The average winter precipitation total throughout the study period was 329.9 mm.

3.3. River flow

Measurements of discharge from Swiss catchments are abundant, with complete year-round series available at hourly interval. Data collected by hydroelectric power companies, e.g., the Grande Dixence S.A., are gauged at many intake points, often immediately downstream of glaciers, where meltwater is extracted. Assessing the seasonal variation in river flow, both the Massa and Lonza are demonstrative of the typical discharge regimes expected of river draining glacierised Alpine catchments. Runoff in the winter months, herein defined as the months October through to November, make up <10% of annual runoff. Throughout April and May, river discharge increases from minimum flow as a result of increasing energy availability and, in turn, melt production. As winter snow melts, and with the rising transient snowline, surface albedo across the glacier surface declines; owing the albedo of ice, 0.3, being lower than that of snow, 0.7, (Braithwaite, 1995). This leads to melt production continuing to rise through June and July, after levels of shortwave radiation begin to decline. Total melt production is driven by both the rate of melt, and the area of ice exposed to net radiation. As net radiation levels fall, the area of glacier surface that is reflecting the vast majority of radiation falls, as the snow cover melts, and the area where more radiation is absorbed increases, as more ice is exposed. Maximum runoff, therefore, occurs in July or August sometime after the maximum level of short-wave radiation in the month of June.

For the ice-free Allenbach, discharge increases throughout April and peaks during May. Discharges of the Allenbach are reduced in June/July, as the snowpack from the previous winter is exhausted. Following this point, runoff in the Allenbach largely reflects precipitation. For the three catchments, Massa and Lonza (glacier-fed) and the Allenbach (ice-free) rivers standard deviation of seasonal riverflow declines with catchment percentage glacierisation. Standard deviation of riverflow falls substantially for rivers that drain catchments of lower than 50 percentage glacierisation, (e.g. Lonza at 3.69 $x10^6$ m^3) and in the Allenbach standard deviation of riverflow is nominal (0.44 $x10^6$ m^3). Comparatively, in the highly glacierised Massa standard deviation of riverflow equated to 16.7 $x10^6$ m^3. Figure 3 illustrates the important difference between glacier-fed seasonal river flows and those of ice-free catchments, even a small glacier will moderate riverflow in an Alpine catchment owing to ice presence.

Figure 3. Average 7-day actual discharge for the Allenbach, Lonza and Massa rivers for the period 2003-2016

Maximum discharge rises with percentage glacierisation, being highest in the Massa and lowest in the ice-free Allenbach. Seasonally variation in river discharge in those that drain glaciers is greater than those that do not. Glacier coverage influences discharge of a basin, a small glacier will moderate flow, reducing variation however, when glacierisation of the basin rises above ~25%, glaciers increase variation substantially, with over 90% of discharge being delayed into the months of April to October.

The ratio of standard deviation to the mean is useful for seasonal comparison of runoff variability across multiple river catchments (Collins, 2006). This Coefficient of Variation (CV), shows that week to week variation in runoff was greatest in the Massa, averaging 1.29 across the study years, averaged 1.07 in the Lonza, and was lowest in the Allenbach with an average of 0.87. There appeared to be no clear link between summer temperatures and week-to-week coefficient of variation in any of the three catchments assessed. Nor did there appear to be a link between coefficient of variation of discharge and winter precipitation of the previous winter and coefficient of variation of discharge.

3.4. Water Temperature

Water temperature of the Allenbach (0% glacierisation) typically reflect those of snow-melt fed rivers. In such streams, water temperature rises in-line with incoming short-wave radiation, January and June, as shown in Figure 4a. Water temperature continues to rise, consistently reaching their maximum about six weeks following peak solar radiation receipts. Water temperature in the Allenbach then fall in July and August, when solar radiation receipts are substantially lower.

Figure 4. Mean average of seasonal water temperature regime for the Allenbach (a), Lonza (b), and Massa (c) for the period 2003-2016.

Despite there being an influence from ice-melt in the Lonza basin (36.5% glacierised), the water temperature of the Lonza demonstrates similar seasonal variation, to that of the ice-free Allenbach (Figure 4b). Although variation in riverflow in the Lonza catchment resembles that of a typical glacier-fed river, volume of water is lower when compared to some of the more highly glacierised catchments. As a result, the water temperature regime of the Lonza mimics that of the ice-free Allenbach in shape. However, one succinct difference between the Lonza and the Allenbach is the much lower water temperature maximum that water will rise to.

In agreement with other studies recently undertaken in this field, basins that are more than 50% glacierised, such as the Massa at 65.9% (Figure 4c.), demonstrate a unique thermal regime. Water temperature of meltwaters that drain more glaciated watersheds initially increase in tandem with received short-wave radiation. The water temperature regime of rivers in such catchments are unusual in that maximum temperature happens early in the year, during spring months of April and May. Peak water temperature occurs, therefore, prior to maximum solar radiation receipts and air temperature maximum. Importantly, water temperature in rivers draining the most highly glacierised catchments are not able to warm as much and are less variable than those draining the less glacierised basins.

For the Massa (Table 2), on average the week of water temperature maximum occur 16 weeks prior to those of the Lonza and Allenbach rivers. Both the Lonza and the ice-free

Allenbach tend to see MWAT occur during week 32 (06 – 12 August) of the year, as opposed to week 16 (16 – 22 April) for the Massa, despite the Lonza having a glacier influence. Generally, the ice-free Allenbach will see an earlier MWAT than the glacier-fed Lonza, probably as a result of the greater volume of water being warmed in the Lonza than that of the Allenbach.

Table 2. Maximum weekly average temperature statistics for the Allenbach, Lonza and Massa rivers for the period 2003-2016.

Figure 5a illustrates water temperature of the five study catchments for the period 26 June – 10 September 2006. Water temperature of the Findelenbach, and more so the Gornera, are low throughout this summer months, with little variation, similar to the those of the Massa. Stream temperatures in the Findelenbach and Gornera are highly responsive to hydroclimatological perturbations. Both rivers appear more responsive to precipitation events, with summer rainfall positively affecting water temperature. When assessing the water temperature of the Findelenbach and Gornera, it is clear that the Findelenbach warms to a higher degree than the Gornera, this is in line with previous thinking whereby the river draining the more highly glacierised catchment has lower water temperatures. Surprisingly, however, maximum weekly water temperatures of the Findelenbach are warmer than those of the Massa despite the Massa draining a less glacierised catchment.

Thermal characteristics of the Findelenbach are different to the Massa and Gornera, Figure 5b, with lower minima and higher maxima water temperature. This greater range in temperature, suggests that unlike the other two rivers draining highly glacierised catchments heat exchange constituents are holding different influences over the Findelebach when compared to the Massa and Gornera.

These data suggest that stream temperatures of the Gornera and Massa are influenced by forces other than solar radiation and air temperature, potentially solely reflecting heat generated from the conversion of potential energy to kinetic energy as the river flows downstream. Assessing the Lonza and Allenbach, less or no glacier influence, it could be assumed that throughout July the weather was warm with lots of available solar radiation, as water temperatures were therefore able to rise. At the beginning of August, the temperature of both streams falls, suggesting that the weather became cooler with more cloud cover inhibiting the received solar radiation at the stream surface. This theory is corroborated in the Massa where the temperature rises and becomes more variable during this time, hinting that the volume of water in the channel decreased as there was less solar radiation and therefore less ice melt. As a result, water was flowing more slowly which would increase the residence time of water within the channel, despite the levels of solar radiation being lower.

Figure 5. a). hourly water temperature observations of the five study catchments and b). box plot showing river temperatures across the five study catchments for the period 26 June 2006 – 10 September 2006.

The multiple linear regression (MLR) used here assessed the relationship between 7-day mean stream temperature and 7-day receipts of solar radiation, 7-day precipitation totals and 7-day average river flow. 7-day statistics were used as they moderate extremes and provide better fit for modelling (Kelleher *et al.*, 2012). To ensure comparison would provide useful information, standardised coefficients (β_{std}), were utilised. β_{std} requires the data to be standardised, such as the variance is equal to 1. This allows the statistics to be comparable across each predictor variable and allows direct comparison of which independent variable is having greatest effect on the dependant variable.

MLR was first conducted across the three study sites for which data is available year-round, including the non-glacierised Allenbach. For consistency, the year 2006 was used for the MLR analysis as it provided good comparison with the second model which incorporated the Gornera and Findelenbach rivers. Owing to a complete data set, with no gaps in the data across all sites, the calendar month of August 2006 was selected for the second MLR model.

To assess the basin properties that most influence water temperature across all five of the study catchments, three basin properties were selected (Table 3). Monthly averages were computed for the water temperature of all five river in this study. When assessing the regression of all five study basins, it was clear that, in-line with the findings of most other studies (Collins, 2009; Fellman et al., 2014; Stahl and Moore, 2006), that percentage glacier cover of the basin, had the greatest effect (β_{std} = -1.11) on stream temperature in the rivers draining those valleys (R^2_{adj}=0.99, y = 0 + -1.11* %Glac + 0.19 * GaugElev +0.12 * StreamArea). However, when assessing the glacier-fed rivers only, stream surface area was a stronger determiner of water temperature (R^2_{adj}=0.92, y = -0.31 + 0.46 * StreamArea + -0.35 * %Glac). Generally, it will be the case that streams of greater percentage glacierisation will be narrower and shorter owing to the basin hypsometry in a glaciated catchment, however this does not always hold true, as displayed by the Findelenbach (Table 1). Percentage glacierisation could, therefore, be said to be a surrogate for stream surface area and in most cases, this would hold true and explain the strong relationship found in previous studies (e.g., Fellman et al., 2014).

Table 3. Statistics of multiple linear regression models of percentage glacierisation, and stream surface area, gauge elevation, and monthly average water temperature for the period 1 August – 31 August 2006 for the five rivers in this study including the ice-free Allenbach, and of multiple linear regression models of percentage glacierisation, and stream surface area, and monthly average water temperature for the period 1 August – 31 August 2006 for only the four glacier-fed rivers in this study .

4. Discussion

Seasonal variation in water temperature in the three study basins, where year-round data are available, is in line with those in other studies including those assessing streams in other regions of the globe. However, when assessing the five study basins, some interesting results have been obtained. Interestingly, this study has highlighted the phenomena first suggested by Collins, 2009 whereby the seasonal thermal regime of rivers that drain highly glacierised basins (i.e., >50%) displays a spring maximum (Collins, 2009; Fellman *et al.*, 2014). This unusual thermal regime sees warming temperatures in line with increasing levels of solar radiation up to a peak after which water temperatures then begin to decline slightly and remain subdued, with little variation, for the entirety of the summer period (May to September). At the end of the summer period water temperatures briefly rise, before decreasing following the falling levels of incoming shortwave radiation.

Meltwater temperatures are subdued as a result of summer discharge from glaciers. Summer discharges from Alpine glaciers account for over 90% of total annual flow (Figure 3 and Figure 4). Outside of this summer period meltwater production is low, if not negligible, and under these conditions meltwaters are quick to respond to energy inputs and therefore able to warm rapidly. However, discharges rapidly rise in the spring and, despite higher levels of energy being available, it becomes more difficult to heat meltwaters when volume of flow is greater.

Seasonal thermal regimes for basins lower than 50% appear to be remarkably similar in shape to basins where there is no ice influence. River flow for rivers draining even a slightly glacierised catchment are highly variable and the high summer discharges recorded in the Lonza (36.5% glacierised) do appear to influence water temperature and this is reflected in the reduced water temperatures of the Lonza when compared to the ice-free Allenbach.

Seasonal variation in river flow of catchments in the European Alps is well understood (Collins, 1989). For glacier-fed rivers timing of maximum water temperature appears to be dependent on the time of increasing discharge. MWAT for the highly glacierised Massa show that Maximum water temperature occurs anywhere between early-April and mid-May. The data shows that there is no link between warm summers and reduced water temperature in glacier-fed rivers, however. For glacier-fed rivers it is likely that timing and magnitude of maximum water temperature in the Spring is influenced by both short-wave radiation receipts in first fourth months of the year, as well as the extent of the winter snowfall over the preceding winter. Winter precipitation will have a clear influence over the timing of rising discharge and, therefore, modify the temperature regime accordingly. Should winter snowfall of the preceding winter be high, the extent of the winter snowpack will be greater, and meltwater production will be delayed. During dry winters, the winter snowline will be higher in the valley and more ice will be exposed to incoming short-wave radiation in the spring. In this scenario, there will be more ice-melt earlier in the year and discharges will rise sooner and potentially be of a greater magnitude (Fleming, 2005). The data used in this study could not definitively show the influence of winter precipitation on water temperature of alpine streams, further studies of the long-term data available linked with meteorological variables not utilised in the present study, e.g., summer air temperature, would be of interest. The results of this cursory analysis linking winter precipitation and summer stream temperature indicate a more in-depth relationship between winter snowfall, discharge, summer air temperature and summer insolation.

Prior to reaching their spring maxima, water temperature in glacier-fed rivers that drain the most highly glacierised catchments show strong daily and seasonal variation. After their spring maxima, daily and seasonal ranges fall dramatically, notably throughout June – September. The unusual summer thermal regime that is unique to highly glacierised glacier-fed rivers is triggered by an increase in discharge within ~10% of the annual total (Figure 3 and Figure 4). Further increases in river flow have little influence over the water temperature.

Previous studies have often suggested that the basin percentage glacier cover is the key determiner of stream temperatures in glacier-fed rivers (Collins, 2009; Fellman et al., 2014; Hood and Berner, 2009; Moore, 2006; Stahl and Moore, 2006). The results of this study suggest that there is a more complex interaction between basin controls and the temperature of glacier-fed streams.

Short-wave radiation was a good predictor for the 7-day mean stream temperature of the Massa, Lonza and Allenbach rivers. Regression slopes when assessing incoming solar radiation increased, albeit only slightly, with rising basin percentage glacierisation. Precipitation also positively influenced water temperature in the three of the catchments.

When assessing the Massa (65.9% glacierised), incoming solar radiation was the best determiner (ranging βstd across the study years from 0.67 to 1.07) for river temperature. Also holding a positive influence over stream temperature (ranging βstd across the study years from 0.11 to 0.29) was precipitation, with the low βstd coefficients indicating a lesser impact that precipitation has as a predictor. As expected, there is a negative relationship between riverflow in the Massa and river temperature (ranging βstd across the study years from -0.04 to -0.38). This corroborates research of North American (Fellman et al., 2014; Moore, 2006) ice-melt-fed rivers, potentially suggesting that the large rise in cold ice-melt during summer months negatively drives river temperature (Uehinger et al., 2003). Low adjusted R^2 values, however, were often demonstrated when assessing the relationship of discharge and water temperature. This is likely due to the reason that as radiation increases, ice-melt from the glacier system significantly reduce water temperatures. As suggested previously, as riverflow increases there is an initial reduction in water temperature. However, as discharge rises further, there appears to be no greater reduction in the temperature of a stream. This suggests that glacier-fed river temperature is not a driven by simple relation between quantity of runoff produced and its greater heating capacity (Gu and Li, 2002), instead there may be a more complex interaction between riverflow, and river dynamics, together with cold ice-melt inputs.

In terms of basin controls over stream temperature, stream surface area was the greatest predictor for the rivers in this study during the month of August, 2006. This explains previous findings, in most glacierised catchments where percentage glacierisation is significant, stream lengths are usually low and stream widths are often confined to steep valley walls. This is true for both the highly glacierised Gornera and Massa. Previous work has demonstrated that stream length is one of the key basin characteristics that influence water temperature (Brown and Hannah, 2007). The Findelenbach however, is much wider as the river is able to widen significantly with rising discharge, thanks to the network of channels that make up the braided channel system. On the other hand, with rising discharge, the Massa and Gornera are confined by their basin profile and have to, therefore, deepen and flow faster. It becomes difficult for heat exchange to occur as residence time is reduced. In the Findelenbach, residence times are longer and the channel is shallower and as a result incoming solar radiation holds much greater control over stream temperature. This allows the Findelenbach to warm to higher temperatures than would be expected for such a highly glacierised catchment and not follow the typical seasonal thermal regime of rivers draining other highly glacierised catchments.

The analysis of data within this study, along with the results of the multiple linear regression, suggest that reduced summer water temperatures, for some glacier-fed rivers, are less influenced by incoming solar radiation than originally thought. It is likely that, as found in Chikita et al. (2010), the greatest component of the heat budget in glacier-fed rivers within narrow channels is friction, the conversion of potential energy to kinetic energy as the river flows down valley. An in-depth heat budget study, of the Gornera and Massa rivers, should be conducted to ascertain if this theory holds true. This theory explains the unique thermal regime of some glacier-fed rivers. Rising water temperature in line with solar radiation is thwarted as river levels begin to rise in the Spring. Such rivers reflect rising discharge by deepening and increased velocity, as this point solar radiation is unable to warm the greater volume of water within in the channel. Throughout the summer months therefore, when discharge of glacier-fed rivers remains high, water temperature is reflecting greater warming from other components of the heat budget. Once discharge subsides in the late summer, temperatures again are influenced, principally, by solar radiation and therefore rise before declining with falling levels of solar radiation to its minimum at the winter solstice.

This study proposes an interesting discussion regarding the response of glacier-fed river temperature to a warming climate. During a time of deglaciation, a retreating glacier will result in river length increasing and, augmented by the deglaciation discharge dividend, an initial rise in river flow from rivers draining glaciated basins. In terms of river temperature response to a retreating glacier, the longer stream length will result in increased residence time (between glacier portal and gauging point), however, the rising volume of water within the channel will decrease residence time, assuming the river flows more quickly as discharge rises. Residence time will directly increase water temperature, as an aliquot of water moving through the system will reside in the channel longer. Rising discharge will, however, mean there will be direct decrease in water temperature as there is a bigger volume of water to be warmed within the reach. However, for this to hold true, and posed by the results of this paper, what is important is how the river responds to rising discharge (Figure 6). Rising river flow will increase velocity, depth, and width. How rivers respond is important, as these three variables have different impacts on stream temperature. Both increased velocity and depth will negatively impact temperature, but width will positively impact temperature as there is a wider area for which heat exchange can take place. In rivers which widen as discharge rises, such as the Findelenbach, will see temperatures also rise in a warming climate. In rivers which instead deepen and flow more quickly, such as the Gornera and Massa, temperature will likely fall as the climate warms and glaciers retreat.

Figure 6. Schematic diagram showing the response of melt water temperature to deglaciation in a glacier-fed river catchment, as well as the response of melt water temperature to increasing discharge and changes in stream width, depth, and velocity.

5. Conclusion

Previous studies have demonstrated that discharge from highly glacierised catchments holds a strong control over water temperature (Collins, 2009; Hood & Berner 2009; Fellman et al., 2014). This theory implies that warm summers with high ice melt will lead to cooler water temperatures. The more glaciated the catchment from which a river drains, the cooler the spring water temperature will be. Such rivers have a unique temperature regime whereby they reach their maxima during the spring and remain consistent and cool throughout the summer, catchments of less than 50% glacierisation do not follow this pattern, with maximum temperatures occurring later in the year and following direct solar radiation. This study, however, has demonstrated that in some circumstances, water temperature of glacier-fed rivers does not follow this pattern. One glacier-fed river in Switzerland, which has been the focus of a stream temperature study since 2003 demonstrates an unusual temperature regime when considering its catchment is over 70% glacierised. It raises questions, to which further studies must be undertaken, as to what the main control of water temperature is in high mountain environments at mid-latitude regions of the globe. The results of this small study potentially indicate that the main control of water temperature during periods of low river flow is solar radiation. However, after river flow surpasses a critical point, solar radiation is not able to excerpt its influence and becomes of less importance in the transfer of energy from the atmosphere to the river.

This is a response to numerous factors including, water velocity, volume and residence time but also channel morphology.

The interesting findings of warmer than expected temperature in the Findelenbach suggests that stream surface area is a key variable in influencing water temperature in high mountain catchments. It poses interesting questions to how the river will respond to a period of climatic change and deglaciation. Augmented by the deglaciation discharge dividend, river flow from glaciated catchments will initially rise, before eventually falling as the ever-shrinking volume of glacier ice will be unable to sustain high river flows. This study suggests that in rivers such as the Findelenbach, where the river is not contained by steep valley sides, increasing river flow will result in a wider river, coupled with the retreat of the glacier increasing the stream length, the surface area of the river will increase and therefore, the water will reach higher temperatures. Previous studies would imply that in the most glaciated catchments there will likely be a decrease in water temperature as glacier-ice melts and river flow increases. Further study into the three highly glaciated catchments used herein should be undertaken to see if this holds true for the Massa and Gornera rivers.

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