Proglacial lake and Rhone river measurements

Tomohiro M. NAKAYAMA, Arlec CHANG

* * * * *

Master’s in Cryosphere Science, Graduate School of
Environmental Science

* * * * *

September 30, 2024

Contents

Proglacial lake and Rhone river measurements

Tomohiro M. NAKAYAMA, Arlec CHANG

September 30, 2024

1 Introduction

In the first half of 21st century, significant retreat and thinning of mountain glaciers were observed worldwide. The global ice mass loss from 2000 to 2019 was −266.6 Gt a^{-1}, with large contributions from glaciers in the arctic regions such as Alaska and Canadian Arctic (Figure 1). Glaciers in Central Europe, while with a small average mass change rate of −1.69 Gt a^{-1}, experienced a consistently large elevation change rate over this ten-year-period (an average of −1.02 m a^{-1}) (Hugonnet et al., 2021). Glacier thinning and retreat at such rate would lead to formation of proglacial, marginal or supraglacial lakes, which can give rise to GLOFs (Glacial Lake Outburst Floods) when lake barriers collapsed, or result in serious landslides due to the exposed unstable valley walls. At Rhone Glacier in Swiss Alps, a lake was formed in front of the terminus since 2000, which underwent an expansion in the subsequent years (Figure 2). Although the lake is barriered by bedrock instead of terminal moraine, which is relatively vulnerable in structure, there is still possibility of break-off of GLOFs in the future as the lake continues to grow in area and volume. Therefore, in order to assess the current situation, we applied field measurements as in the previous years of monitoring the behaviour of the proglacial lake and the river by conducting meteorological- and hydrological observations from August 29th to September 1st, 2024.

The past reports of the Swiss Alps Glacier Field Course neglected to discuss the observation methods and the errors caused by the observations, which is a problem because it is difficult to know how correct the observation sites are. Therefore, the causes of the errors caused by the observations and measures to improve them are also proposed.

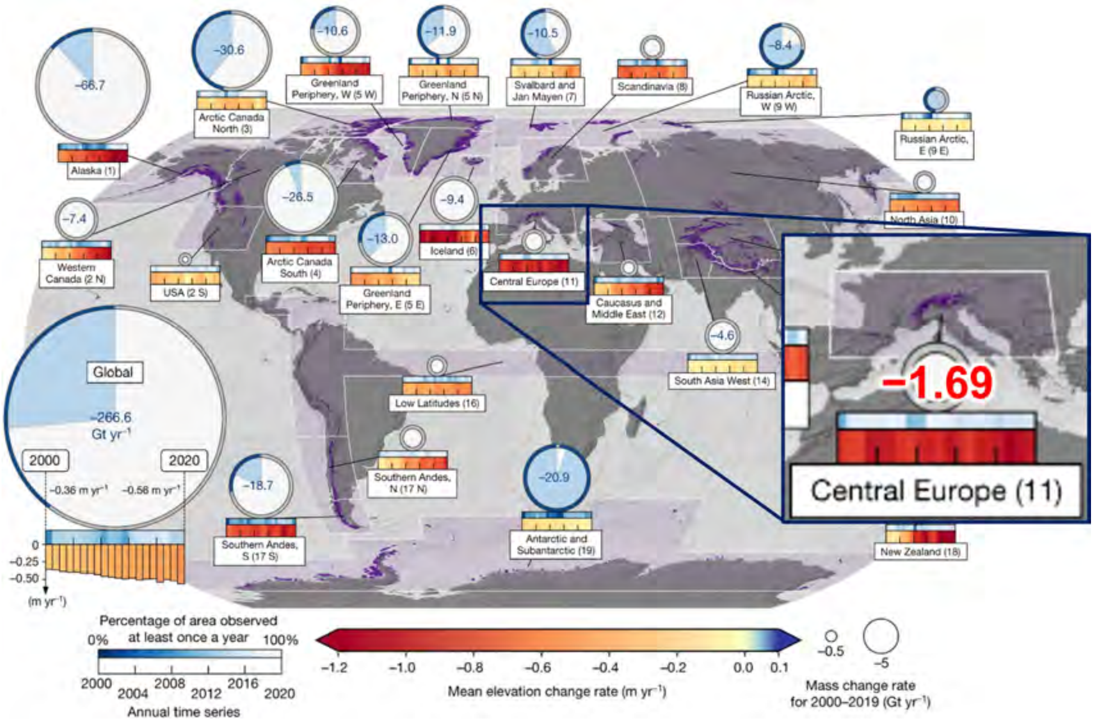


Figure 1: Regional glacier mass changes from 2000 to 2019. The enlarged figure illustrates the average mass change for the Central Europe area (Hugonnet et al., 2021).

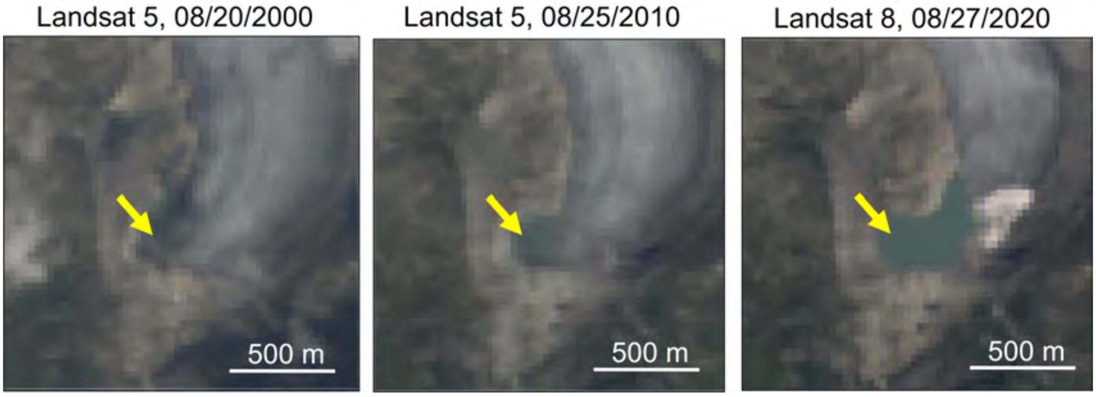


Figure 2: Formation and expansion of the proglacial lake at Rhone Glacier in 2000, 2010, and 2020. The arrow indicates the location of the lake.

2 Study site

Rhone Glacier is located in Furkapass, Canton du Valais, central-south Switzerland (Figure 3). Meltwater from the glacier pours into a proglacial lake, then down a steep, four-hundred-metre-high granite cliff, before entering the Rhone river which flows westwards. The glacier was at its maximum advance in the 17th century, with the terminus reaching a tiny chapel in Gletsch, a small town roughly 3 km downstream from the nowadays glacier front. Since then, the glacier was in a retreat trend. There was a considerable retreat in 2001, as the terminus receded all the way back to the top of the cliff (Omoto 2018). In the early 2000s, a lake began to form at the glacier front. The size of the lake was approximately 0.188 km^2 as on August 23rd, 2024 (calculated based on Sentinel-2 imagery), and the glacier front is now around 700 m upstream from the cliff.

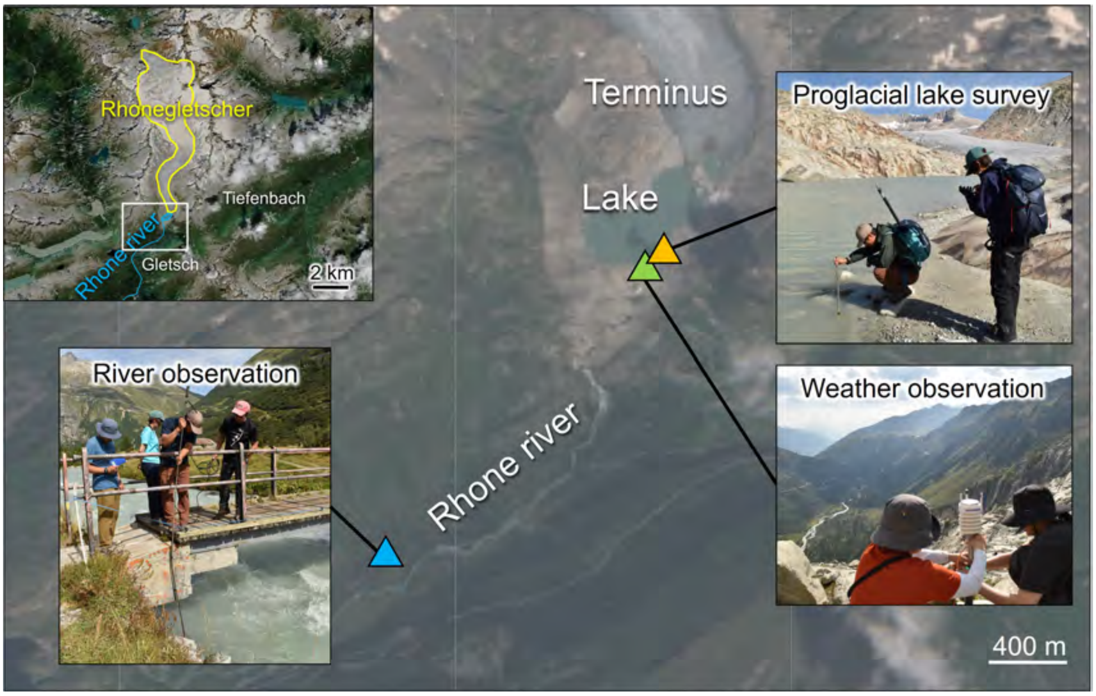


Figure 3: Locations of meteorological- and hydrological measurements. The inset on the top left shows location of the study site. The background is Sentinel-2 imagery, acquired on August 23rd, 2024.

3 Methods

To monitor changes in air and water temperatures and water level, we conducted the following meteorological- and hydrological measurements at the terminus area and Rhone river (Figure 3).

3.1 Meteorological observations

Meteorological measurements were set up on the top of a cliff on the left bank (Figure 3). The instrument used in this study was Vaisala weather transmitter WXT520, which measures six parameters: wind speed and direction, precipitation, atmospheric pressure, air temperature and relative humidity. The data was logged and stored by compact logger CFM100 from August 13:05 29th to 08:35 September 1st every 5 minutes (UTC time).

3.2 Proglacial lake observations

To measure the water pressure, water temperature and water level, water level logger HOBO U20 (Onset company) was attached to one side of a steel stick and settled in the bed around several centimetres below water level (Figure 3). In addition, another logger was settled inbetween rocks located several metres from the lake to monitor air pressure. All data were logged from 10:00 August 28th to 13:00 September 1st every 5 minutes (UTC time).

The water level was calculated with the following equation:

$$H = \frac{\rho_W - \rho_A}{\rho_W g} \tag{1}$$

where H = water level (cm), ρ_{W} = water pressure (kPa), ρ_{A} = atmospheric pressure (kPa), g = gravitational acceleration.

3.3 Discharge measurement

To measure the melting rate of Rhone Glacier, discharge measurement was conducted in Rhone River, Gletsch (46°33’44”N, 8°21’41”E).

The observation was conducted seven times from August 30th to September 1st.

To measure the discharge of the river, electromagnetic current meter TK-106X, aluminum staff and 50-meter-measure were used. (Figure 4, 5)

Figure 4: TK-106X

Figure 5: Aluminum staff

3.3.1 River bed terrain measurement

To measure the discharge rate, it is necessary to determine the shape of river bed terrain. The discharge measurement point must be determined same and robust point that the bedrock terrain hardly to change throughout the observation. In addition, it is favourable that the river bed is as smooth as possible. But the point observation conducted was not such a place, so it was necessary to measure the bed terrain per every measurement.

An aluminum staff (the length is about 3 m) was inserted into the river per 0.5 m from the bridge above the river, and water level data were recorded. After that, the data were plotted and the shape of river bed terrain was obtained.

3.3.2 Water flux measurement

To measure the discharge, it is necessary to calculate the water flux flow through the cross-section of the river bed. The obtained depth was shallower than 0.7 metres, thus, ”One point measure method” was used for current measurement.
To measure the water flux, The cross-section is divided into 1 m interval and the velocity is measured at 0.5 m (0.5, 1.5, 2.5 ...) in the middle of the section (Figure 6).
TK-106X electromagnetic current meter was inserted into the river from the bridge, and fixed manually to keep 60 percent depth of the water level (The red particles on Figure 6).

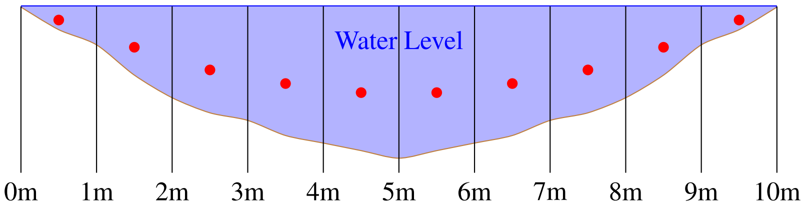


Figure 6: The image of dividing cross-section of river bed terrain.

3.3.3 Water level observation

The discharge data obtained from these method is only ”discontinuous data”, and not continuously observable. There is a correlation between water level and discharge. If a dataset of discharge and water level, exhibiting a correlatable relationship, can be established, it would be possible to estimate discharge from continuously observed water level data.
Hence, we installed one water pressure sensor in the river, and one air pressure sensor on land as we did at proglacial lake. However, when collecting data from the sensors, the whole data were deleted accidentally. Since this accident, the author (Nakayama) visited VAW ETH on September 3rd, and ask Dr. Andreas Bauder to provide the discharge and water level data at Gletsch observed by FOEN.[4] Hence we used the discharge data at Gletsch instead of in situ data.
The time resolution of Gletsch’s data is 5 minutes, and the watar level is defined as meter above sea level. To simplify the conversion equation, the decimal point values of the water level data were rounded off and used in the analysis.
Thanks to Dr. Andreas, the analysis of data was completely succeeded.

3.3.4 Conversion equation

The conversion equation between water level and discharge is generally defined by the exponential function $y = ax^b$. However, since the range of values obtained in this observation is narrow, a linear approximation was considered acceptable. Consequently, the conversion equation was defined as $y = ax + b$. By using Gnuplot to optimize the parameters a and b, the observed values were fitted. Through these processes, the continuous discharge data was obtained.

4 Results

Note that the time referred to hereafter is the local time (UTC+2).

4.1 Meteorological data

Temperature and wind speed obtained from the meteorological measurements are indicated in Figure 7. The air temperature during the observing period recorded a maximum value of 18.4°C at 17:20 August 31st local time, and a minimum value of 9.1°C between 07:05–07:15 September 1st. Diurnal cycles are clear during the observing period, as the temperature declined to a minimum of 10.1°C, 9.7°C, and 9.1°C in the early mornings, and rose to the peak of 16.7°C, 16.5°C, and 18.4°C at nights, respectively.

As regards wind speed, it fluctuated between 0.29 and 6.13 m s^{-1} throughout the whole period. There is a general trend that when the wind speed increased, decline in air temperature was recorded. It is also noteworthy that the wind speed inclined to die down at night. For instance, between 23:55 August 29th and 02:20 August 30th, it slowed down to 0.59–0.66 m s^{-1}, with a maximum of 2.65 m s^{-1} at 00:30. During this time period, the air temperature also increased and maintained a relatively high value, from 12.5°C to 13.6°C.

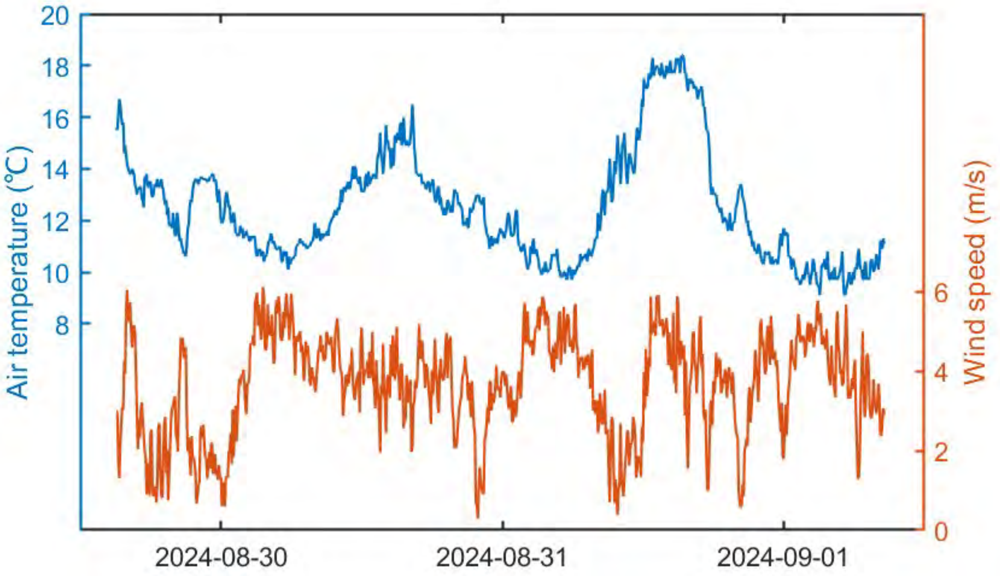


Figure 7: Temperature and wind speed obtained from the weather observations.

4.2 Air temperature and water level at proglacial lake

Air temperature and water level at the proglacial lake show a diurnal cycle (Figure 5). The temperature reached a maximum of 14.5°C and 15.6°C at 18:35 August 30th and 18:45 August 31st, respectively. The minimum values were 10.6°C at 07:20–08:10 and 09:15–09:25 for the August 30th, and 10.2°C for the August 31st.

The water level recorded a maximum of 0.322 m and 0.326 m at 17:55 August 30th and 18:55 (19:00) August 31st, respectively. It recorded a minimum of 0.092 m and 0.032 m at 10:20 August 30th and 10:55 August 31st. Given the above, the daily maximum of both air temperature and water level have a 15–40 min time lag.

In terms of water temperature, the value averaged 1.66°C during the observing period. Daily peaks were also observed: first at 12:10 (3.68°C) and second at 18:00 (2.84°C) on the 30th, and first at 11:35 (5.24°C) and second at 18:00 (3.05°C) on the 31st.

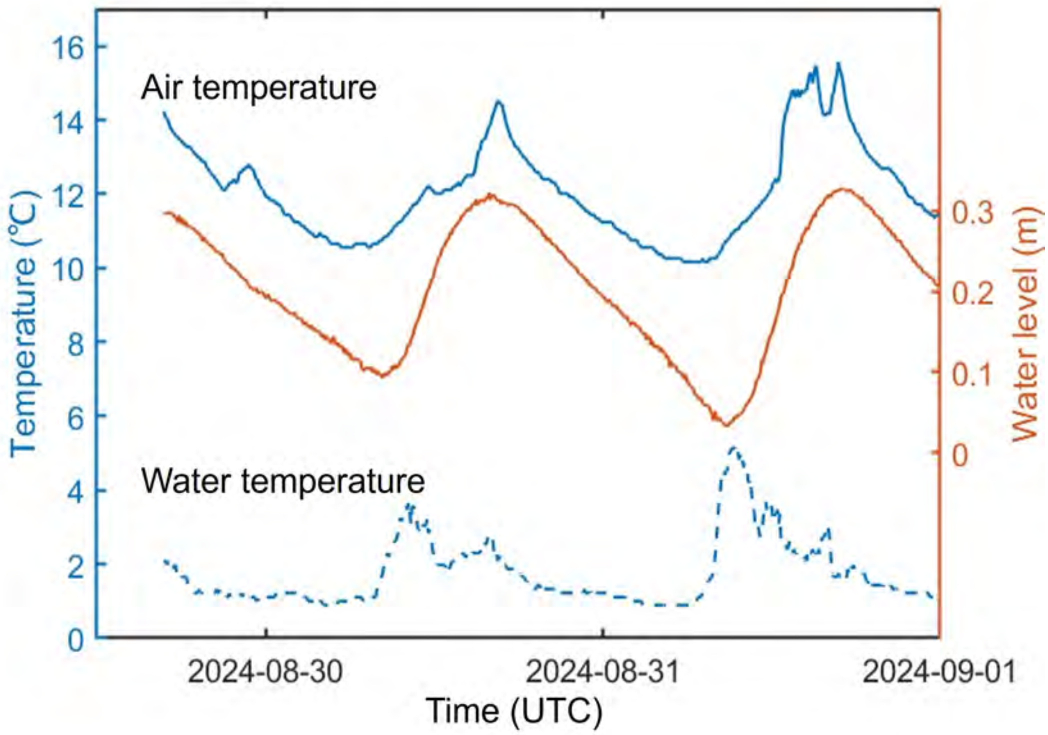


Figure 8: Air and water temperatures and water level. The water level was calculated with the formula shown in Equation (1).

4.3 Discharge data by FOEN

Figure 9 shows the discharge and water level observed by FOEN. The station installed by FOEN is located 180 m downstream from our observation point. The riverbed around that station is covered by concrete, so the shape of bed terrain must be stable. By the way, there should be clear robustness of the data[4].
The discharge data is converted from observed water level by using correction formula made by FOEN. However, the correction formula may change over time.

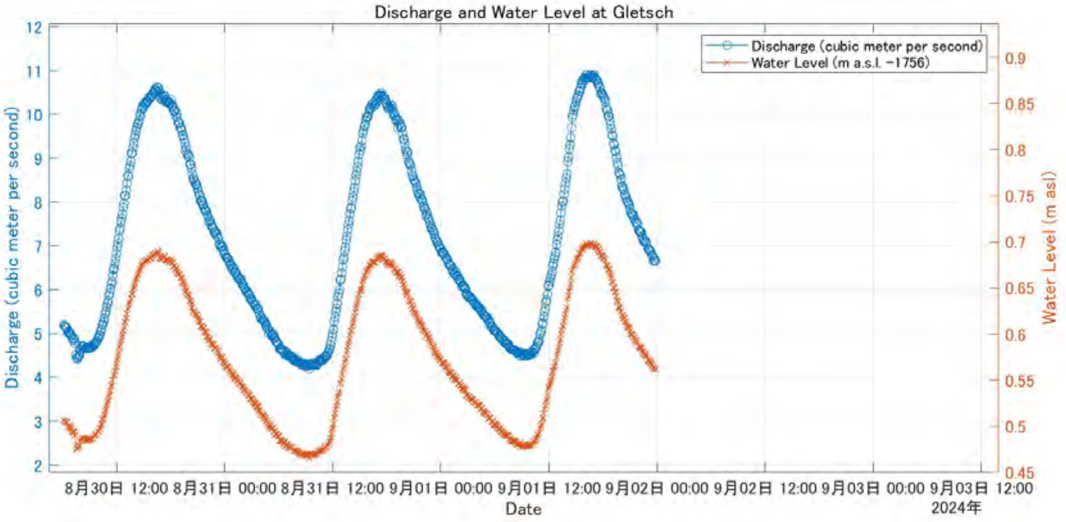


Figure 9: Water level and discharge plot at Gletsch FOEN.

4.4 Discharge data from the river observations

We conducted discharge observation seven times. Table 1 shows details of the observed discharge data.

Table 1: Water Level and Discharge Data

Datetime (UTC)	**Water Level (m)**	**Discharge (m^3/s)**
8/30 8:10–9:13	0.4855	5.19745
8/31 13:20–13:50	0.5820	7.75130
8/31 14:15—14:50	0.6260	7.77400
9/1 7:45–8:13	0.4840	4.96498
9/1 8:25—8:53	0.4810	5.50150
9/1 8:59–9:28	0.4800	5.59193
9/1 9:29–9:55	0.4790	5.69435

4.5 H-Q plot and fitting

The H-Q curve was plotted by using FOEN's water level data [4] and seven observed discharge data by ourselves. The fitting curve was calculated by parameterization of $y = ax + b$. After that, a and b were determined as 18.45169 and −3.46764. The left graph shows the H-Q curve used in FOEN, which is the official data at Rhone river, Gletsch.

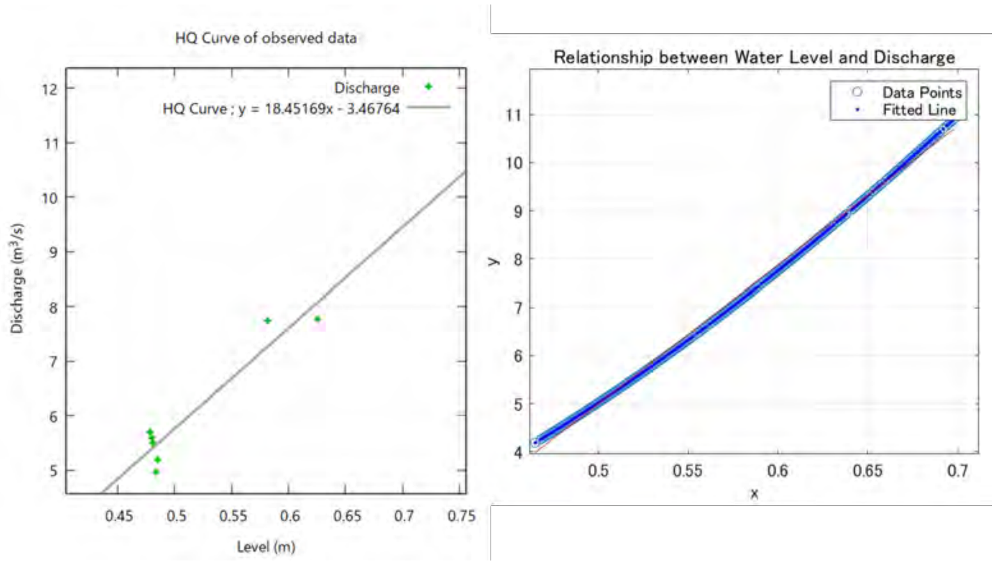


Figure 10: H-Q plot of 7 observed data (left), and FOEN's H-Q curve at Gletsch (right).

4.6 Shape of riverbed

The shape of riverbed was obtained manually when we started the discharge observation. It is depends on where we insert aluminum staff into the river, and how high the water level was. So the shape of riverbed must be different for each observation unless the bed is covered by smooth concrete. Figure 11 shows all observed riverbed terrain at Gletsch.

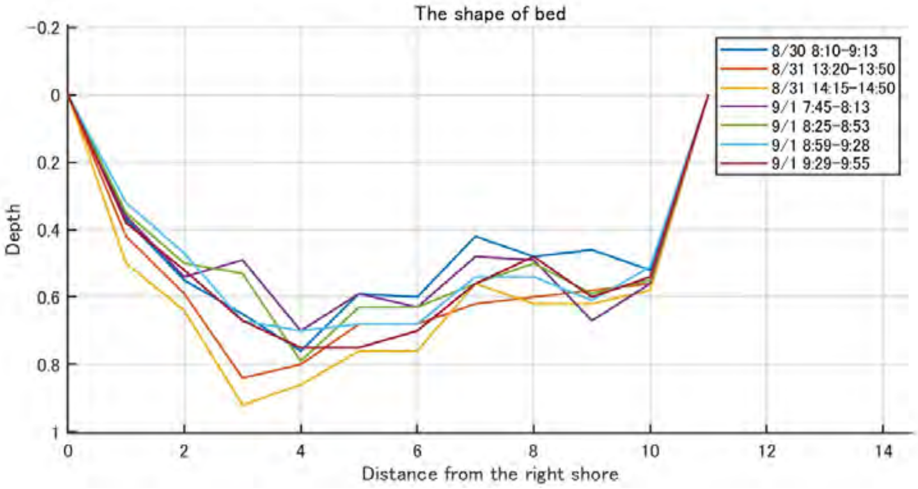


Figure 11: Cross profile of the riverbed terrain at Gletsch. Coloured lines indicate results from each observation.

5 Discussions

5.1 Correlations between air and water temperatures and water level

5.1.1 Time lags between air temperature and water level

Time lags between air temperature and water level were observed: 15–40 min for the maximum values, and 65 min and 85 min for the first minimum on the 30th and the second minimum on the 31st (Figure 8). Additionally, the air temperature tended to increase between around 13:00–16:35(16:45) before the water level reached the peak at around 15:00–16:00. The possible reason could be the difference in the latent heat, as the water is heated up and cooled down slower then the air.

5.1.2 Peaks in water temperature

Figure 12 shows that peaks of water temperature corresponded to the lows of air temperature and water level. When the air temperature decreases, less melt from the glacier front is expected, which would lead to drop in the water level. In this case, the sensor in the lake might have been exposed to the air or close to the surface, thus the increase in the recorded values.

5.2 Comparison with data at Gletsch station

Observation data from this study (orange particle) is plotted with FOEN's H-Q curve on Figure 13.

The HQ curves are generally consistent with the locations of the observed discharge data. Thus, the observed discharge data indicates that FOEN's HQ curves are generally correct. However, we were only able to conduct observation seven times, and the discharge data forms two clusters (around 5.5 $m^3 s^{-1}$ and around 8.0 $m^3 s^{-1}$), thus it is necessary to obtain more variable data and conduct more observations.

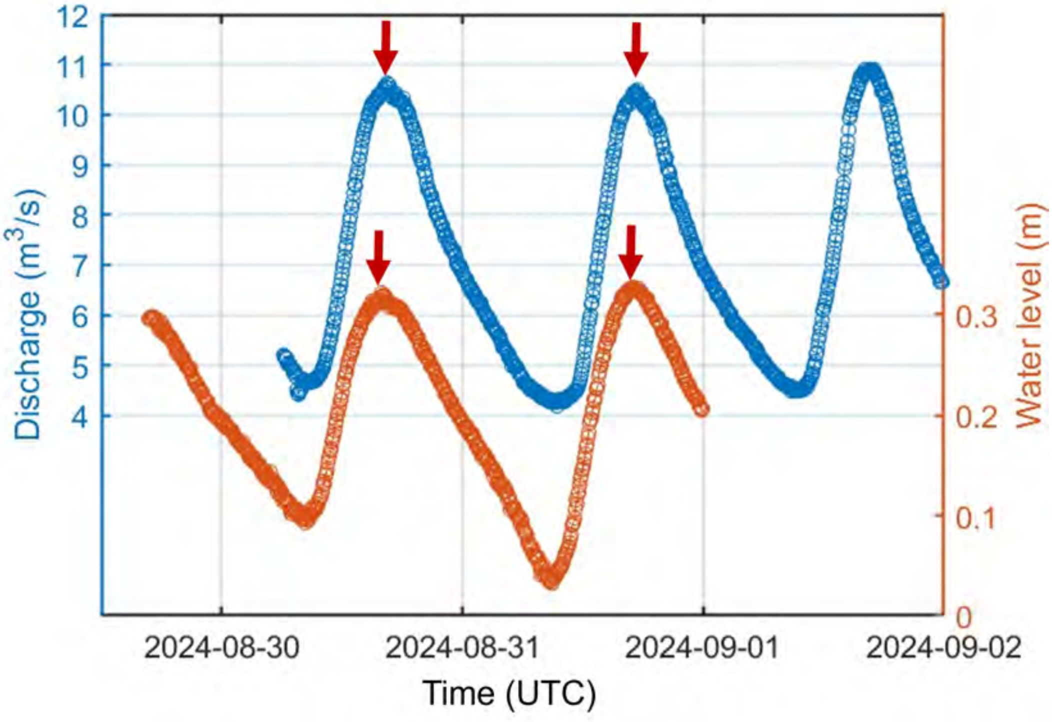


Figure 12: Correlations between discharge at Gletsch and water level at the proglacial lake. The red arrows illustrate timing of each peak.

5.3 The discussion of error

5.3.1 Caused by terrain measurement

One of the factor cause the error is terrain measurement. The shape of riverbed terrain was obtained manually, but the position where the aluminum staff was inserted was not the same for each observation. Figure 14 shows the difference of the riverbed terrain in the morning of September 1st. The error bar of the terrain data is about 0.2 m, and the tendency of instability is significant in the central part of the river.
FOEN's water level data was stable throughout the period, thus it is indicated that the instability of the bed terrain data was caused by manual water level observation. Two possible sources of error are indicated below.

In the central part of the river, the water level was considerably deep that strong water current could wash out the aluminum staff which was fixed manually.
On the other hand, there are many huge rocks on the riverbed, so it is possible to cause such a error about 0.2 m.

For these reasons, the instability of riverbed terrain is caused.
The table below the plot shows how much the effect of the instability of riverbed data change the discharge rate. $\pm 0.25 \mathrm{m}^3\,\mathrm{s}^{-1}$ error could be caused by its instability.

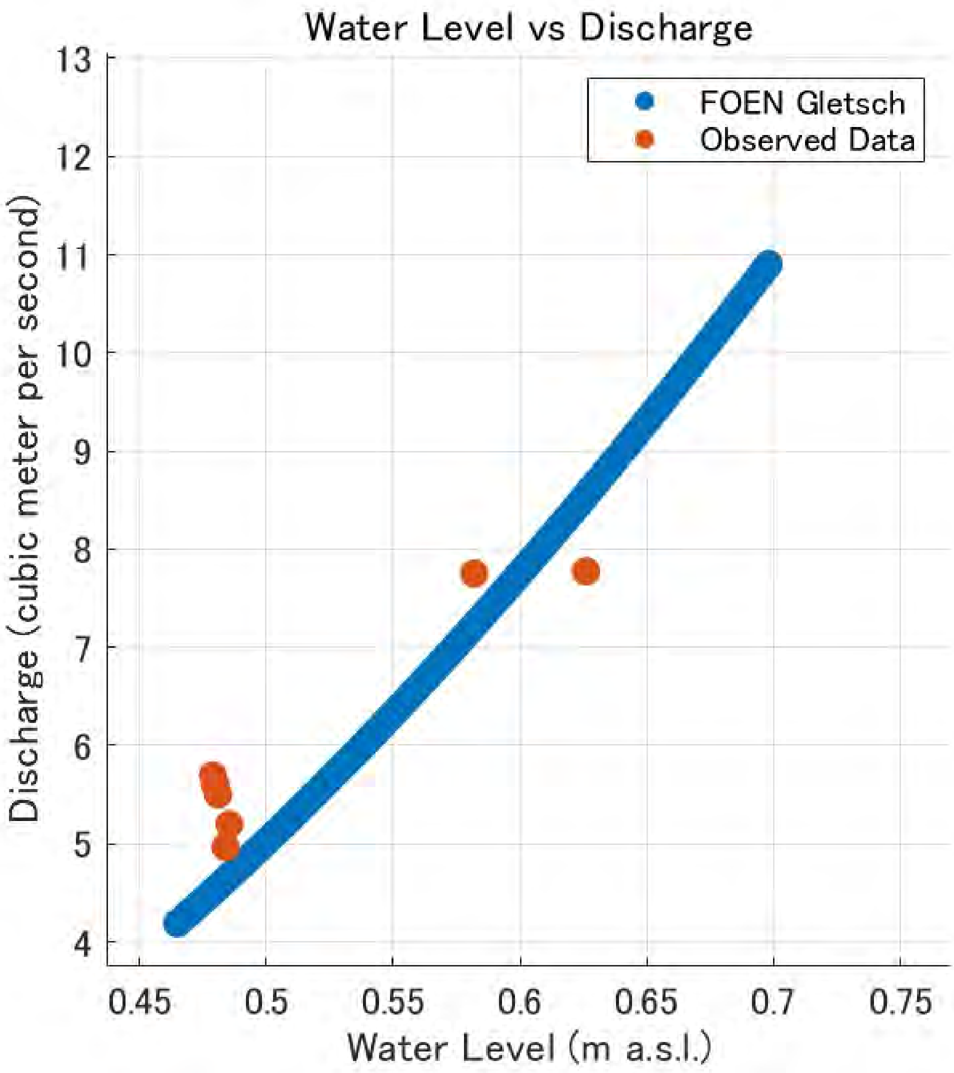
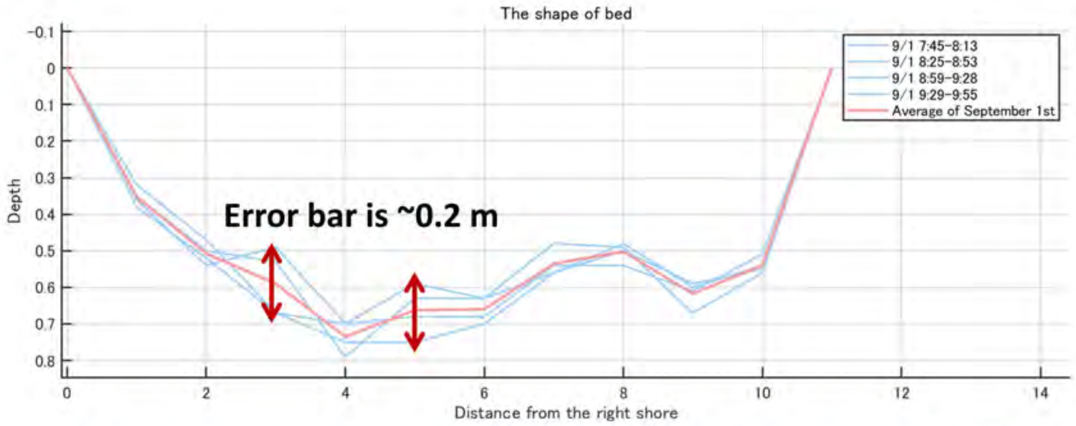


Figure 13: Our observation data guaranteed the robustness of the H-Q curve made by FOEN.



Mean terrain (m^3s^{-1})	5.412444	5.508217	5.578256	5.216156
RAW data (m^3s^{-1})	5.69435	5.591933	5.5015	4.964975
Error (m^3s^{-1})	0.281906	0.083717	-0.07676	-0.25118

Figure 14: The riverbed terrain data observed on September 1st (blue), and the average of them (red).

5.4 Caused by current measurement

The other factor of the error is current measurement. When we measured the current speed, the electromagnetic current meter was inserted into the river from the bridge over the river. This is the biggest source of error in current measurements.

Unstable holding electromagnetic current meter

It is very difficult to hold current meters in a certain place from the bridge over the river above 3 meters high. Strong waterflow and eddies wash out sensor, so instability of the observed value caused.

Instability of values caused by eddies

Eddies are always caused by rough riverbed, especially around a big rock. When negative current caused by eddies, it may decrease the observed value.

Sampling bias caused by reading data from different people

When we record the data, we read the value displayed on the data logger. The value changes per ONE SECOND, so there should be sampling bias depending on individual.

5.5 Solutions

Use more and MORE ROBUST current meter

The current meter's shaft is easy to be broken by strong current, and it is difficult to keep holding from three meters higher from the water surface. Hence, more robust current meter is needed to improve the robustness of the data.

Reduce the range of acceptable errors to 0.1 $\mathrm{m^3\,s^{-1}}$ to reduce measurement error

In this observation, we allowed the error less than 0.3 $\mathrm{m^3\,s^{-1}}$ to shorten the observation time. It is not suitable for scientific observation. When the author (Nakayama) conducted discharge measurement in Qaanaaq, Greenland, only the error less than 0.1 $\mathrm{m^3\,s^{-1}}$ was allowed to improve H-Q curve.

Remove the big rocks before observation starts

The condition of riverbed affect the value of water level because sometimes the aluminum staff hit rocks. By the way, it is necessary to clean the riverbed and keep it smooth. When it is difficult to walk into the river, it is also a good pathway to choose smooth water surface.

Solutions that can be implemented in Swiss 2025

Since the time for Swiss Glacier Course is limited, it is important to improve the accuracy of discharge data without extending the observation time as much as possible.

To improve the robustness of the data, the first proposal is purchasing more ROBUST current meter, shaft and water level staff that not be broken by strong current. By solving the ”holding problem”, the instability of the current velocity data will be decreased.

The second proposal is to create a common manual for those who read discharge data. In this case, the recorder had the discretion to decide how much error to allow, and some of the data were nearly twice as large as the original data, but were not redone.

While such data are a cause of increased uncertainty in discharge, it is a simple problem that can be solved without increasing the observation time.

The third proposal is to create a manual for water level measurement.

In this observation, the observer had the discretion to decide what to do when STAFF hit a rock on the bottom of the river. This caused the topography of the riverbed to change each time, resulting in an instability of the discharge of $\pm 0.25\ \mathrm{m^3\,s^{-1}}$.

Therefore, there is an urgent need to establish a manual for measuring the depth at a place where there are no rocks when the staff hits a rock.

6 Conclusion

15-30 minutes time lag was observed between discharge at Gletsch and lake water level. However, the water temperature data of HOBO pressure sensor installed at Gletsch were erased accidentally, the relationship between the temperature of lake and river could not revealed.

The errors were caused by the instability of the measurements. The riverbed terrain measurement is inaccurate due to the presence of rocks, and the discharge values may be affected by eddies. The depth at which the current meter was inserted was unstable because of strong currents and eddies. Additionally, the manually recorded values are subject to potential human error, as they rely on individual judgment.

To improve the observation on the next year, it is necessary to use robuster current meter, and establish common manual for each observation. These solution do not require to lengthen the observation time, so it is really realistic for the next year's.

7 Acknowledgment

We would like to thank the Hokkaido University Learning Satellite Project for their support of my participation in the Swiss Glacier Field Trip. We thank Prof. Daniel Farinotti and Dr. Andreas Bauder of VAW ETH for their kind cooperation in providing us with the Gletsch data.

We also thank Prof. Sugiyama and Prof. Shiraiwa for leading the field trip to Switzerland.

References

[1] Hugonnet R, McNabb R, Berthier E, Menounos B, Nuth C, Girod L, Farinotti D, Huss M, Dussaillant I, Brun F, Kääb A. (2021) Accelerated global glacier mass loss in the early twenty-first century, Nature 592, 726–731.

[2] Omoto (2018) Retreating Rhone Glacier and Extending Glacial Lake Rhonesee in the Central Alps: Change to Rhone Glacier and Rhonesee Recorded in Photographs and Maps. Journal of Geography 128(6), 953–958.

[3] Sommer, C., Malz, P., Seehaus, T.C. Lippl, S., Zemp, M., Braun, M. H. (2020) Rapid glacier retreat and downwasting throughout the European Alps in the early 21st century. Nature Communications 11, 3209.

[4] Federal Office for the Environment (FOEN) `https://www.bafu.admin.ch/bafu/en/home/office/divisions-sections/hydrology-division.html`