



Linking Landforms to Water Signatures: Hydrological and Hydrochemical Variability in Two Alpine Catchments

GEO 511 Master's Thesis

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Abstract

Alpine catchments are often a complex combination of geomorphological landforms that each play an important role in groundwater storage and discharge. As climate change accelerates glacier mass loss and alters snow cover duration and extent, the importance of the hydrological buffering capacity of these periglacial landforms to sustain and regulate downstream flow increases. However, the internal structure and subsurface flow paths of these landforms remain understudied. This thesis investigates the flow from periglacial and glacial landforms in two small Alpine catchments in the Engadine, Switzerland. The objectives are to (1) characterize and compare the physical, chemical and isotopic signatures of discharge from different geomorphological landforms and water sources within the catchments; (2) to analyze the seasonal and diurnal variability of the discharge from an end moraine and the two rock glaciers between July and October; and (3) to evaluate the relative contributions and the hydrochemical influence of the different landforms for the downstream river system. These objectives were addressed through continuous monitoring of water temperature, electrical conductivity (EC), and water level across four streams. This was supplemented by biweekly manual measurements of water temperature and EC, as well as sampling for stable isotope analysis at 21 additional locations.

Significant hydrochemical differences were identified between streams and landforms. The end moraine, rock glaciers, and scree slope had elevated EC, consistently low water temperatures, and a high deuterium excess, confirming previous findings of ice within these landforms and suggesting a prolonged residence time and intense mineral-water interaction. In contrast, the flow from the ground moraine and lake had a higher variability in water temperature, lower EC, and lower deuterium excess, suggesting improbable permafrost occurrence within the ground moraine. While the absolute values of water temperature, EC, and deuterium excess for the end moraine and the rock glaciers were similar, the seasonal and diurnal patterns revealed different storage and discharge mechanisms. Both landforms likely consist of multiple flow paths with a deeper groundwater flow underneath the ice that sustains baseflow throughout the summer, and a faster flow component on or within the ice. However, the faster response of the end moraine to precipitation events suggests shorter flow paths and a potentially more intact ice core than for the rock glaciers. During warm and dry periods, the end moraine had an inverse diurnal relationship between water level and EC, pointing to dilution through ice melt. Conversely, the direct relationship observed in the rock glacier discharge indicated a flushing of solute-rich water or a groundwater response to melting ice.

The discharge from these landforms impacted the downstream river system, with a majority of discharge from the rock glacier and the scree slope during the summer, despite draining only 10% of the catchment area. This discharge significantly lowered the water temperature and increased the EC and deuterium excess of the water at the catchment outlet. The second-highest contributions were from the end moraine, ground moraine, and lake outflow. These findings highlight the importance of periglacial landforms as Alpine aquifers, emphasizing their impact on water quality, runoff magnitude, and timing to the downstream river system.

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List of Abbreviations

a.s.l. Above sea level

EC Electrical Conductivity

GPR Ground-penetrating radar

MAAT Mean Annual Air Temperature

MAGST Mean Annual Ground Surface Temperature

PCA Principal Component Analysis

PERMOS Swiss Permafrost Monitoring Network

VSMOW Vienna Standard Mean Ocean Water

1 Introduction

Alpine catchments often contain a complex combination of geomorphological features (Engel et al., 2019). Among these landforms, rock glaciers are common and are widely distributed in the European Alps (Amschwand et al., 2025). Together with moraines, talus slopes, and meadows, they play an important role in groundwater storage and discharge in Alpine catchments (Hayashi, 2020). Under a warming climate, the timing and magnitude of discharge from Alpine catchments are expected to change due to glacier mass loss and shifts in snow cover extent and duration (Arenson et al., 2022; Hayashi, 2020; Jones et al., 2019). In this context, the hydrological buffer of Alpine headwaters becomes increasingly important for storing meltwater and releasing it over time. While groundwater storage was long considered negligible in Alpine catchments, recent research has shown that Alpine aquifers are a widespread feature in high-altitude zones (Hayashi, 2020). However, while glacier hydrology has been a subject of intense research, less research has been conducted on the hydrology of mountain permafrost (Arenson et al., 2022), even though the presence of periglacial landforms and permafrost affects the amount and the properties of runoff from high mountain watersheds (Bearzot et al., 2023; Geiger et al., 2014; Jones et al., 2019). Due to prolonged contact of meltwater with mineral surfaces, chemical weathering can be enhanced (Brighenti et al., 2024; Colombo et al., 2018a; Jones et al., 2019; Munroe, 2018). Discharge from rock glaciers thus often has high solute concentrations, including high concentrations of heavy metals, which have the potential to alter the water quality of the downstream river system (Brighenti et al., 2026). These landforms thus not only influence the sources and flow paths towards downstream rivers, but also their chemical composition (Engel et al., 2019). Despite their influence on the downstream river system, the internal structure and subsurface flow paths of these landforms, their storage-discharge patterns, as well as their effect on hydrochemistry, remain a significant source of uncertainty in Alpine hydrology (Jones et al., 2019; Seelig et al., 2026). The large heterogeneity of Alpine catchments in terms of geology, geomorphology, and permafrost conditions introduces further complexity (Arenson et al., 2022).

Although the debris layer of rock glaciers and other ice-rich landforms acts as a thermal buffer that delays their response to atmospheric changes, they are still affected by climate warming (Amschwand et al., 2025; Arenson et al., 2022; Del Siro et al., 2023; Jones et al., 2019). As a result, their hydrological contribution, groundwater storage, discharge patterns, and water chemistry might change in the future (Jones et al., 2019; Noetzli & Phillips, 2019). Nevertheless, how permafrost degradation and with it changes in the internal structure of these landforms contribute to and change streamflow in mountain regions is still understudied (Arenson et al., 2022).

To evaluate how different landforms influence the hydrology of high-alpine environments, a variety of measurements can be used, such as water temperature, electrical conductivity (EC), or the abundance of the stable isotopes of hydrogen and oxygen (from here on water stable isotopes for brevity). Spring water temperature can be an indication of permafrost presence. In areas with probable and possible permafrost, water temperatures tend to remain consistently low, often below 2°C (Carturan et al., 2016). In contrast, the EC and stable isotope values tend to vary seasonally, with typically increasing EC and water that is less depleted in heavy isotopes during summer months. This trend is often attributed to a decreasing influence of snowmelt and a growing contribution from precipitation, ice melt, and groundwater (Jones et al., 2019). Therefore, analyzing these aspects of streamwater chemistry can give insights into both spatial and temporal variations in runoff sources in high-alpine environments (Munroe & Handwerger, 2023a).

Multiple studies have examined the spatial and temporal variability of water chemistry in rock glacier catchments in the European Alps (Amschwand et al., 2025; Brighenti et al., 2023; Brighenti et al., 2021a; Carturan et al., 2016; Carturan et al., 2024; Del Siro et al., 2023). Because many of these investigations have focused on the discharge of individual landforms or broader regional patterns, this thesis aims to complement existing research by analyzing the temperature, EC, and isotopic composition of stream water in the complex geomorphological setting of two neighboring small Alpine catchments. This allows for a spatial comparison between the discharge from different landforms – such as rock glaciers, talus slopes, moraines, and groundwater sources – and their seasonal and diurnal variation throughout the summer. Furthermore, the contribution and influence of the different landforms on the river system can be assessed.

The Val Muragl and Val Champagna catchments are particularly suitable for such an investigation, since the Val Muragl has been the focus of extensive previous research. Different studies have mapped the geomorphological landforms (Kneisel et al., 2000; Kunz & Kneisel, 2020), analyzed the surface displacement and movement of different landforms (Kellerer-Pirklbauer et al., 2024; Kneisel & Kaeae, 2007; PERMOS, 2025), and conducted geophysical surveys to better understand the internal structure of the rock glacier and the moraine complex (Kneisel & Kaeae, 2007; Kunz & Kneisel, 2020; Springman et al., 2012). In addition, multiple boreholes on the Muragl rock glacier provide temperature and displacement data, with the most recent one drilled in 2024 (PERMOS, 2026). Furthermore, the small scale of the catchments constrains the influence of climatic gradients, such as air temperature or precipitation. By minimizing the potential impact of external environmental fluctuations, differences between the hydrological responses and signatures of the individual landforms and water sources can be clearer.

By focusing on hydrological measurements, this thesis aims to add a hydrological perspective to the existing data for this area. By comparing the water chemistry with existing geomorphological mapping and modeled permafrost distribution, this thesis seeks to enhance the understanding of the relationship between different landforms and their discharge signatures, their role in regulating downstream flow, and their contribution to the downstream river system throughout the summer season. Furthermore, it is assessed whether this methodological approach can be used to map permafrost landforms in areas with limited data availability, such as the Champagna rock glacier. Thus, this thesis can not only build on existing knowledge but also aims to offer new insights and a deeper understanding of this complex landscape.

More specifically, the thesis aims to address the following research questions:

1. How do water temperature, electrical conductivity, and stable isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) differ among geomorphological landforms and water sources in Val Muragl and Val Champagna?
2. What are the seasonal and diurnal variations in water temperature, electrical conductivity, and stable isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) across different landforms between July and October?
3. What are the relative hydrological and hydrochemical contributions of different landforms to the downstream river system, and how do these contributions change throughout the summer season?

2 Theoretical Background

2.1 Alpine Catchments

Alpine catchments generate substantial runoff because of the high precipitation amounts due to orographic effects, and low evapotranspiration resulting from the low temperatures and sparse vegetative cover (Hayashi, 2020). In the past, the storage of Alpine headwaters was often considered negligible due to the large amount of exposed bedrock and little soil and vegetation. However, this underestimates the capacity of groundwater storage in catchments with coarse sediments (Arnoux et al., 2021; Hayashi, 2020; Spencer et al., 2019). Alpine catchments are often characterized by large amounts of sediment due to their steep topography and past glacial processes, which function as a hydrological buffer (Rogger et al., 2017). These landforms can act as Alpine aquifers and are able to sustain stream discharge over a long period. Furthermore, they have the potential to recharge underlying bedrock (Arnoux et al., 2021; Hayashi, 2020; Spencer et al., 2019). While talus slopes, moraines, and rock glaciers generally consist of coarse sediment and thus result in a relatively fast drainage, this initial fast recession is usually followed by a slow recession able to sustain baseflow in low-flow periods (Hayashi, 2020). However, determining the role of groundwater storage in Alpine catchments is challenging due to the large heterogeneity across such areas (Cochand et al., 2019), and complex subsurface flow paths, storage, and responses to precipitation within periglacial and glacial landforms (Spencer et al., 2019).

2.1.1 Runoff Generation Mechanism

Water flow paths influence the geochemical evolution and the contact and residence time within the subsurface (Beven, 2012; Michener & Lajtha, 2007). The most rapid contribution of precipitation to streamflow is direct input of precipitation water into the channel or near-stream areas. While the amount is usually small, it can still lead to a chemical dilution of stream water (Michener & Lajtha, 2007). The precipitation that reaches the soil surface can infiltrate and contribute as subsurface flow. However, if the rainfall intensity is larger than the infiltration capacity, overland flow can move over the surface downslope (also called Horton or infiltration-excess overland flow) (Beven, 2012; Brutsaert, 2023). Precipitation falling on a saturated soil, e.g., because of a shallow water table or saturation from below where subsurface flow returns to the surface, is called saturation-excess overland flow (Brutsaert, 2023; Michener & Lajtha, 2007). The water is transported to the stream either by movement of the water itself or by displacement of water through pressure propagation. New rainfall thus displaces previously stored water

to the stream, which leads to a much faster reaction (Beven, 2012; Michener & Lajtha, 2007). Subsurface flow is usually slower than overland flow (Michener & Lajtha, 2007). Subsurface flow can be further divided into shallow flow, which is also called subsurface stormflow, and deep flow, depending on its depth and the regional extent of the aquifer system. Deeper groundwater flow can sustain baseflow even through dry seasons, since it moves slowly through connected pore space (Beven, 2012; Michener & Lajtha, 2007). Shallow subsurface flow, on the contrary, is water that moves laterally within the soil profile, thus contributing rapidly to streamflow (Michener & Lajtha, 2007). This lateral movement during storm events occurs either because a layer of lower hydraulic conductivity is reached, through the displacement of water stored prior to precipitation, or through macropores and other preferential flow paths (Brutsaert, 2023; Michener & Lajtha, 2007). The different runoff generation mechanisms are illustrated in Figure 2.

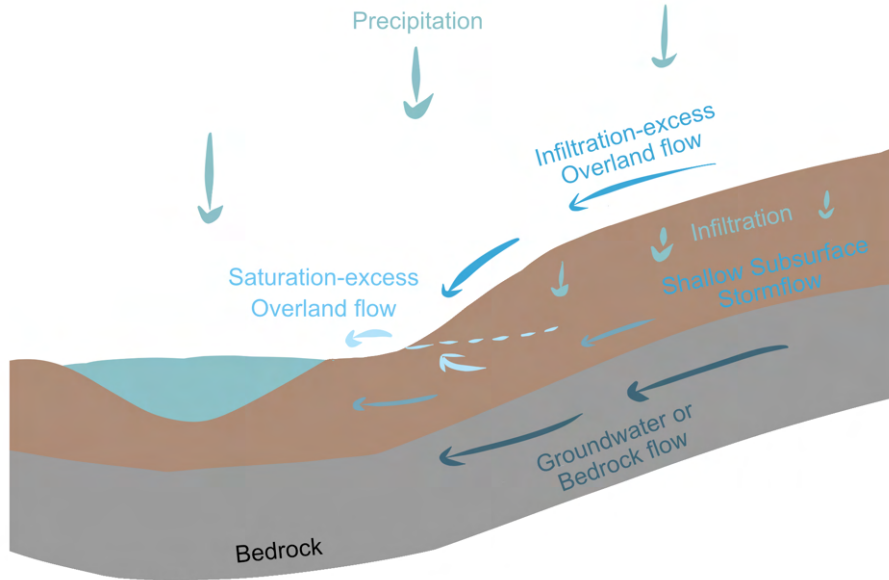


Figure 2: Sketch of the runoff generation mechanisms after precipitation on a slope, based on Figures by Beven (2012) and Brutsaert (2023), and information by Michener and Lajtha (2007).

2.1.2 Alpine Permafrost and its Influence on Hydrology

In Alpine environments, permafrost is widespread (Noetzli & Phillips, 2019). Permafrost is defined as unconsolidated sediment, bedrock, or ground that remains below 0°C for at least two consecutive years (Arenson et al., 2022; Ballantyne & Murton, 2018; Colombo et al., 2018b; Noetzli & Phillips, 2019; Noetzli et al., 2025; Rogger et al., 2017). It thus is a thermal phenomenon and is not defined through its water or ice content (Colombo et al., 2018b). In Switzerland, it is estimated that permafrost underlies approximately 3 - 5% of the area, typically at elevations above 2200 m a.s.l. (Noetzli & Phillips, 2019; Noetzli et al., 2025). Due to complex and steep topography, which influences surface

cover, subsurface characteristics, and snow distribution, ground temperature can vary considerably over short distances (Arenson et al., 2022; Noetzli & Phillips, 2019). Two potential origins of mountain permafrost are discussed: Congelation ice, which is formed through in-situ freezing of water or ice segregation, existing both as massive ice or ice lenses. Sedimentary ice, in contrast, represents buried surface ice, typically from buried avalanche deposits or relict glacier ice (Noetzli & Phillips, 2019).

The ice content in periglacial landforms can vary significantly, from low ice content in frozen bedrock slopes, to large volumes in rock glaciers or talus slopes (Noetzli & Phillips, 2019). However, the ice content can vary significantly within and between rock glaciers as well (Jones et al., 2019), from 40% to over 70% in intact rock glaciers (Berthling, 2011; Hayashi, 2020). Furthermore, considerable amounts of ground ice are also found within moraines or in recently deglaciated glacier forefields (Noetzli & Phillips, 2019). Permafrost distribution is typically classified by its spatial extent. A continuous zone indicates a large area ($> 90\%$) is underlain by permafrost, while a discontinuous zone features a fragmented coverage (between 10% and 90%). Areas where permafrost covers less than 10% are classified as isolated patches of permafrost (Ballantyne & Murton, 2018; Colombo et al., 2018b).

In Alpine catchments, the presence of permafrost influences the hydrology of the catchment by changing the storage capacity and subsurface flow paths, consequently also altering the overall runoff of a catchment (Arenson et al., 2022; Noetzli & Phillips, 2019; Rogger et al., 2017). The presence of permafrost reduces the subsurface storage, which leads to faster runoff and a larger amount of discharge leaving the catchment (Arenson et al., 2022; Geiger et al., 2014; Rogger et al., 2017). By restricting water movement and recharge of groundwater, permafrost is commonly described as an aquitard (Arenson et al., 2022; Colombo et al., 2018b). Usually, there are different flow paths within permafrost landforms: shallow flow on top of buried ice, and a slower and deeper flow within a fine-grained layer below the ice or through fractures within the bedrock (Rogger et al., 2017). As permafrost thaws, the development of taliks and the increased permeability of partially frozen ground enhance hydrologic connectivity, which influences the velocity and volume of different flow paths (Colombo et al., 2018b; Rogger et al., 2017).

2.1.3 Rock Glaciers

Within mountain permafrost, rock glaciers are a prominent and widespread feature (Am-schwand et al., 2025; Kellerer-Pirklbauer et al., 2024). A rock glacier is a tongue-shaped or lobate landform consisting of a mixture of poorly sorted rock fragments and ice that moves

downslope due to gravity-driven creep through the deformation of internal ice (Jones et al., 2019). Rock glaciers are characterized by an active layer, which is a seasonally thawed debris layer (Amschwand et al., 2025; Colombo et al., 2018b). The depth of the active layer is determined by the surface temperature and the subsurface properties (Colombo et al., 2018b). It is typically a few decimeters to meters thick (Jones et al., 2019; Noetzli & Phillips, 2019) and consists of coarse blocky clasts that protect the underlying perennial ice from melting by acting as a thermal insulator. This leads to a slower melt of the ground ice compared to snow or glacier melt at the surface (Amschwand et al., 2025; Jones et al., 2019). Below the active layer lies the permanently frozen ice core, consisting of ice-rich debris (Amschwand et al., 2025). Underneath is typically an ice-poor or ice-free fine-grained sediment layer, which acts as an aquifer (Jones et al., 2019; Moradi et al., 2024).

The downslope movement of a rock glacier is driven by a combination of internal deformation within the ice-saturated permafrost core and through shearing of a layer within or near the base of the frozen body (Kellerer-Pirklbauer et al., 2024). They usually creep with a horizontal surface velocity of a few centimeters to meters a year (Kellerer-Pirklbauer et al., 2024). A rock glacier can be classified based on its movement and ice content (Jones et al., 2019). While an active rock glacier contains ice and is currently moving, an inactive one still contains ice, but no longer displays any movement (Jones et al., 2019; Moradi et al., 2024). Active and inactive rock glaciers are categorized as intact rock glaciers, reflecting the presence of an ice core (Moradi et al., 2024). A relict or fossil rock glacier no longer contains any ice. However, it must be noted that distinguishing between these categories can be challenging, and there is a continuous transition between these statuses (Jones et al., 2019).

2.1.4 Hydrology of Rock Glaciers

Water storage within a rock glacier occurs at different time scales. Long-term storage encompasses permafrost ice within the rock glacier core, while intermediate-term storage includes the storage and release of snowmelt and runoff from the active layer on a seasonal timescale (Amschwand et al., 2025; Jones et al., 2019). While the ice volumes of the seasonal storage are generally smaller than those in the permafrost core, they respond more rapidly to atmospheric and hydrospheric changes (Amschwand et al., 2025). Short-term storage includes the drainage of water within or beneath the rock glacier on a diurnal timescale (Jones et al., 2019).

The hydrology of a rock glacier is influenced by the ice core. Within an intact rock glacier, it restricts, but does not exclude, the exchange between surface water and sub-

permafrost water (Amschwand et al., 2025; Arenson et al., 2022). This leads to discharge from the shallow, permeable supra-permafrost aquifer, which responds quickly to precipitation (Amschwand et al., 2025; Jones et al., 2019). Furthermore, intra-permafrost flow is possible, where water can percolate through taliks or permeable zones, especially in discontinuous mountain permafrost (Amschwand et al., 2025; Brighenti et al., 2021a; Jones et al., 2019; Mutter & Phillips, 2012). Slow sub-permafrost flow occurs in the fine-grained, unfrozen sediment underneath the ice core, which sustains baseflow for months or years (Amschwand et al., 2025; Brighenti et al., 2021a; Wagner et al., 2020). The water within the sub-permafrost flow is more chemically altered than the supra-permafrost flow (Amschwand et al., 2025). A hypothetical model of these internal flow paths by Jones et al. (2019) is illustrated in Figure 3.

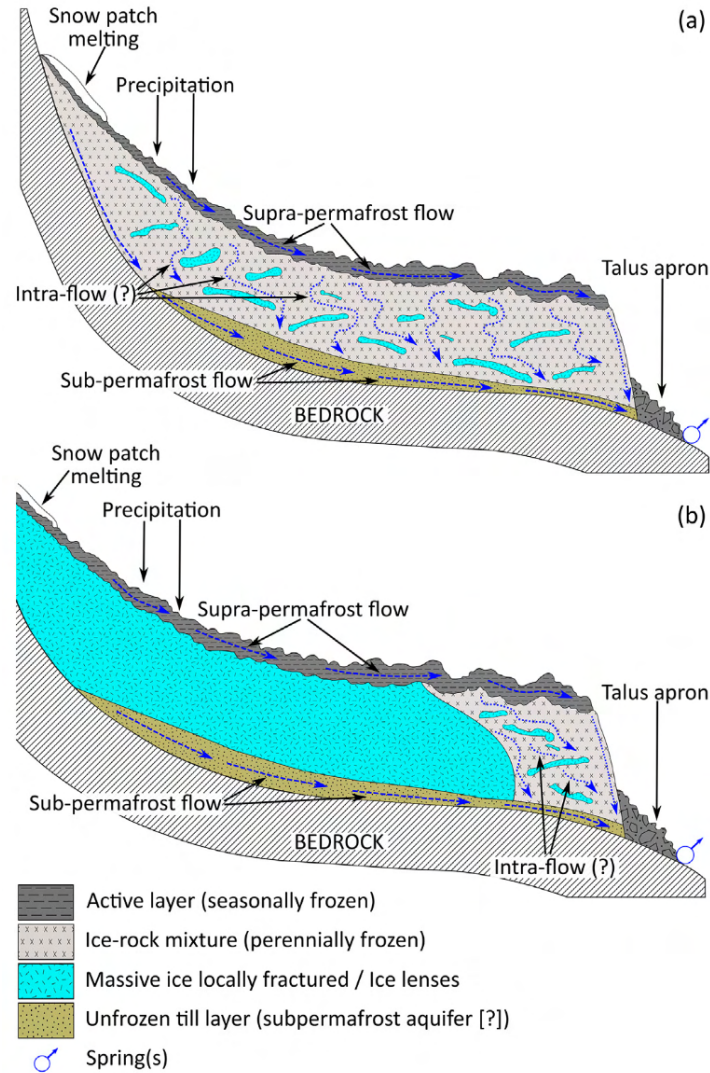


Figure 3: Simplified hypothetical model of flow paths through an active rock glacier (Jones et al., 2019).

The discharge from intact rock glaciers includes contributions from different water sources, such as the melting of winter snowpack during early summer, melting rock glacier ice during late summer, precipitation, and groundwater (Jones et al., 2019). Discharge is usually highest during snow melt in early summer and declines gradually throughout the summer (Jones et al., 2019). Subsequently, precipitation is the dominant water source during summer (Arenson et al., 2022; Krainer & Mostler, 2002). As the active layer is fully developed by late summer, water frozen in the perennial permafrost core might be released as the permafrost undergoes thermal degradation (Arenson et al., 2022). However, different studies suggest that the contribution of ice melt from the perennial ice core to the total discharge is comparably small (Amschwand et al., 2025; Harrington et al., 2018; Jones et al., 2019). However, quantifying the fraction of ice melt in the total runoff, or distinguishing between runoff of seasonal and perennial ice, remains challenging (Amschwand et al., 2025; Arenson et al., 2022; Noetzli & Phillips, 2019).

2.2 Hydrochemistry and Isotopic Signatures

Different variables can be measured to gain insight into the hydrochemical differences between streams and the influence of rock glacier discharge on downstream flow (Bearzot et al., 2023).

2.2.1 Water Temperature

Water temperature in late summer has been demonstrated to be a reliable indicator of the presence or absence of permafrost within the catchment. Water temperature above 1.8 - 2.2 °C usually indicates improbable permafrost, whereas water temperature above 0.9 - 1.1 °C suggests possible permafrost. Temperatures below 0.9 °C indicate probable permafrost (Carturan et al., 2016). These findings are supported by different studies, which report constantly low water temperatures in rock glacier discharge (Amschwand et al., 2025; Brighenti et al., 2019, 2021a; Carturan et al., 2016; Moradi et al., 2024; Munroe & Handwerger, 2023a). This low water temperature is attributed to the contact of water with permafrost within this landform (Brighenti et al., 2026; Munroe & Handwerger, 2023a). Not only the absolute temperature, but also the temporal variability can be used as an indication, since both the inter-annual and inter-seasonal variability in water temperature are low in rock glacier springs (Carturan et al., 2016).

2.2.2 Solute Enrichment

Electrical conductivity (EC) is the ability of water to conduct an electrical current through the movement of ions. As such, the measured conductivity is closely related to the total amount of dissolved ions in the water (Benettin & Van Breukelen, 2017; Hayashi et

al., 2012), and depends on the hydrogeochemical processes occurring within a catchment (Cano-Paoli et al., 2019). Water flow paths and subsurface residence time within a catchment can influence geochemical signatures of the discharge by determining the degree of mineral interaction and the contact time with weatherable material in the soil and bedrock (Del Siro et al., 2023; Michener & Lajtha, 2007).

Through the analysis of EC, major ions and trace elements, different studies have demonstrated that the discharge of rock glaciers is enriched in solutes and weathering products relative to other water sources such as the melt of glaciers or snow (Colombo et al., 2018b; Jones et al., 2019). Both long-term trends over multiple years and seasonal trends with increasing EC towards late summer have been reported for rock glacier discharge (Brighenti et al., 2021a; Colombo et al., 2018b). This is attributed to increased permafrost and ground ice degradation, a deepening of flow paths within landforms, and a higher contribution of deep groundwater (Colombo et al., 2018b), and can have an impact on the water quality of surface waters and downstream river systems (Brighenti et al., 2021a; Colombo et al., 2018b). Furthermore, EC measurements can help to distinguish between baseflow, which typically has a higher EC, and quickflow of water from precipitation events or snow melt with a low EC. EC measurements can thus give insight into flow paths within such landforms (Jones et al., 2019).

2.2.3 Stable Isotope Composition

Water entering the watershed as precipitation has a characteristic isotopic fingerprint based on its origin. Once in the catchment, the isotopic composition only changes through mixing or fractionation during evaporation and condensation (Michener & Lajtha, 2007). The stable isotopes of deuterium (^2H) and oxygen (^{18}O) can therefore be used as natural tracers to determine the age, geographic origin, and residence time of runoff within a watershed. They provide a unique isotopic fingerprint of the water because their abundance varies based on the physical processes they have undergone (Michener & Lajtha, 2007). The typical abundance in ocean water is shown in Table 1.

Table 1: Natural abundance of stable oxygen and hydrogen isotopes (Michener & Lajtha, 2007; Mook, 2000).

Element	Isotope	Abundance (%)
Oxygen	^{16}O	99.760
	^{17}O	0.035
	^{18}O	0.2
Hydrogen	^1H	99.985
	^2H	0.015

The isotopic composition of water is expressed in delta notation as permil (‰) relative to the international standard VSMOW (Vienna Standard Mean Ocean Water), by calculating the ratio of the heavier to the lighter isotope, for example ($^{18}\text{O}/^{16}\text{O}$):

$$\delta^{18}\text{O} = \left(\frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}}}{(^{18}\text{O}/^{16}\text{O})_{\text{standard}}} - 1 \right) \times 1000 \quad (1)$$

A negative value thus represents a depletion of heavy isotopes in the water sample compared to the standard (Beria et al., 2018).

While the water moves through the hydrological cycle, it undergoes fractionation and mixing. Since processes do not occur at the same rate for heavy and light molecules, this leads to a different isotope composition (Michener & Lajtha, 2007). Heavier molecules have a lower mobility, which leads to a lower diffusion velocity and a lower collision frequency with other molecules (Mook, 2000). Additionally, the binding energies are generally higher for heavier molecules (Mook, 2000). This leads to a slower reaction for heavier isotopes during phase changes, such as evaporation, condensation, and melt (Michener & Lajtha, 2007). Evaporation is faster for lighter isotopes, which leads to an isotopically depleted water vapor compared to the water from which it is formed. Condensation, on the contrary, is faster for heavier isotopes, such that the precipitation is isotopically heavier than the vapor from which it formed (Beria et al., 2018; Michener & Lajtha, 2007). Fractionation is temperature dependent and is greater at colder temperatures (Michener & Lajtha, 2007), resulting in precipitation that is more enriched in heavier isotopes if it is formed at higher air temperatures compared to precipitation formed at lower air temperatures (Beria et al., 2018).

There are different types of isotope fractionation:

- Kinetic fractionation occurs during irreversible or one-way processes. If water vapour is moved away from the water sources immediately after evaporation, this

fractionation can not be reversed (Mook, 2000).

- Equilibrium fractionation is reversible and results within a chemical or thermodynamic equilibrium, where isotopes are continuously exchanged between two phases at a constant rate (Mook, 2000).

Since isotope fractionation processes in natural systems are rarely purely kinetic, they are often termed non-equilibrium fractionation. This occurs, for example, during evaporation over an open body of water, where the evaporation is not irreversible since condensation does occur, but the rate of evaporation is higher, preventing the system from reaching an equilibrium (Mook, 2000).

Precipitation can vary in its isotopic composition, since it reflects its vapor source, fractionation during evaporation, and multiple cycles of condensation along the pathway of the air mass (Michener & Lajtha, 2007). The isotopic composition of a vapor mass that forms over an ocean depends on the sea surface temperature, wind speed, salinity, and humidity. When this vapor moves towards the continent and cools down, condensation will occur. Fractionation during rainout leads to rain that is more enriched in heavy isotopes compared to the water vapour. As the water vapour moves further, subsequent precipitation will be depleted in heavy isotopes compared to previous precipitation from the same water vapour (Michener & Lajtha, 2007), as illustrated in Figure 4.

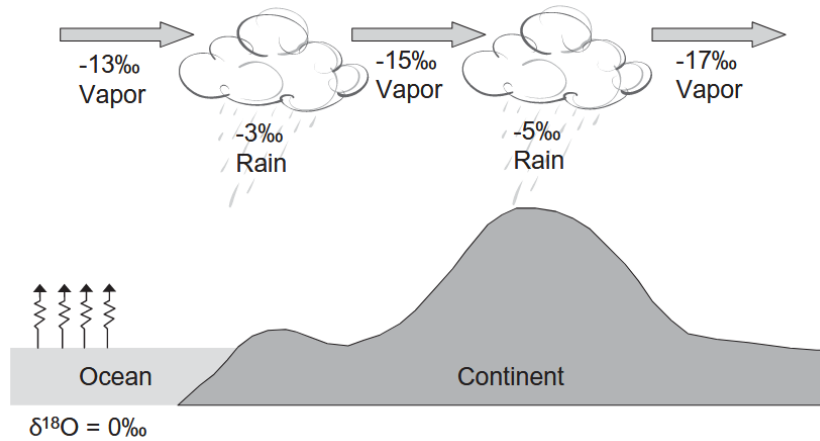


Figure 4: Isotopic composition of water vapour and the effects of fractionation during evaporation and rainout on its way over the continent (Michener & Lajtha, 2007).

The Global meteoric water line (GMWL) indicates the relationship between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in rain and snow (Michener & Lajtha, 2007). It has a linear relationship of approximately:

$$\delta^2\text{H} = 8 \cdot \delta^{18}\text{O} + 10 \quad (2)$$

The intercept with the ^2H axis is referred to as deuterium excess (d-excess), and quantifies the deviation from the GMWL (Mook, 2000). This deviation is useful to distinguish between equilibrium and non-equilibrium processes (Beria et al., 2018). For the global meteoric water line, the deuterium excess is 10 ‰, however, this can vary depending on the humidity and temperature at the source where the evaporation occurred (Mook, 2000). The deuterium excess can also change with subsequent evaporation. Since fractionation occurs during phase changes, the isotopic enrichment can be used to estimate evaporation rates (Michener & Lajtha, 2007). Since evaporation is a non-equilibrium process, the isotope fractionation does not follow the same slope as the GMWL, but typically follows a lower slope (Beria et al., 2018; Mook, 2000). This is caused by the differential enrichment rates in $\delta^2\text{H}$ and $\delta^{18}\text{O}$, where the remaining liquid becomes proportionally more enriched in $\delta^{18}\text{O}$ relative to $\delta^2\text{H}$ (Beria et al., 2018). The lower the humidity during the evaporation, the larger the deviation from the global meteoric water line (Michener & Lajtha, 2007).

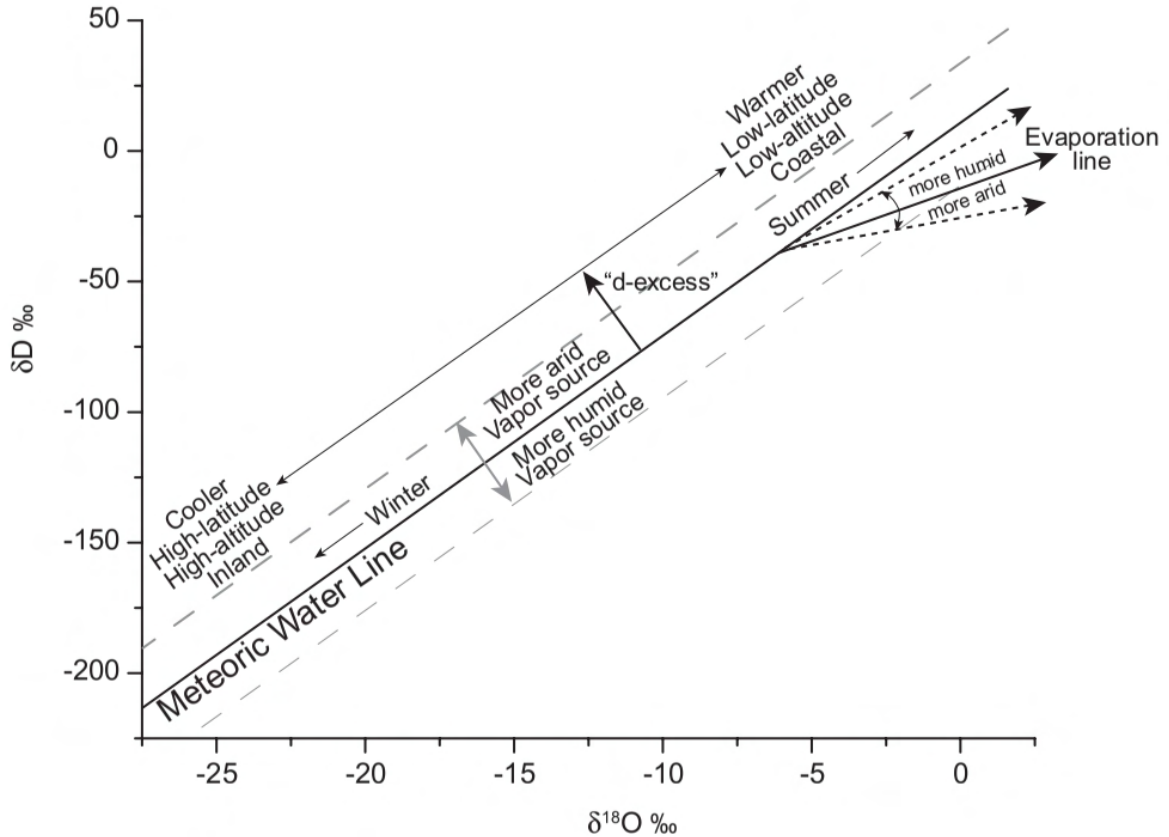


Figure 5: Schematic meteoric water line showing factors leading to deviations from the global meteoric waterline (Michener & Lajtha, 2007).

The isotopic composition of precipitation is mainly controlled by two variables: the temperature, which determines the magnitude of isotopic fractionation, and the amount of the initial vapor mass that remains after a rainout event (Michener & Lajtha, 2007). These fractionation processes lead to typical geographic and temporal patterns in precipitation (Michener & Lajtha, 2007). More depleted $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are found at increasing latitude, at higher elevations, further inland, and during winter (Michener & Lajtha, 2007; Mook, 2000), as shown in Figure 5.

- Continental effect: As an air mass moves from the ocean toward the interior of a continent, it becomes progressively depleted in heavy isotopes due to the ongoing rainout effects (Michener & Lajtha, 2007).
- Elevation effect: Within orographic precipitation, air masses move upward due to the topography. This leads to a preferential rainout of heavy isotopes, resulting in progressively more depleted precipitation at higher elevations (Beria et al., 2018; Michener & Lajtha, 2007). In Switzerland, the average isotope composition in precipitation shifts by 1.9‰ / 100 m for $\delta^2\text{H}$, and 0.27‰ / 100 m for $\delta^{18}\text{O}$ (Beria et al., 2018).
- Amount effect: In small storms, the moisture is relatively low, which leads to more evaporation of a water drop on the way to the ground, and thus the water drop is more enriched in the heavy stable isotopes (Michener & Lajtha, 2007). In larger storms, the precipitation becomes progressively depleted due to the earlier rainout of heavier isotopes (Beria et al., 2018).
- Latitude effect: As air masses move towards regions with cooler temperatures, the condensation temperature decreases and fractionation increases. By the time air masses reach higher latitudes, it has become progressively more depleted in heavy isotopes (Michener & Lajtha, 2007).
- Seasonal effect: In temperate regions, air masses are more depleted in heavy isotopes in winter than during summer due to the temperature effect on fractionation (Beria et al., 2018; Mook, 2000). Consequently, summer rainfall is typically more enriched in heavier isotopes compared to winter snowfall (Beria et al., 2018).

Within a snow pack, the isotopic composition initially reflects the signature of the precipitation (Michener & Lajtha, 2007). However, the snow pack undergoes significant changes from its deposition until melting, due to snow sublimation, snow pack metamorphism, and snow melt (Beria et al., 2018). Snow sublimation is a non-equilibrium fractionation process that leads to an isotopic enrichment with a reduction in deuterium excess, similar to changes by evaporation (Beria et al., 2018). During initial snow melt,

meltwater is depleted in heavy isotopes compared to the snow pack due to the preferential melting of lighter isotopes. Consequently, both the remaining snow pack and the subsequent meltwater become progressively enriched in heavy isotopes as the snow melt season advances (Beria et al., 2018; Michener & Lajtha, 2007). Despite this enrichment trend, the average isotopic composition of a snow pack typically remains more depleted than summer rainfall. The distinct isotopic composition of winter and summer precipitation can thus be used as a tracer for the evolution and contribution of snow to hydrological pathways, and to estimate residence time of water within a catchment (Beria et al., 2018).

Once the water is in the subsurface, and thus does not undergo further evaporation, the isotopic composition only changes through mixing. The isotopic composition of a mixture depends on the relative contribution of the different water sources and their isotopic signatures (Michener & Lajtha, 2007). This can be used to quantify the contribution of two different sources to a mixture, if they have a distinctly different isotopic composition (Mook, 2000). This is why stable water isotopes can be used in mixing models to determine different contributions from groundwater, snow and ice melt, precipitation, or to distinguish between contributions from glacial and periglacial sources within the catchment (Brighenti et al., 2023).

The stable water isotope composition can also be used to learn about the contribution of different water sources to rock glacier discharge and its evolution through the summer season (Jones et al., 2019). The reaction of stable water isotopes after precipitation events can help to distinguish between quickflow and baseflow within rock glaciers and thus give insight into water storage and release (Jones et al., 2019). Furthermore, the isotope signature can give insight into processes occurring within the rock glaciers, such as freeze-thaw cycles (Arenson et al., 2022). By comparing the discharge of different landforms with summer precipitation or modeled precipitation values (Nelson et al., 2021), information about the residence time of water within these landforms can be derived.

2.2.4 Hydrochemical and Isotopic Tracers of Alpine Streamflows

Different studies have used water temperature, EC, and stable water isotopes to differentiate between different water sources within Alpine catchments. There is often a large spatial and temporal variability in isotopic and chemical tracers in such high-elevation catchments (Delpero et al., 2025).

Water temperature has successfully been used as a first assessment to map permafrost conditions in Alpine catchments (Carturan et al., 2016), and to distinguish between intact and relict rock glaciers (Carturan et al., 2016; Carturan et al., 2024). In fact, Carturan

et al. (2024) suggests that a significant amount of rock glaciers classified as relict should be redefined as pseudo-relict based on the water temperature in their discharge. Water temperature is especially useful since it remains constantly cold throughout the summer season (Carturan et al., 2016). Towards the catchment outlet, there is typically an increase in water temperature (Brighenti et al., 2026). Furthermore, higher fluctuations in water temperature towards the outlet of a catchment are reported, both on an annual and diurnal scale, that are generally correlated with variations in air temperature. This is explained by the long enough travel time of water within the streams to allow for an exchange of atmospheric heat (Michelon et al., 2023).

EC and isotopic composition show a higher variability throughout the summer, but also between different years, and are influenced by precipitation events, which complicates their use as a tracer for permafrost occurrence (Carturan et al., 2016). Carturan et al. (2016) did not find any significant differences in EC or $\delta^2\text{H}$ values between probable and improbable permafrost, or within intact and relict rock glaciers. However, different studies used EC and isotope signatures to distinguish between different water sources within Alpine catchments (Brighenti et al., 2023; Delpero et al., 2025). Both Brighenti et al. (2023) and Delpero et al. (2025) reported significantly lower EC in precipitation and snowmelt, and higher EC in rock glacier discharge. Spring unaffected by intact rock glaciers within the same catchment are reported to have lower EC values than those from active rock glaciers (Thies et al., 2013). Regarding the isotopic signature, snow melt is the most depleted in heavy isotopes, followed by rock glacier runoff, while summer precipitation is more enriched in heavy isotopes (Brighenti et al., 2023; Delpero et al., 2025). However, while Delpero et al. (2025) reports lower EC and more depleted water in glacier discharge than in rock glacier discharge, Brighenti et al. (2023) did not report a significant difference between glacier and rock glacier discharge based on these variables.

3 Study Site

The investigated sites are located in two neighboring Alpine catchments in the eastern Swiss Alps, within the upper Engadine region: Val Muragl and Val Champagna (Figure 6 and Table 2). Both valleys are characterized by a high-alpine landscape and diverse geomorphological landforms, such as rock glaciers, a moraine complex, scree slopes, and meadows (Maisch et al., 2003). They were chosen due to the presence of diverse periglacial and glacial landforms, and extensive research previously conducted on permafrost and rock glacier dynamics in Val Muragl (Kääb & Kneisel, 2006; Kneisel & Kaeaeab, 2007; Kneisel et al., 2000; Kunz & Kneisel, 2020; PERMOS, 2026), which provides a foundation for further investigation of the hydrology and runoff regimes of these catchments.

3.1 Geography and Topography

The Val Champagna catchment ranges in elevation from 1682 to 3158 m a.s.l., while Val Muragl covers a similar extent from 1724 to 3163 m a.s.l. (Swisstopo, 2025). Samples were collected down to the catchment outlet in Val Muragl to capture the influence on the downstream river system, but the investigations in Val Champagna were restricted to the uppermost part (2510 to 3158 m a.s.l.) (Swisstopo, 2025). The Muragl catchment and the upper part of the Champagna catchment encompass areas of 5.9 km² and 1.03 km², respectively (Swisstopo, 2025). Both valleys are used for livestock farming during the summer season.

Geologically, the study area is situated within the Languard nappe, a crystalline sub-unit of the Austroalpine unit. While the upper part of Val Champagna is dominated by augen gneiss (orthogneiss), Val Muragl is primarily composed of strongly foliated and layered biotite gneiss (paragneiss) (Peters, 2005; Springman et al., 2012).

Table 2: Descriptive characteristics of the two studied catchments.

Variable	Val Muragl	Val Champagna
Area (km ²)	5.9	1.03
Minimum Elevation (m a.s.l.)	1724	2510
Maximum Elevation (m a.s.l.)	3163	3158
Geology	Paragneiss	Orthogneiss
Mean annual air temperature	−4 to −2°C	
Mean annual precipitation	1000–1200 mm/yr	

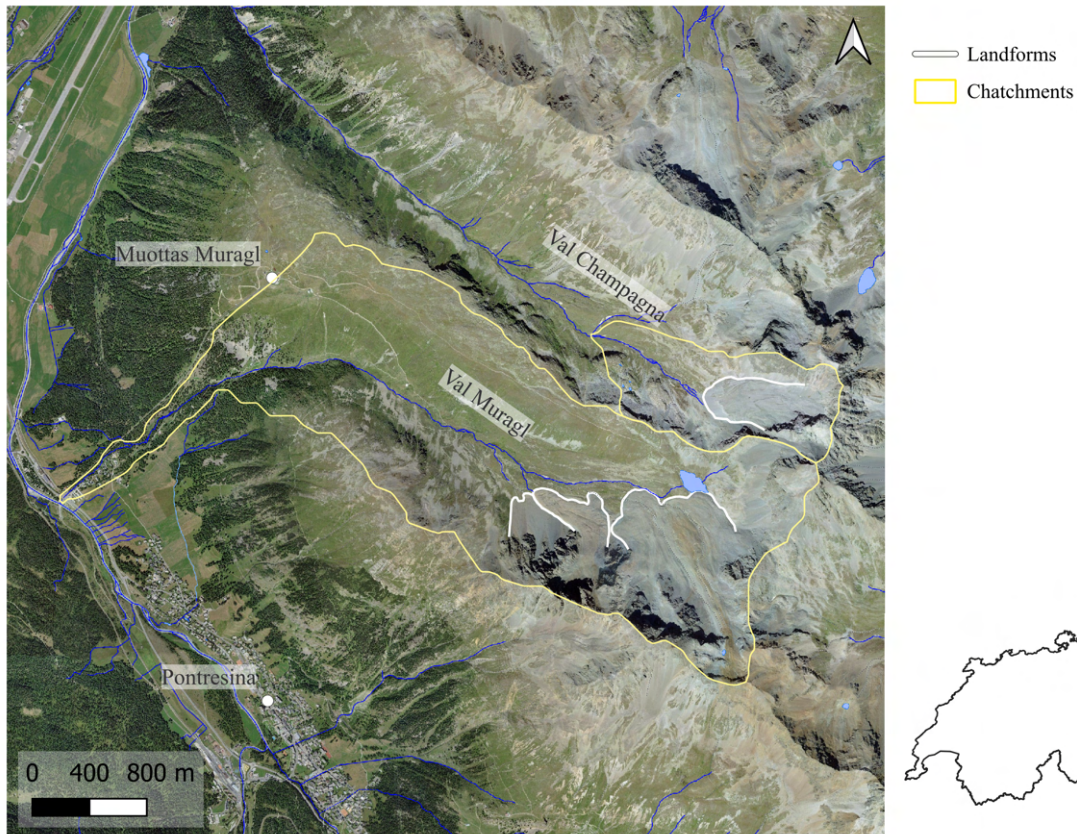


Figure 6: Aerial photograph of the Val Champagna and Val Muragl, with the location in Switzerland shown in the inset. Yellow lines indicate the outlines of the catchments, white lines highlight prominent landforms within the catchments, and blue lines mark streams within the area.

The local climate has a continental regime, with relatively low precipitation, but a high seasonal temperature variability (Kneisel & Kaeae, 2007; Kneisel et al., 2000; Kunz & Kneisel, 2020). The mean air temperature lies between -2 and -4°C at the elevation of the moraine complex, while the mean annual precipitation amounts to $1000 - 1200$ mm/yr (Kunz & Kneisel, 2020). The stream network of Val Muragl, including Lake Muragl, converges into the Ova da Val Muragl, which flows into the Flaz, before joining the Inn. The Val Champagna valley drains into the Ova da Val Champagna, which connects directly to the Inn (Swisstopo, 2024).

3.2 Geomorphology

3.2.1 Glacial History

During the Lateglacial period following the Last Glacial Maximum, both Val Champagna and Val Muragl were glaciated, leaving behind distinct moraine systems in Cinuos-chel, Samedan, and Pontresina. Since the onset of the Holocene, approximately 10'000 years BP, glacier extents are assumed to have fluctuated within the conditions of the Little

Ice Age around 1850 and the current extent (Maisch et al., 2003). On current satellite images, no remnants of the Muragl glacier are observable (Swisstopo, 2026). Figure 7 shows the reconstructed glacier extent since 1850 (Swisstopo, 2020). With glacier retreat, the significance of periglacial debris and discontinuous permafrost grew (Maisch et al., 2003).

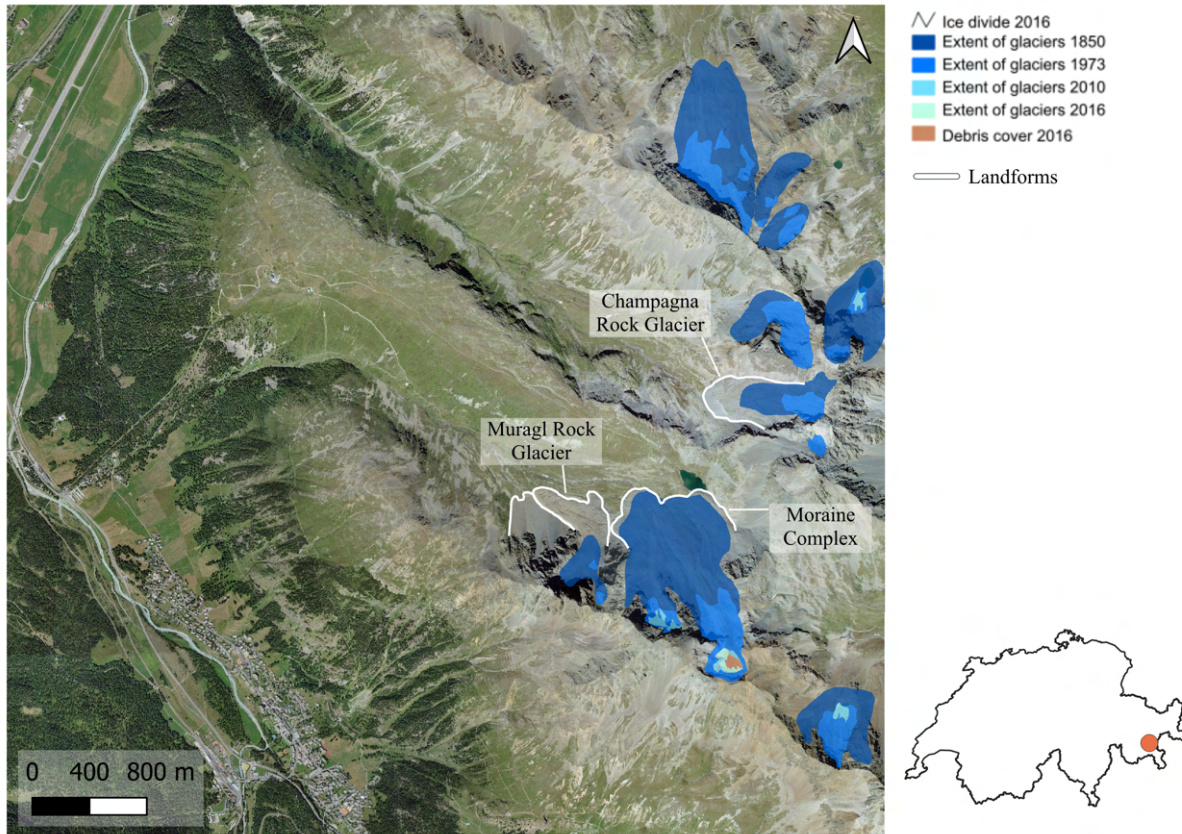


Figure 7: Reconstructed glacier extent between 1850 and 2016 (Extent of glaciers, Swisstopo, 2020).

3.2.2 Muragl and Champagna Rock Glaciers

The Muragl and Champagna rock glaciers are prominent geomorphological features in the study area. While limited research has been conducted on the Champagna rock glacier, the Muragl rock glacier has been the subject of long-term monitoring and intensive research (Kääb & Vollmer, 2000; Kunz & Kneisel, 2020; PERMOS, 2026). It is located on the western slope of Piz Muragl at an elevation of 2490 to 2750 m a.s.l. and covers an area of approximately 0.15 km² (Kellerer-Pirklbauer et al., 2024). This complex landform is a multi-unit rock glacier system composed of several lobes and partly overlapping units (Kellerer-Pirklbauer et al., 2024). The Muragl rock glacier is characterized by a series of multiple transverse and longitudinal ridges and depressions. The typical diameter of the surface debris is 0.5 – 1.5 m (Kääb & Vollmer, 2000). Its main lobe moves roughly 1.5

m/yr, has a thickness of about 25 m, and a surface slope of 20° (Cicoira et al., 2019). In the Muragl rock glacier, the horizontal displacement occurs mainly within a distinct shear horizon at the bottom of the permafrost body, with 77 – 82% of the surface deformation occurring in this shear zone. Additionally, some creep is detected above this shear horizon (Arenson et al., 2002). The Muragl Rock glacier is characterized by both inter-annual and seasonal variations in movement. While its velocity decreases during winter, a strong acceleration is measured at the beginning of summer during snow melt. The highest velocities are recorded towards the end of the summer, when ground surface temperatures are highest (Noetzli et al., 2025). During recent years, inter-annual variations have been observed, with a velocity peak in 2016 – 2017 and 2019 – 2020, followed by a period of deceleration (Kellerer-Pirklbauer et al., 2024). Overall, there is a trend of increasing multi-annual velocities (Cicoira et al., 2019). Figure 8 and Figure 9 give an impression of the Champagna and Muragl rock glaciers and the surrounding landscape.



Figure 8: Champagna Rock Glacier from the ridge between Val Champagna and Val Muragl (Kathrin Habegger, 2025).

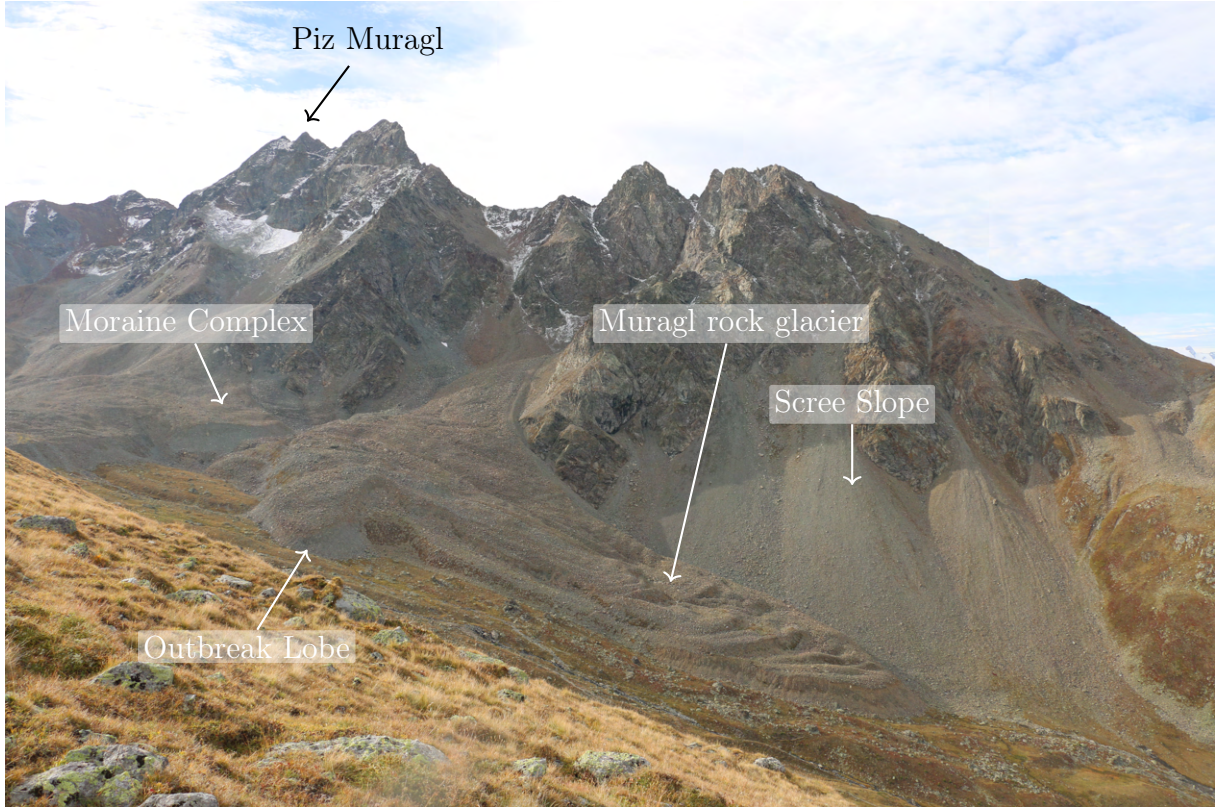


Figure 9: Muragl Rock Glacier and surrounding landforms in Val Muragl (Kathrin Habegger, 2025).

Information about the stratigraphy of the Muragl rock glacier was gained through geophysical surveys and the drilling of multiple boreholes (Springman et al., 2012). Out of the four boreholes drilled in 1999, one lies outside the active part of the rock glacier with no permafrost, but a high permeability due to coarse sand and gravel. Within the active part of the rock glacier, the ice core is approximately 15 m thick (Springman et al., 2012). Within the frozen layer of the Muragl rock glacier, a large heterogeneity and a low ice content of about 40 – 70% with warm ice close to 0°C was found (Arenson et al., 2002). This heterogeneity has been confirmed during the drillings of 5 boreholes in August 2024 on Muragl rock glacier, where large amounts of water were observed within the permafrost body (Noetzli et al., 2025). Underneath the frozen layer, a highly permeable layer with coarse gravel and blocks was found. This layer is assumed to be connected to the atmosphere based on the seasonal temperature variations at the permafrost base. Underneath this layer, the bedrock was reached (Springman et al., 2012). A sketch of the internal structure of the Muragl rock glacier by Arenson et al. (2002) is shown in Figure 10.

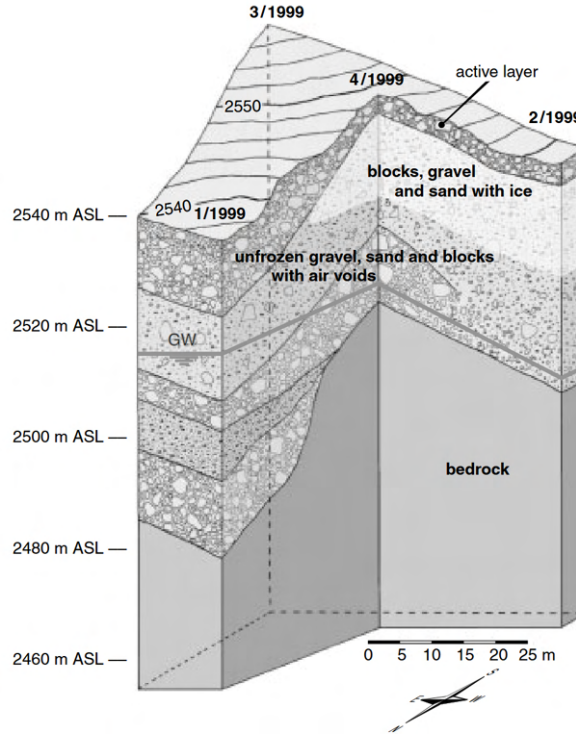


Figure 10: Internal structure of the Muragl rock glacier based on borehole information of the 1999 boreholes (Arenson et al., 2002).

In the boreholes of 1999, the active layer was estimated to be 2 – 6 m thick, while the base of the permafrost was detected at a depth of 18 – 20 m (Springman et al., 2012). Measurements from the 2024 boreholes suggest that the active layer is up to 5 m deep during the summer season (PERMOS, 2026). Field observations found water flowing within the active layer on top of the permafrost body at a depth of less than 1 m (Springman et al., 2012). The measured temperature at different depths within the Muragl rock glacier is shown in Figure 11.

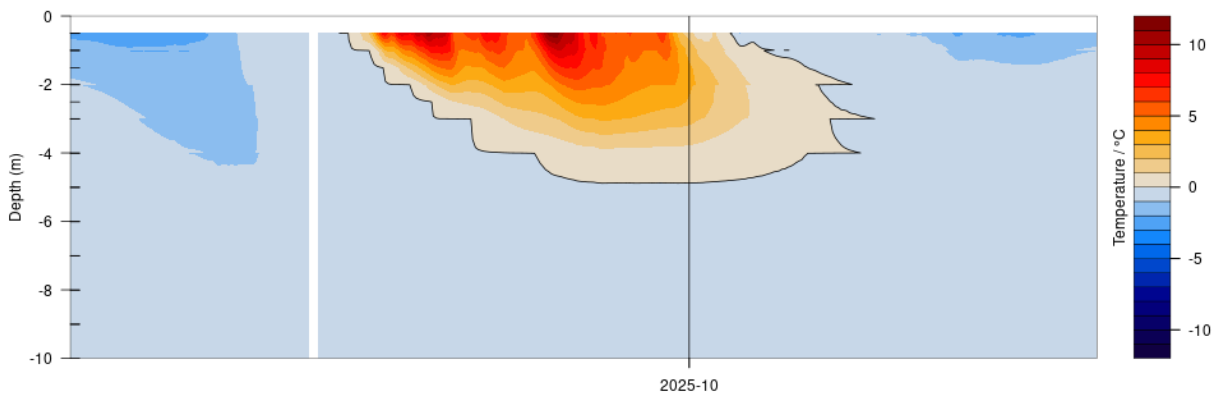


Figure 11: Temperature (°C) at different depths within the borehole of the Muragl rock glacier between 23.02.2025 and 23.02.2026 (PERMOS, 2026).

3.2.3 Moraine Complex

In addition to the rock glacier, Val Muragl is characterized by a variety of other geomorphological landforms. East of the Muragl rock glacier, there is a glacier forefield located between 2650 m and 2920 m a.s.l. (Figure 12), resulting from the retreat of the Muragl glacier (Kneisel & Kaeaeab, 2007; Kunz & Kneisel, 2020; Maisch et al., 2003). It is dominated by a raised sediment bed with a thickness of several (10s of) meters. The presence of glacial flutes in the central part of this forefield indicates that the glacier was warm-based in this region. On the contrary, the well-developed thrust moraine northeast of this forefield implies glacier-permafrost interactions. The coexistence of these features suggests a polythermal regime of the former Muragl glacier, with temperate conditions at its central part and cold temperatures at its borders (Kneisel & Kaeaeab, 2007; Kunz & Kneisel, 2020; Maisch et al., 2003). This thrust moraine, together with a well-developed end moraine, marks the limits of the Muragl glacier at the maximum of the Little Ice Age at around 1850. Both the moraine and the sediment bed are currently undergoing permafrost-induced creeping (Kunz & Kneisel, 2020).

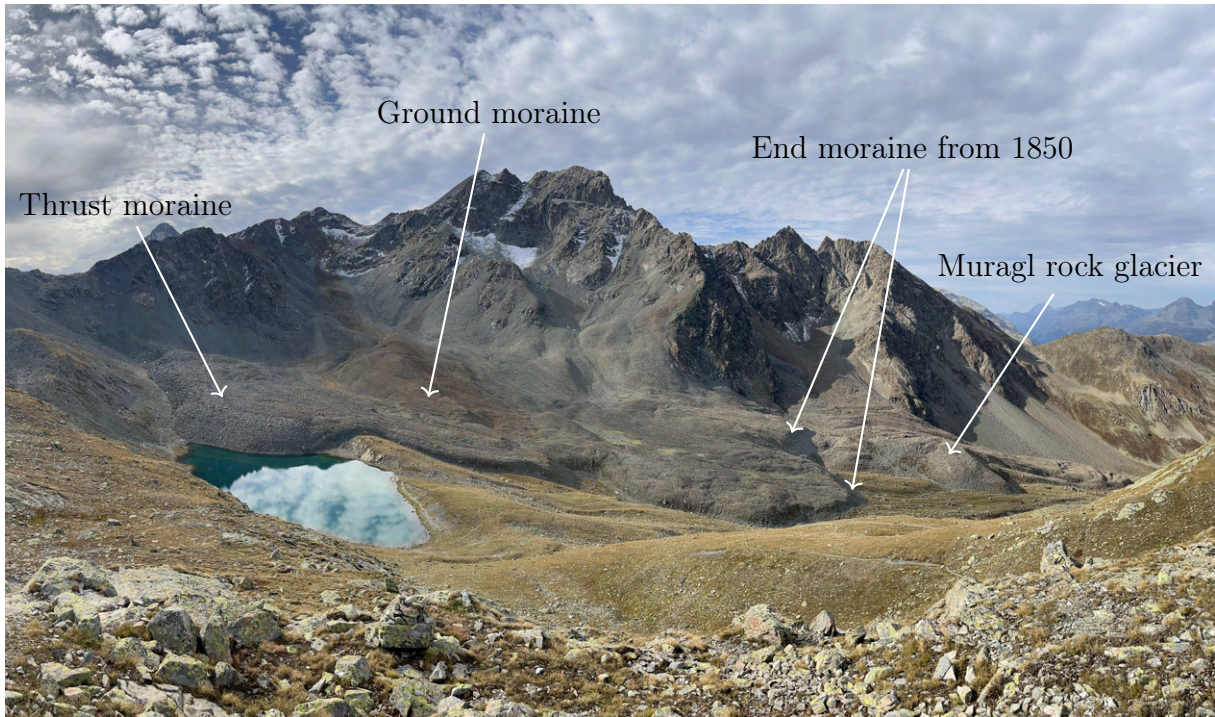


Figure 12: Glacier forefield of the former Muragl glacier (Stephan Habegger, 2025).

3.2.4 Permafrost Distribution Within the Muragl Catchment

The glacier forefield is characterized by both glacial and periglacial landforms in close proximity to each other, such as the thrust moraine, creeping permafrost, and permafrost-free glacial till (Kneisel & Kaeab, 2007; Kneisel et al., 2000). These complex conditions, indicating a polythermal regime of the Muragl glacier, have an impact on the permafrost distribution in the glacier forefield, even after the retreat of the glacier (Kunz & Kneisel, 2020; Maisch et al., 2003). Together with other factors such as sediment characteristics, climatic conditions, snow cover, and aspect, it results in a discontinuous distribution of Alpine permafrost in this area (Kääb & Vollmer, 2000), located at the lower regional boundary of discontinuous permafrost distribution (Kääb & Kneisel, 2006). A possible distribution of permafrost and ground ice modeled by the SLF based on thermal conditions, elevation, burial of ice or snow by rockfall, and its relocation is shown in Figure 13 (Kenner et al., 2019).

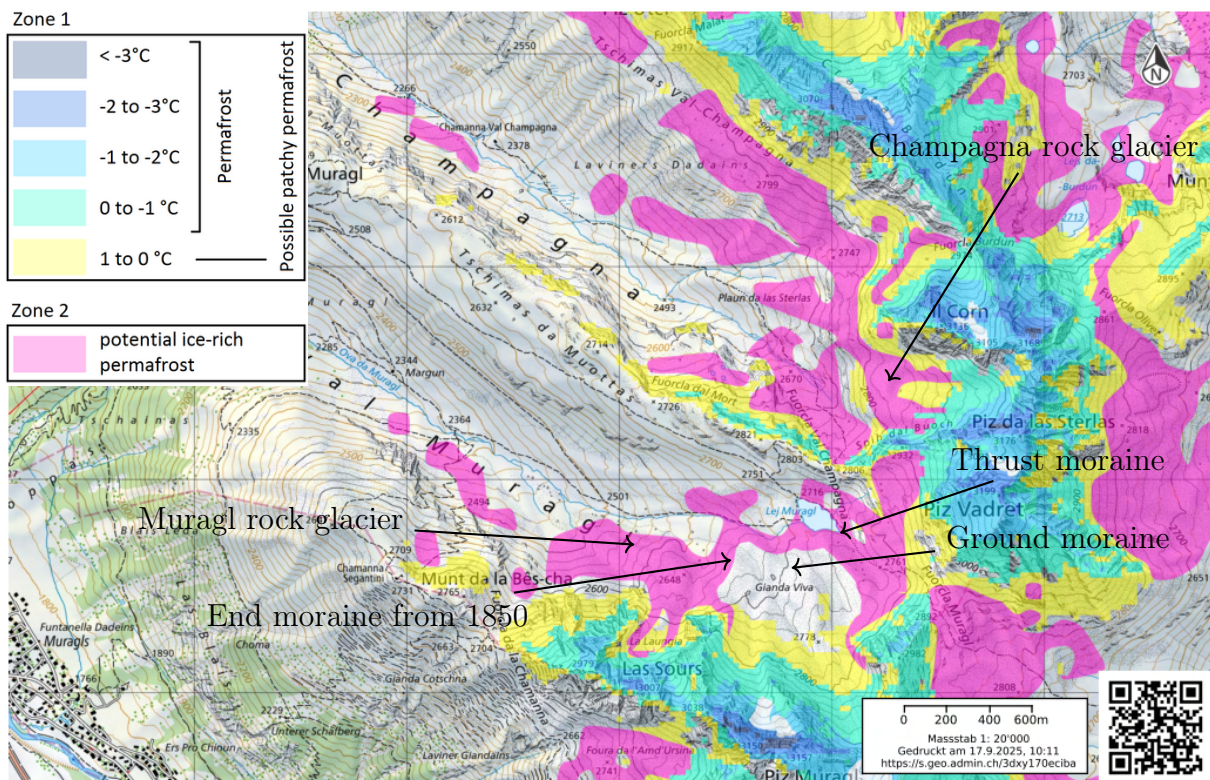


Figure 13: Spatial variation in permafrost and ground ice cover in the study area, as modeled by the SLF. Ice-rich permafrost includes permanently frozen sediments whose ice content exceeds the pore volume. Ice-poor refers to permafrost in rock walls or in dry talus slopes. This map is only an indication of a possible permafrost distribution (Kenner et al., 2019; SLF, 2025).

The permafrost distribution in the glacier forefield has been investigated using different geophysical methods. A measurement of the bottom temperature below the winter snow cover (BTS measurements) has shown that permafrost occurrence is probable in the higher parts of the cirque and at the outermost parts of the glacier forefield close to the glacier extent around 1850 (Kneisel et al., 2000). This finding is supported by 2D geoelectrical surveys, which indicate a permafrost body within the 1850 end moraine. The resistivity surveys suggest warm permafrost close to 0°C, which would also explain the high movement of this part of the moraine compared to the low slope angle of less than 15° (Kneisel & Kaeaeb, 2007). In the central part of the glacier forefield, bottom temperature measurements indicate that permafrost is either possible or improbable (Kneisel et al., 2000). The 2D geoelectrical surveys suggest that shallow permafrost with a low ice content is possible within the ground moraine, and likely formed after the retreat of the glacier ice. However, settlement features in this area also suggest that permafrost might be degrading (Kneisel & Kaeaeb, 2007). Within the thrust moraine, temperature measurements indicate that permafrost is probable, and geoelectrical surveys suggest that there is a massive ice core within (Kneisel & Kaeaeb, 2007; Kneisel et al., 2000). These findings are supported by measurements using electrical resistivity tomography and ground-penetrating radar (GPR) of the thrust moraine, which were able to identify an active layer at the top, ice-rich permafrost within, and unfrozen material beneath the thrust moraine. Furthermore, shear planes with fine-grained sediments and an overall high proportion of debris within the ice were detected in the ice core, supporting the assumption of glacier-permafrost interaction during the formation of the moraine (Kunz & Kneisel, 2020). To summarize, Val Muragl is characterized by a complex pattern of discontinuous permafrost, likely consisting of both permafrost preserved beneath cold surface ice, younger permafrost formed after the retreat of the Muragl glacier, active permafrost creep, and degrading permafrost (Kneisel & Kaeaeb, 2007; Kneisel et al., 2000).

4 Methods

To analyze how different landforms and water sources affect the catchment’s hydrology, this thesis applied a quantitative monitoring approach. A combination of measurement methods was used to obtain both temporal and spatial information. Continuous data recorded at four locations provided data for analyzing temporal trends on both diurnal and seasonal scales. To complement this, manual measurements and water samples were collected bi-weekly from 25 locations to identify spatial differences throughout the catchment and to determine how specific landforms influence downstream river flow. This approach ensures that changes over time are captured, while maintaining an overview of how water characteristics vary by location.

4.1 Site Selection

4.1.1 Sampling Locations

A total of 25 sampling locations were selected to capture the spatial variability across the different landforms, land cover types, and water sources. Of these sites, four are located in Val Champagna and 18 in Val Muragl. In addition to stream water, precipitation, and snow samples were collected at the Muragl rock glacier, with further snow samples taken at the scree slope whenever conditions allowed. Their location and elevation are illustrated on the map in Figure 14 and summarized in Table 3.

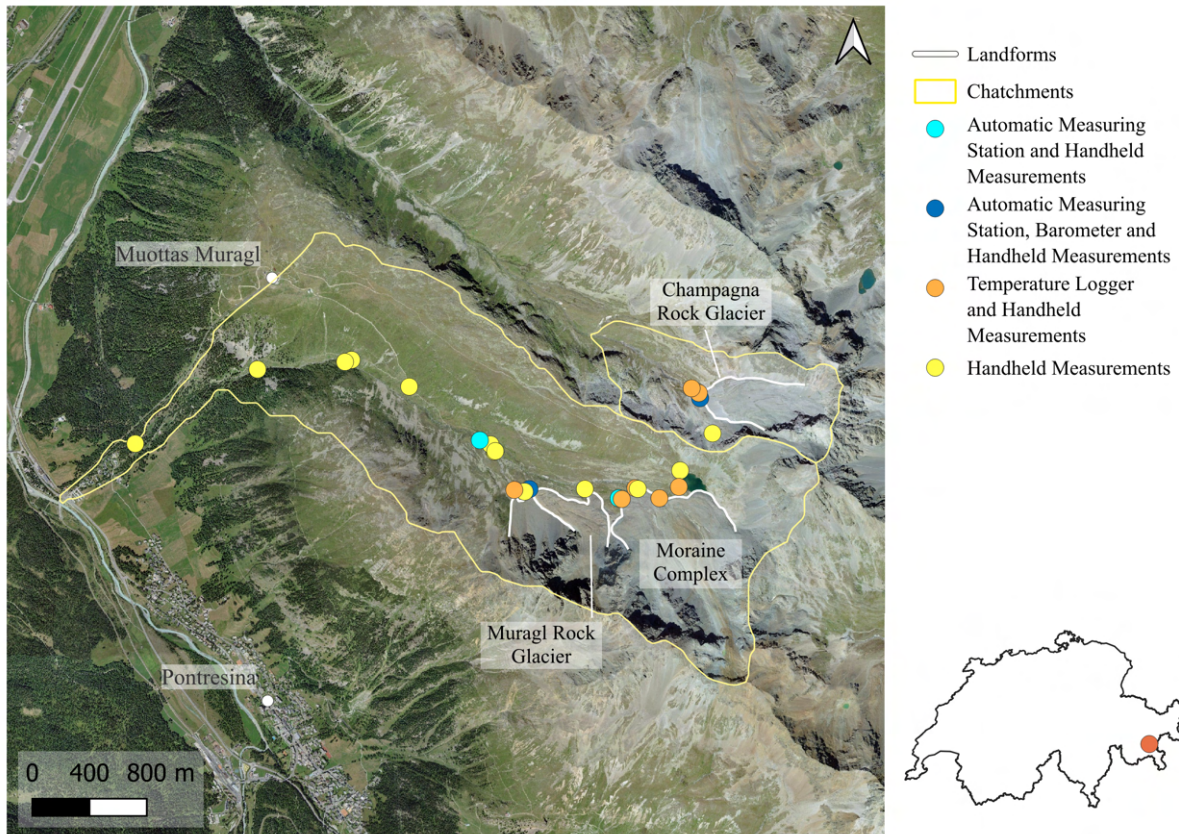


Figure 14: Location of the sampling sites in Val Muragl and Val Champagna. Colour represents the type of instrument or measurement method used to collect data. Automatic Measurement stations collected data on water temperature, EC, and water level, while temperature loggers measured water temperature. During handheld measurements, water temperature and EC were recorded for these sites as well, while water samples were taken.

Table 3: Location, coordinates (LV95), elevation, instrument type, water source, and permafrost occurrence at each sampling site.

Location	Easting [LV95]	Northing [LV95]	Elev. [m a.s.l.]	Instrument	Water Source	Permafrost Occurrence
Champ1	2'791'981	1'154'413	2'684	Keller CTD / Barometer	Rock Glacier	Probable
Champ2	2'791'972	1'154'449	2'685	HOBO Tidbit	Exfiltrating Hillslope Water	Possible
Champ3	2'791'922	1'154'482	2'679	HOBO Tidbit	Mixed Upstream Sources	Mixed
Champ4	2'792'068	1'154'167	2'761	Handheld	Exfiltrating Hillslope Water	Possible
Muragl1	2'791'842	1'153'908	2'722	Handheld	Lake Outflow	Mixed
Muragl2	2'791'833	1'153'793	2'716	HOBO Tidbit	Lake Outflow	Mixed
Muragl3	2'791'697	1'153'714	2'667	HOBO Tidbit	Ground moraine	Possible
Muragl4	2'791'412	1'153'714	2'621	Keller CTD	End moraine	Probable
Muragl5	2'791'434	1'153'708	2'625	HOBO Tidbit	End moraine	Probable
Muragl6	2'791'529	1'153'785	2'634	HOBO Tidbit	Ground moraine	Mixed
Muragl7	2'791'176	1'153'779	2'569	Handheld	Exfiltrating Hillslope Water	Mixed
Muragl8	2'790'789	1'153'778	2'486	Keller CTD / Barometer	Rock Glacier	Probable
Muragl9	2'790'755	1'153'760	2'480	Handheld	Rock Glacier	Probable
Muragl10	2'790'683	1'153'772	2'470	HOBO Tidbit	Scree Slope	Possible
Muragl11	2'790'543	1'154'039	2'427	Handheld	Rock Glacier	Probable
Muragl12	2'790'547	1'154'045	2'428	Handheld	Rock Glacier	Probable
Muragl13	2'790'517	1'154'089	2'420	Handheld	Lake Outflow	Mixed
Muragl14	2'790'442	1'154'119	2'417	Keller CTD	Mixed Upstream Sources	Mixed
Muragl15	2'789'949	1'154'493	2'339	Handheld	Exfiltrating Hillslope Water	Improbable
Muragl16	2'789'546	1'154'680	2'255	Handheld	Exfiltrating Hillslope Water	Improbable
Muragl17	2'789'500	1'154'666	2'236	Handheld	Mixed Upstream Sources	Mixed
Muragl18	2'788'889	1'154'614	2'095	Handheld	Mixed Upstream Sources	Mixed
Muragl19	2'788'035	1'154'095	1'831	Handheld	Mixed Upstream Sources	Mixed
Muragl20	2'791'546	1'153'779	2'637	Handheld	Ground moraine	Improbable
Muragl21	2'790'550	1'154'043	2'427	Handheld	Exfiltrating Hillslope Water	Mixed

4.1.2 Determination of Permafrost Occurrence

The permafrost occurrence within the study area was defined by overlaying the catchment boundaries of each stream, derived from a Digital Elevation Model swissALTI3D (Swisstopo, 2024), with the permafrost map of the Swiss Institute for Snow and Avalanche Research (Kenner et al., 2019; SLF, 2025), as illustrated in Figure 15. Catchments were delineated in QGIS using the GRASS GIS provider (r.watershed and r.water.outlet) to define boundaries of the area draining into each sampling point. The catchments draining to the sampling points were classified into four categories based on the modeled ground temperature and the ice content:

- Probable influence of permafrost on the stream: The majority of the catchment lies in zones with a mean annual ground temperature of below 0°C.
- Possible influence of permafrost on the stream: The majority of the catchment lies in zones with a mean annual ground temperature between 0°C and 1°C, or ice-rich permafrost is possible.
- Improbable influence of permafrost on the stream: The majority of the catchment lies within regions where the SLF map assumes no permafrost.
- Mixed streams: If the sampling point is below the confluence of different streams, of which one is classified as draining a catchment with probable or possible permafrost, while the other stream emerges from zones with improbable permafrost, the downstream mixing is classified as a mixed stream.

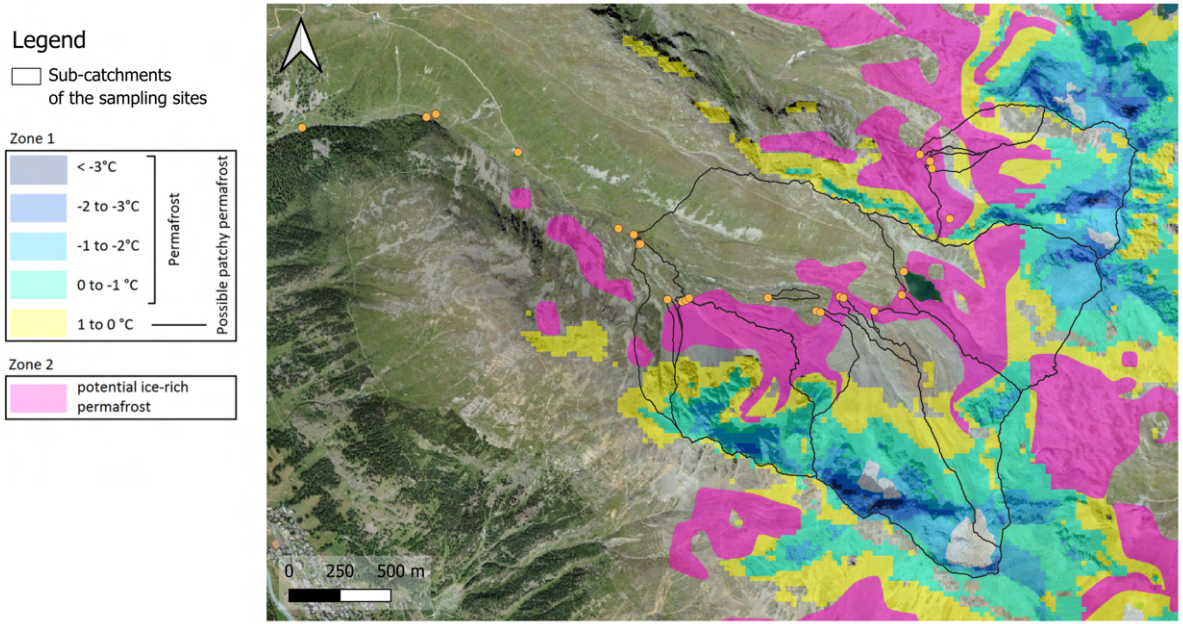


Figure 15: Modeled permafrost distribution by SLF (Kenner et al., 2019; SLF, 2025) and sub-catchments of the different sampling sites to determine potential permafrost occurrence within the sub-catchment.

4.2 Field Measurements and Sampling

Field measurements were conducted over a summer season, spanning from mid-July to mid-October 2025. Data collection involved a combination of automatic loggers and bi-weekly handheld measurements and water sampling (Figure 19).

4.2.1 Automatic Measurement Stations

A total of eleven continuous loggers were installed to obtain high-resolution temporal data. Four stations were equipped with Keller DCX-22-CTD sensors to record water temperature, EC, and water pressure at a ten-minute interval. Two of those stations, one in Val Champagna and one in Val Muragl, additionally contain a Keller DCX-22-Baro barometer to record atmospheric pressure. However, due to large fluctuations of the barometer in Val Muragl, this dataset was excluded. Instead, the data of a barometer on top of the Muragl rock glacier by the SLF was used (WSL Institute for Snow and Avalanche Research SLF, Research Group Permafrost (Bast / Phillips), 2025). A comparison between the Val Champagna and SLF data revealed that while absolute pressure values differed due to differences in elevation, both stations exhibited a comparable diurnal and seasonal pattern. Table 4 shows the uncertainties of each instrument.

Table 4: Uncertainty of the data loggers for the automatic monitoring stations (Keller Pressure, 2025a, 2025b).

Measurement	Keller DCX-22-CTD	Keller DCX-22-Baro	HOBO Tidbit
Water temperature	± 0.1 °C	–	± 0.2 °C
Temperature Top of Bridge (Sensor)	± 0.5 °C	± 0.5 °C	–
Pressure	max. $\pm 0.1\%$ of the Full scale (0–10 mH ₂ O) → ± 1 cm	typ. $\pm 0.05\%$, max, 0.1% of the Full scale (1.3 bar) → ± 0.65 –1.3 mbar	–
Electrical conductivity	max. $\pm 2.5\%$ of selected Range (0–2 mS/cm) → 50 μ S/cm	–	–

The stations required a water level sufficiently deep for the sensor to be submerged at all times and safe from falling debris. This is why they were placed several meters downstream of the first point of emergence to the surface of the springs. The chosen locations are not ideal for water level measurements as the rivers mainly become wider with increasing flow, instead of deeper. However, better sites were not available. The sensors were fixed to a metal pole, which was hammered into the stream, as shown in Figure 16. A plastic pipe, mounted to the metal pole with zip ties, was used to protect the sensor from external damage. The sensor was secured within the plastic pipes using a non-elastic rope to prevent vertical displacement. Holes in the pipe, protected with filter cloth, allow for a free exchange of water without fine sediment filling the pipe. The barometers were positioned above the pipes and fixed to the metal poles with non-elastic rope. They were initially exposed to incoming solar radiation, but were protected with a reflective shielding from 08.09.2025 on to minimize heating up of the sensor and thus the influence of temperature on air pressure.



Figure 16: Photos of the automatic monitoring station in front of the Muragl rock glacier with and without the shielding of the barometer (Kathrin Habegger, 2025).

Seven additional streams were monitored using HOBO Tidbit loggers to measure water temperature at a ten-minute interval. Because of the small size of these loggers, they do not require such a deep water level and thus could be placed closer to the first point of discharge. The uncertainties of these instruments are given in Table 4. HOBO Tidbit temperature sensors were secured directly to short metal poles within the streams, as shown in Figure 17.

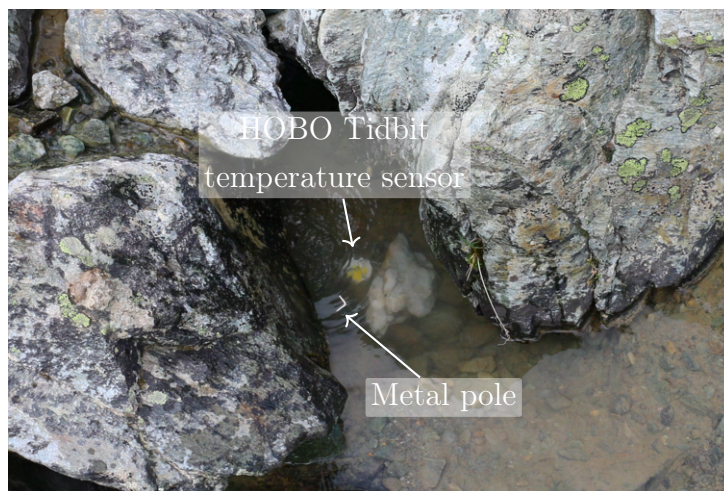


Figure 17: HOBO Tidbit temperature sensor secured in the stream using a short metal pole (Kathrin Habegger, 2025).

Aside from the exclusion of the unreliable barometric data, no significant data gaps or sensor malfunctions occurred. Although the metal pole in front of the Muragl rock glacier exhibited slight bending, no sudden shift in the water level data was observed; thus, it is unlikely that the pipe or the sensor was affected.

4.2.2 Sensor Calibration

Data on water temperature and EC from the automatic loggers were compared to the manual measurements taken with the handheld meter (see section section 4.2.4). Since the deviations in water temperature and EC were within the uncertainty of the measurement devices, no further calibration or offset adjustment was applied. For all analyses, the temperature-compensated electrical conductivity to 25°C (EC_{25}) was used. This compensation was performed directly by the loggers, normalizing the data linearly to a reference temperature of 25°C (Keller Pressure, 2025b).

4.2.3 Barometric Compensation of Water Pressure

To remove fluctuations in atmospheric pressure from the measured water pressure, barometric pressure data were collected from two additional reference stations: one situated on top of the Muragl rock glacier (WSL Institute for Snow and Avalanche Research SLF, Research Group Permafrost (Bast / Phillips), 2025) and another in Val Champagna. Since the barometer on top of the Muragl rock glacier recorded hourly, this data was interpolated linearly to the 10-minute interval of the discharge measurements. Moreover, due to the different elevations of the three measurement stations in Val Muragl, air pressure recorded by the barometer on top of the Muragl rock glacier was vertically adjusted to the elevation of each automatic measurement station within Val Muragl. This was calculated using a barometric gradient of 1hPa per 8 m (0.001bar/8 m).

$$P_{\text{atm}} = P_{\text{ref}} + \frac{(Z_{\text{ref}} - Z_{\text{station}})}{8m} \times 0.001 \text{ bar} \quad (3)$$

P_{atm} represents the calculated atmospheric pressure at the location of each measurement site, while P_{ref} is the reference atmospheric pressure recorded on top of the Muragl rock glacier. Correspondingly, Z_{station} and Z_{ref} refer to the elevation of the measurement site and the reference location on top of the Muragl rock glacier, respectively.

The elevation-corrected barometric pressure (P_{atm}) was then subtracted from the total pressure measured by the submerged loggers (P_{total}) to obtain the water pressure (P_{water}).

$$P_{\text{water}} = P_{\text{total}} - P_{\text{atm}} \quad (4)$$

The water level (cm) was calculated by multiplying the water pressure (P_{water}) by a conversion factor of 1019.7 cm/bar.

$$Waterlevel = P_{water} * 1019.7cm/bar \quad (5)$$

Note that the calculated values represent relative water levels rather than absolute depths, as the sensor was anchored above the streambed.

4.2.4 Bi-weekly Handheld Measurements and Water Sampling

Handheld measurements of water temperature and EC were conducted bi-weekly between mid-July and mid-October 2025 at all 25 measurement locations using a WTW Cond 3310 handheld meter, as shown in Figure 18. Water samples were taken at all 25 locations during these site visits as well. The measurement and sampling routine followed the same route and started at a similar time on each sampling day to minimize the influence of the sampling time. The location and elevation were confirmed using a Garmin GPS 60 device, with an uncertainty of 3 – 7 m depending on the location. The uncertainty of the handheld measurements is given in Table 5.



Figure 18: Handheld measurements with a WTW Cond 3310 (Ilja van Meerveld, 2025).

Table 5: Uncertainty of the WTW Cond 3310 sensor (Xylem Analytics Germany Sales GmbH & Co. KG, WTW, n.d.).

Measurement	WTW Cond 3310
Water temperature	± 0.1 °C
Electrical conductivity	$\pm 0.5\%$ of the measured value between 0 and 1000 mS/cm

The water samples ($n = 209$) were collected in 20 ml glass bottles. They were rinsed three times with stream water before collection and filled to the brim to ensure no air bubbles remained inside. After collection, samples were transported in a cooling bag and stored in the fridge until further processing to limit temperature fluctuation.

Rainwater was collected in a bottle close to the measurement station in front of the Muragl rock glacier, with a narrow aperture to minimize evaporation. Because the collector was emptied bi-weekly, the samples represent a mixture of all precipitation events occurring during the previous two weeks. Although the bottle was shielded with stones and boulders on the side, evaporation from the bottle can not be ruled out. Therefore, it is possible that fractionation may have slightly altered the original isotopic composition of the rainwater.

Snow samples were collected during two field campaigns in October, while snow was present in the catchment. One snow sample was collected in front of the Muragl rock glacier, and a second one in front of the scree slope next to the rock glacier. Small glass bottles were filled with fresh snow and immediately sealed to let the snow melt inside the bottle. It was tested whether the melting of the snow prior to filling the bottles to the brim resulted in a different isotopic signature. However, both methods yielded a comparable stable isotope composition.

4.2.5 Laboratory Analysis

Water samples were processed and analyzed for the abundance of the stable isotopes of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$). All samples were filtered using a $0.45\ \mu\text{m}$ PTFE/L filter and transferred into 2 mL glass vials. They were sent to the University of Freiburg, Germany, and analyzed using a Picarro L2140-i cavity ring-down spectrometer (CRDS) with an uncertainty of $\pm 0.16\text{‰}$ $\delta^{18}\text{O}$ and $\pm 0.6\text{‰}$ $\delta^2\text{H}$. The isotopic compositions are reported in delta notation (δ) in units of ‰ relative to VSMOW (Vienna Standard Mean Oceanic Water).

Deuterium excess (‰) was calculated with the following equation:

$$\text{d-excess} = \delta^2\text{H} - 8 \cdot \delta^{18}\text{O} \quad (6)$$

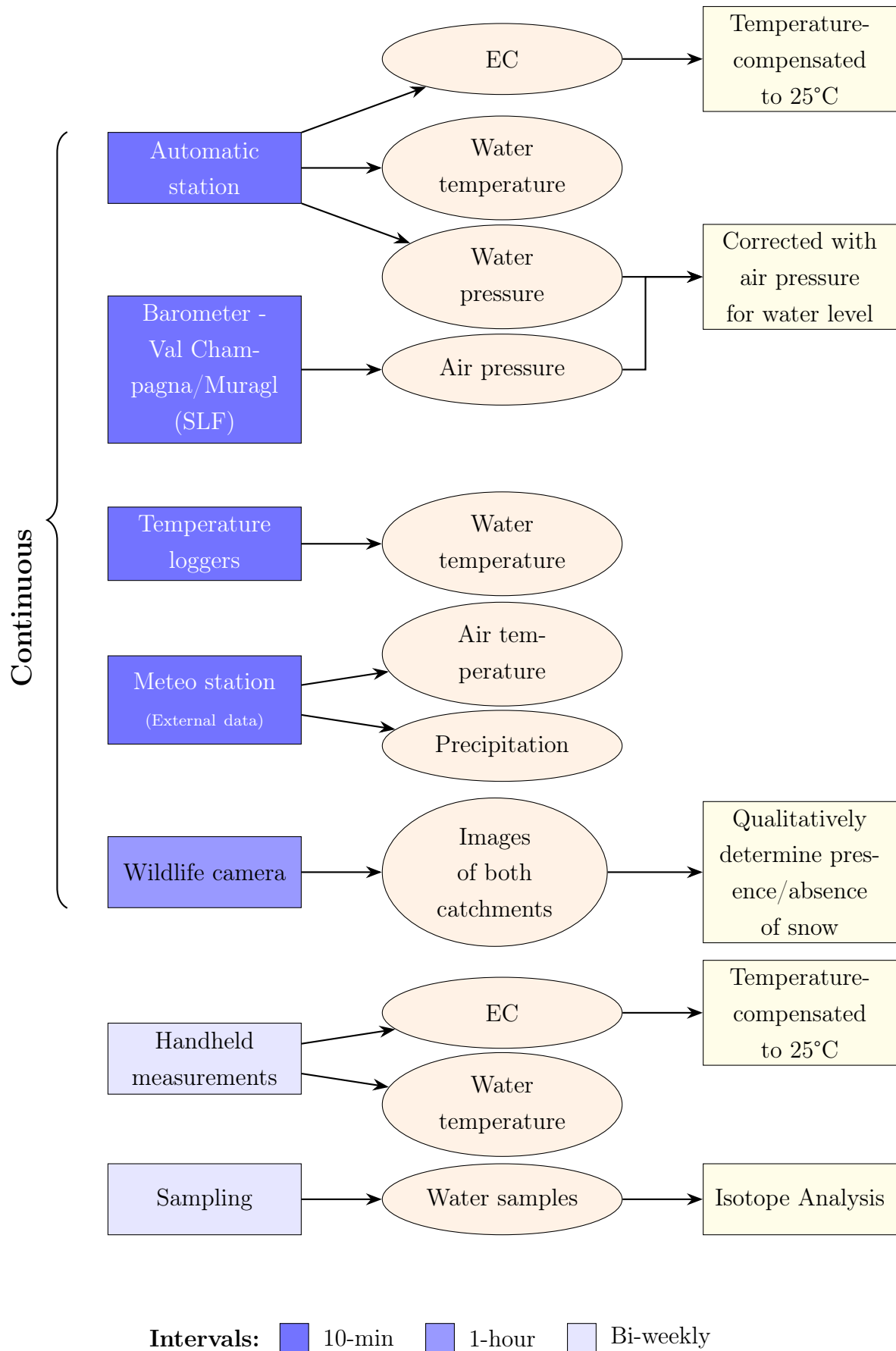


Figure 19: Workflow overview: Shading indicates sampling intervals. The bracket identifies continuous monitoring instruments.

4.3 Other Data

4.3.1 Data Acquisition from Other Sources

To qualitatively monitor the presence or absence of snow cover, a wildlife camera was installed in each catchment. Since snow melt affects the EC and isotope signature, hourly photographs were evaluated to document the presence of snow.

To compare seasonal and diurnal patterns between air temperature and water temperature, approximate air temperatures were calculated for the elevation of the measurement station in front of the Muragl rock glacier (2478 m a.s.l.) using a lapse rate of $0.65^{\circ}\text{C}/100$ m. This correction was applied to the meteorological data from the Bernina pass station (MeteoSchweiz, 2025) at an elevation of 2260 m a.s.l. The precipitation data from the Bernina pass station (MeteoSchweiz, 2025) were used without any additional correction.

4.3.2 Modeled Stable Isotope Composition of Precipitation by Piso.AI

To provide a baseline for the interpretation of the stable isotope composition of the different water samples, the isotopic composition of the local precipitation ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) was modeled using the Piso.AI platform (Nelson et al., 2021). This model predicts the abundance of oxygen and hydrogen stable isotopes using a machine learning model trained on geographic and climate data (Nelson et al., 2021). The model outputs were generated for the period from 15.01.1950 to 15.12.2020 for two different locations to account for their different elevations:

1. At the measurement station in front of the Muragl rock glacier at an elevation of 2741 m a.s.l.
2. At the location of the former Muragl glacier at an elevation of 2939 m a.s.l.

For both elevations, the modeled isotopic signatures were extracted for the full year, the summer season (June - August), and the winter season (December - February). These values and their standard deviations are summarized in Table 6. As expected, the precipitation is slightly more depleted in heavy isotopes in winter and at higher elevation than in summer and at lower elevation (Figure 20 and Figure 21).

Table 6: Modeled stable isotope composition of precipitation at the Muragl Rock glacier (2741 m a.s.l.) and the former Muragl glacier (2939 m a.s.l.) based on Piso.AI (Nelson et al., 2021).

Period	Muragl Rock Glacier (2741 m a.s.l.)		Former Muragl Glacier (2939 m a.s.l.)	
	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)
Annual Mean	-12.95 ± 3.6	-95.98 ± 29.0	-13.73 ± 3.4	-102.06 ± 28.0
Summer Mean	-8.66 ± 1.4	-61.63 ± 12.4	-9.53 ± 1.7	-67.83 ± 15.3
Winter Mean	-16.96 ± 1.7	-129.22 ± 13.2	-17.31 ± 1.5	-131.82 ± 13.0

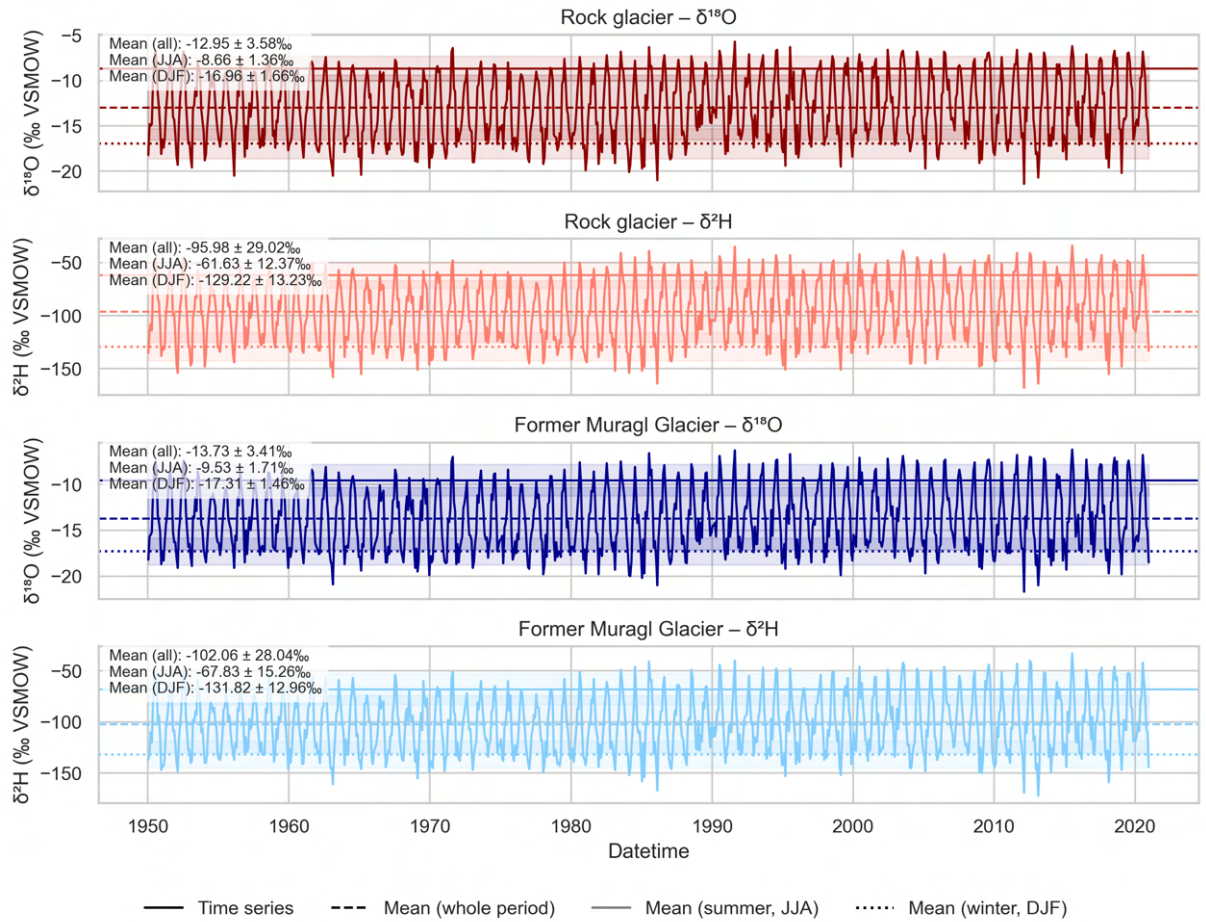


Figure 20: Modeled stable isotope composition in front of the Muragl rock glacier and at the elevation of the former Muragl glacier. Data source: (Nelson et al., 2021).

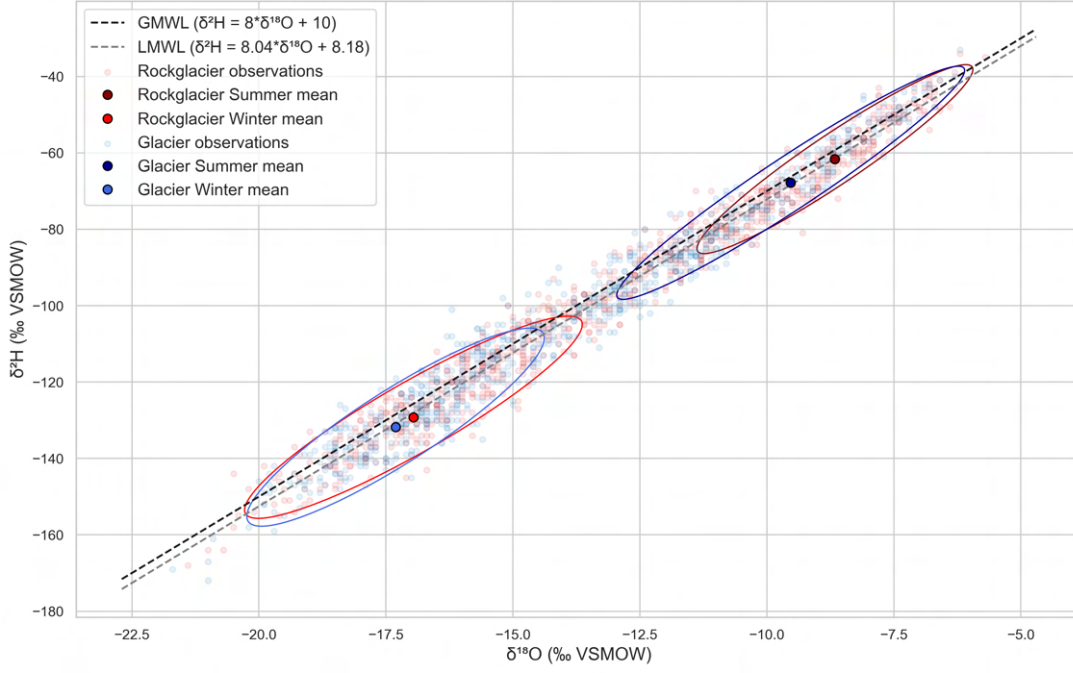


Figure 21: Modeled isotope signature of winter and summer precipitation at the measurement station in front of the Muragl rock glacier and the location of the former Muragl glacier. Data source: (Nelson et al., 2021).

4.4 Data Analysis

4.4.1 Statistical Analysis

To evaluate whether there are significant differences between different water sources (as defined in the field), statistical analyses were performed on water temperature, EC, and isotopic signatures. For this evaluation, all samples collected over time were included. It is acknowledged that this approach leads to a dataset that is not entirely independent from each other, since it includes repeated measurements over time at the same locations and occasional sampling of multiple locations along the downstream path of the same stream. Nevertheless, a Shapiro-Wilk test was used to assess normality, and a Levene's test to test for homogeneity of variances. Since these assumptions of normality and homogeneity were not met, a non-parametric Kruskal-Wallis test was used, followed by a Dunn's post-hoc test. A p-value of 0.05 was used to determine significant differences between the different water sources. The test was repeated with the different sampling sites being grouped by likelihood of permafrost presence according to the permafrost map by SLF (2025) and Kenner et al. (2019).

4.4.2 Principal Component and Cluster Analysis

To complement the univariate analysis of variance, which identifies differences within individual parameters, a multivariate analysis was conducted in R Studio to assess whether the different water sources can be identified based on the water temperature, EC, $\delta^{18}\text{O}$ and deuterium excess.

First, a Principal Component Analysis (PCA) was used to identify the specific variables that contribute most to the variance between the sources. To conduct the PCA, the data was first centered and scaled, and a biplot was constructed to visualize the relationship between the measured variables and the distribution of the samples. The 68% confidence ellipses were added to evaluate if the predefined water sources can be distinguished from each other. Second, a K-means cluster analysis was performed to partition the samples into groups based on their chemical similarity. By comparing these clusters with the predefined groups of sources (based on field observations), it can be determined if the water chemistry can be used as a fingerprint for each source. The optimal number of clusters ($k = 4$) was determined using the Within Sum of Squares (WSS) method and was further validated through a Silhouette Analysis. The data was first normalized before running the model with 25 random initializations to find the best result. Finally, the frequency of samples from each water source within each cluster was counted to assess whether the measured hydrochemical variables could successfully distinguish the different water sources.

4.4.3 Isotopic Mixing Model

To quantify the relative contributions of different water sources to the downstream river system, a two-component linear mixing model approach was employed using $\delta^2\text{H}$ values. This approach investigates the contribution of two streams at their confluence. By using the isotopic signature of each end-member, the contribution of each source to the combined downstream flow is calculated. The samples were collected shortly before the streams join and approximately 100 m from their junction to ensure sufficient mixing of the two upstream tributaries. The mixing is defined by the following linear equation:

$$\delta_M = f_A \cdot \delta_A + f_B \cdot \delta_B \quad (7)$$

Where:

- δ_M is the measured $\delta^2\text{H}$ signature at the downstream location.
- δ_A and δ_B are the $\delta^2\text{H}$ signatures of the two upstream tributaries measured shortly before the junction.

- f_A and f_B are the relative fractions of each source, where $f_A + f_B = 1$.

Since the sum of the two fractions must be 1, the contribution of the first source f_A is calculated as:

$$f_A = \frac{\delta_M - \delta_B}{\delta_A - \delta_B} \quad (8)$$

This calculation was performed for the water samples taken bi-weekly, to allow for the detection of a possible change in the contribution of the two streams throughout the season.

The same model was used to assess the contribution of exfiltrating hillslope water to the downstream river system. To achieve this, the output from the first mixing model was used as one end-member, and the measured exfiltrating hillslope water as the second end-member. For this specific model, it is assumed that the exfiltrating hillslope water is the only additional water input to the downstream river between the first mixing point and the last sampling location, which strongly simplifies the complex reality of water input into the stream and neglects other water sources or other processes, such as potential evaporation. An overview of the streams used for the mixing model can be found in Figure 22.

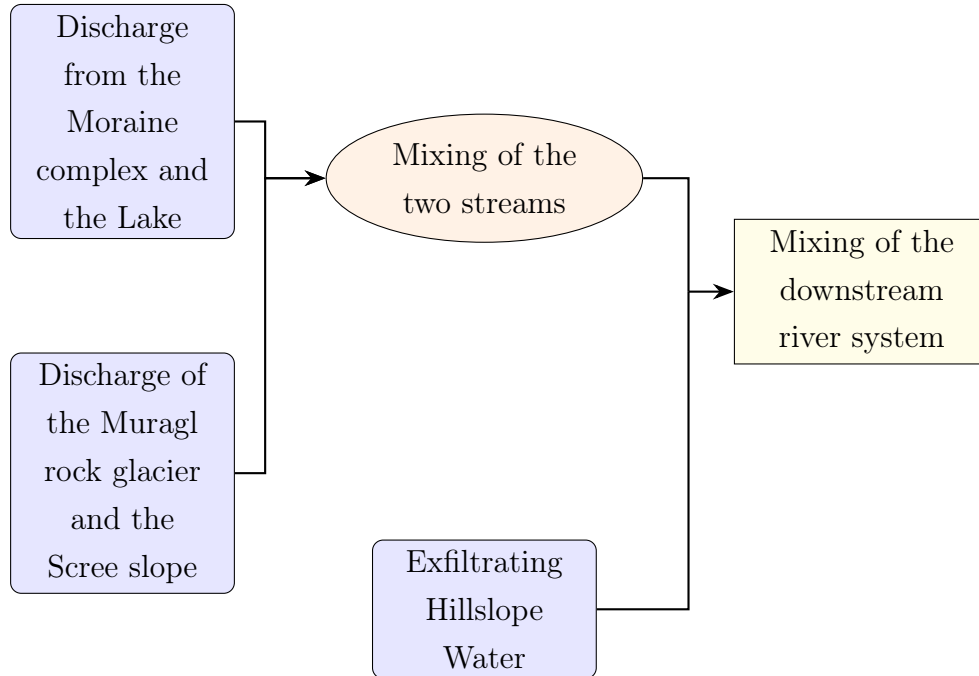


Figure 22: Overview of the streams for which the isotopic mixing models were applied.

5 Results

5.1 Physical and Chemical Water Quality Characteristics for the Different Measurement Sites

There was considerable spatial variability in physical and chemical water characteristics across the sampling sites, as well as distinct differences between the two valleys. For the four sampling sites in Val Champagna, shaped mainly by the Champagna rock glacier, there was relatively little variation in water temperature and EC, as indicated in Table 7. In contrast, there were more pronounced differences in these parameters across the Val Muragl with multiple periglacial landforms, including the Muragl rock glacier, a moraine complex of the former Muragl glacier, a scree slope, and the lake and main stream downstream to the catchment outlet. However, not only did the landforms differ for the catchments, but also the area and elevation range (5.9 km² in Val Muragl with an elevation between 1724 and 3163m a.s.l. and a total of 21 measurement sites, compared to four measurement sites in Val Champagna with an area of 1.03 km² at an elevation of 2510 to 3158m a.s.l. (Swisstopo, 2025)).

Table 7: Minimum and maximum values for water temperature, EC, and elevation ranges of the measurement sites across the two study catchments (based on the bi-weekly hand-held measurements).

Catchment	Water Temperature [°C]		EC [μ S/cm]		Elevation [m a.s.l.]	
	Min	Max	Min	Max	Min	Max
Val Champagna	0.3	7.0	41	304	2684	2761
Val Muragl	0.7	15.7	31	750	1831	2722

These spatial patterns are illustrated in Figure 23, which shows the measurement locations within both catchments and their mean water temperature and EC. The highest water temperatures were recorded at the lake in Val Muragl, whereas the lowest temperatures were observed for spring water from Val Champagna. Notably high EC was measured at the base of the scree slope next to the Muragl rock glacier, while the lowest values were found in exfiltrating hillslope water in Val Muragl. The water in the moraine complex varied depending on the location within the landform. Closer to the lake, the measurements showed intermediate values for both water temperature and EC, while the water of the end moraine, closer to the Muragl rock glacier, had a lower temperature and higher EC. Downstream in the main stream channel in Val Muragl, water temperature increased progressively toward the catchment outlet and thus lower elevation, while the EC decreased slightly.

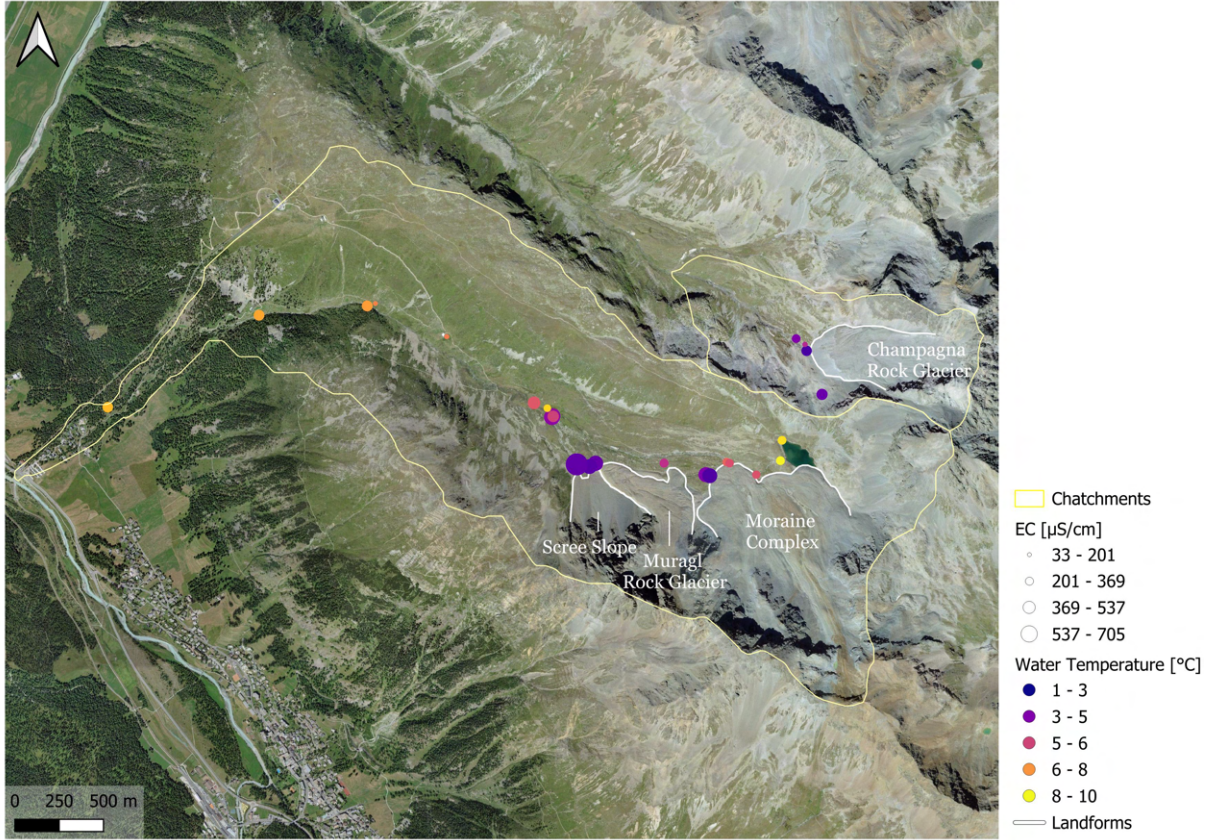


Figure 23: Map of the Muragl and Champagna catchments (yellow lines) with the glacial and periglacial landforms (white lines), the mean water temperature (color), and mean EC (size of the marker) for the measurement sites.

5.1.1 Temporal Variation

While the mean values at each site provide insight into the spatial patterns, the temporal variability and the seasonal changes in water characteristics are equally important for differentiating different water sources. Figure 24 illustrates these temporal changes by showing water temperature, EC, the abundance of stable water isotopes ($\delta^2\text{H}$), and deuterium excess for each sampling location throughout the measurement period from July to October 2025.

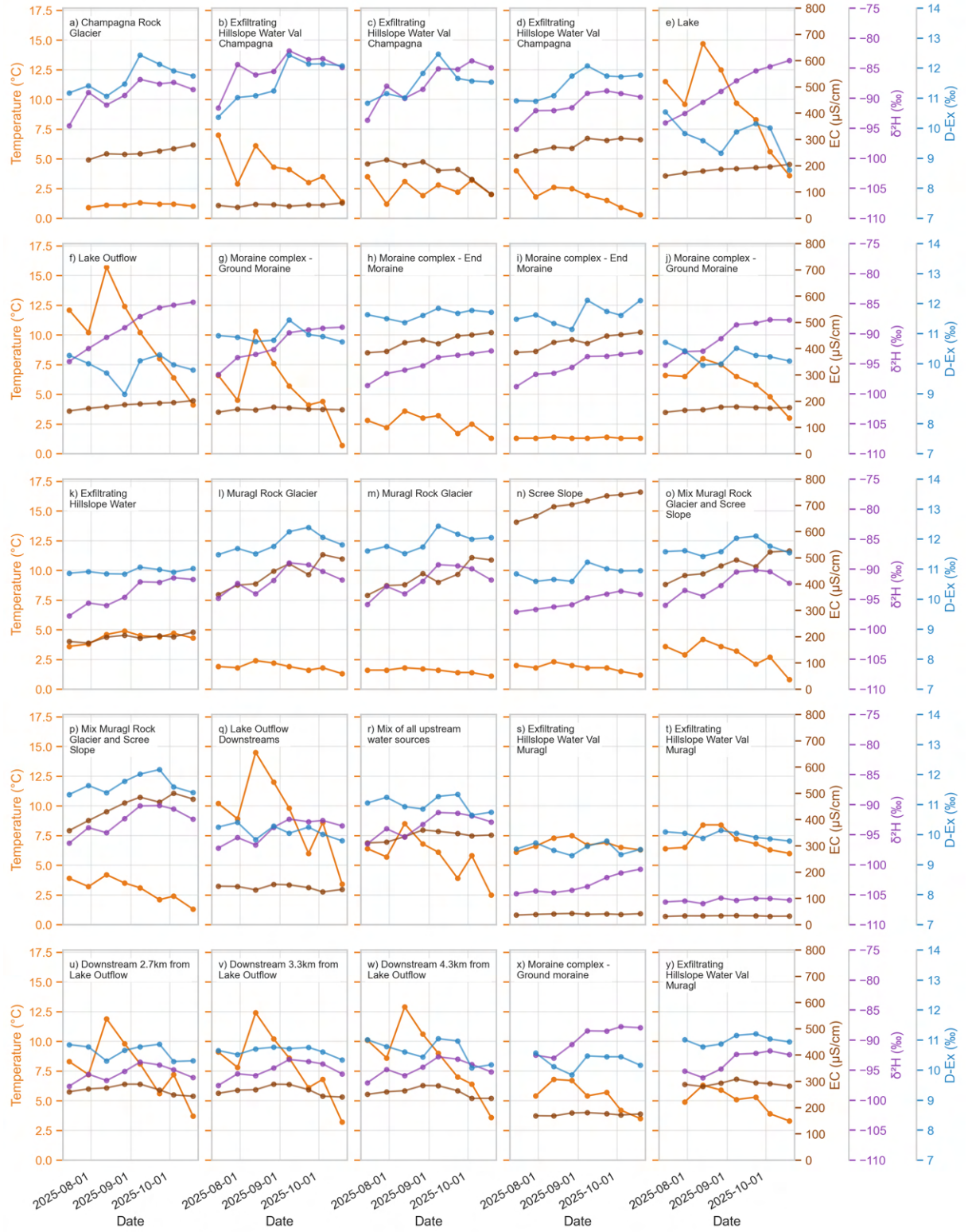


Figure 24: Time series of water temperature, EC, and isotopic composition ($\delta^2\text{H}$ and deuterium excess) for each measurement location.

Water temperature regimes varied significantly across the study area. For some locations, such as the lake outflow (Figure 24, e - f) and the downstream sites (Figure 24, u - w), there was a pronounced seasonal variability with peak temperatures in August. For the rock glaciers, the scree slope, and the end moraine, water temperatures remained relatively stable and low. The EC also differed between the sources. For both rock glaciers, the end moraine, the lake, and the scree slope, the EC increased during the summer season. For other water sources, such as exfiltrating hillslope water, water from the ground moraine, or the main stream at a lower elevation, the EC remained stable or slightly decreased as the season progressed. Isotopic signatures demonstrated a trend towards less negative $\delta^2\text{H}$ values between July and August at most sites. However, a shift towards more negative $\delta^2\text{H}$ values in October occurred for all samples of Val Champagna, and sites in Val Muragl below 2569m a.s.l. While deuterium excess fluctuated considerably during the summer season for most locations, there was a peak in deuterium excess for the majority of samples in mid-September. The temporal evolution of these variables across the different water sources is summarized in the Appendix (Figure 57).

5.1.2 Spatial Variability in Individual Water Quality Parameters Across Different Water Sources and Landforms

The classification of the measurement sites according to their water sources and landforms from which they originated revealed unique hydrochemical fingerprints for water temperature, EC, and stable water isotope composition ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) for the different water sources and landforms, as illustrated in Figure 25 and corresponding mean values summarized in Table 8.

Table 8: Mean $\pm$ Standard Deviation of the temperature, EC, $\delta^2\text{H}$, and deuterium excess for the different sources and n = number of samples.

Assumed Source	Temp. [°C] (Mean $\pm$ SD)	EC [$\mu\text{S}/\text{cm}$] (Mean $\pm$ SD)	$\delta^2\text{H}$ [‰] (Mean $\pm$ SD)	d-excess [‰] (Mean $\pm$ SD)	n
Exfilt. Hillslope Water	4.8 $\pm$ 2.0	145 $\pm$ 113	-95.5 $\pm$ 7.5	10.7 $\pm$ 0.8	47
Lake Outflow	9.5 $\pm$ 3.4	170 $\pm$ 24	-90.5 $\pm$ 4.2	9.9 $\pm$ 0.5	24
Mixed Upstream	6.5 $\pm$ 3.1	262 $\pm$ 56	-93.2 $\pm$ 3.6	10.9 $\pm$ 0.5	40
End Moraine	1.9 $\pm$ 0.8	427 $\pm$ 27	-95.2 $\pm$ 1.9	11.6 $\pm$ 0.3	16
Ground Moraine	5.7 $\pm$ 2.0	171 $\pm$ 7	-90.8 $\pm$ 2.7	10.5 $\pm$ 0.4	23
Rock Glacier	2.1 $\pm$ 1.0	411 $\pm$ 88	-91.6 $\pm$ 2.5	11.8 $\pm$ 0.3	39
Scree Slope	1.8 $\pm$ 0.3	705 $\pm$ 40	-95.4 $\pm$ 1.3	10.8 $\pm$ 0.2	8
Rain	—	15 $\pm$ 14	-63.2 $\pm$ 12.8	10.7 $\pm$ 4.2	6
Snow	0.0 $\pm$ 0.0	12 $\pm$ 1	-72.0 $\pm$ 9.6	19.3 $\pm$ 1.3	5

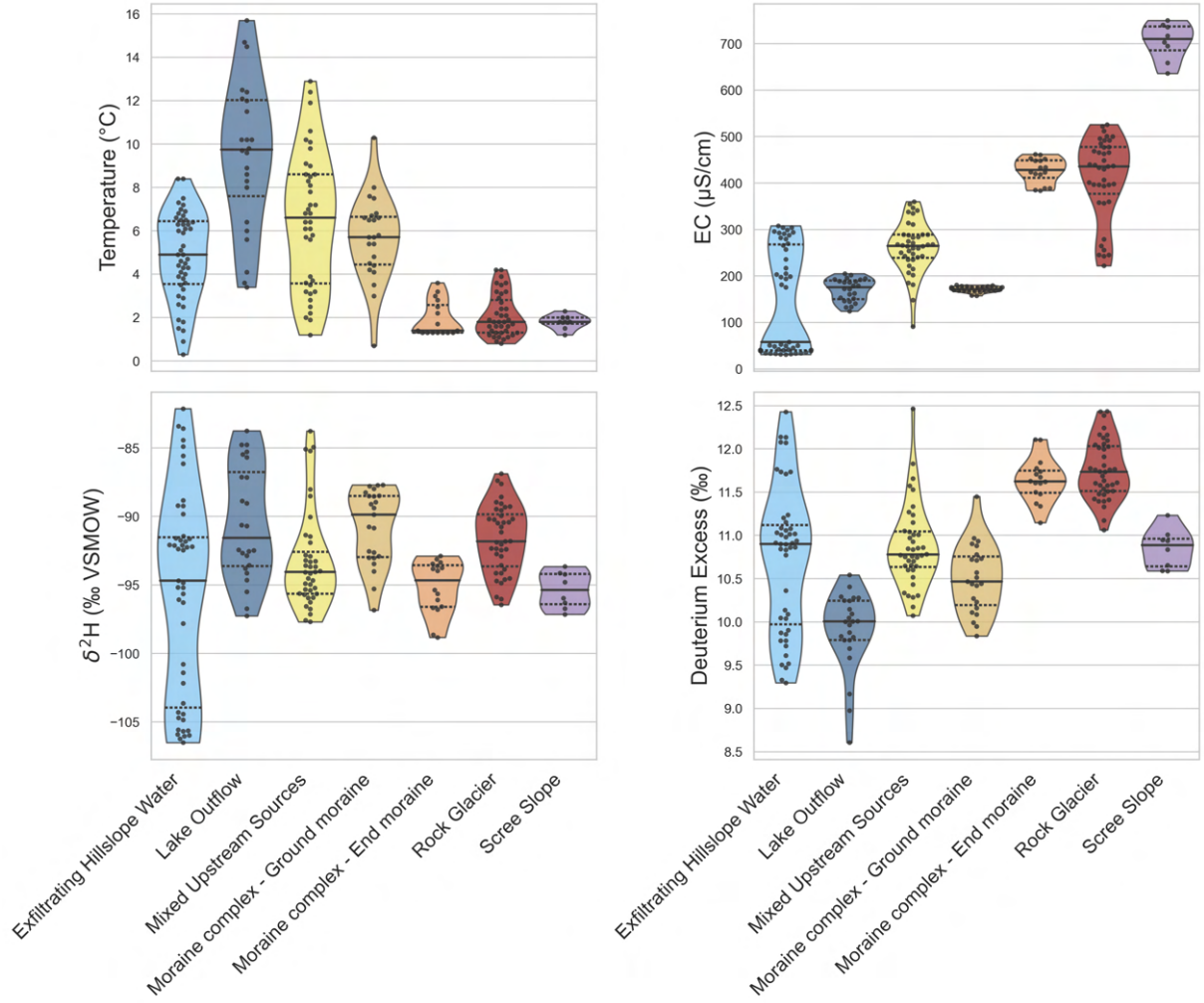


Figure 25: Violin plots of the Water temperature, EC, and stable water isotope composition of the different measurement sites grouped by water source or landform. The colored area extends to the minimum and maximum measured value, the dashed lines represent the quartiles (25th and 75th percentile), the solid line represents the median (50th percentile), and the dots represent the actual measurements.

Discharge from rock glaciers was characterized by high thermal stability and distinct geochemical signatures. Their discharge was defined by low water temperatures ($2 \pm 1^\circ\text{C}$) and high EC ($411 \pm 88\mu\text{S}/\text{cm}$). Isotopically, the rock glaciers were characterized by intermediate $\delta^2\text{H}$ values ($-91.6 \pm 2.5\text{‰ VSMOW}$) but higher deuterium excess ($11.8 \pm 0.3\text{‰}$) compared to most other water sources. When analyzing the results for the individual measurement sites within this group (see Figure 26), it was evident that the variance was mainly due to seasonal evolution rather than spatial differences between the sites. An exception was the EC, where the rock glacier in Val Champagna had distinctly lower EC than the Muragl rock glacier.

The water from the end moraine was similar to that of the rock glaciers, with a low water temperature ($1.9 \pm 0.8^\circ\text{C}$), high EC ($426.5 \pm 27.4\mu\text{S/cm}$), and a high deuterium excess ($11.6 \pm 0.3\text{‰}$). The $\delta^2\text{H}$ values ($-95.2 \pm 1.9\text{‰VSMOW}$) were more negative and at the lower end of the observed groups. The variability within the group was mainly due to seasonal changes between July and October. Only for water temperature, the range of values could be explained by both spatial and seasonal differences.

Similarly to the neighboring rock glacier, water from the scree slope had a consistently low water temperature ($1.8 \pm 0.3^\circ\text{C}$). A notable difference was the very high EC at this site with a mean value of $704 \pm 40\mu\text{S/cm}$. Isotopically, the water from the scree slope was within a similar range as the end moraine, while the deuterium excess remained intermediate ($10.8 \pm 0.2\text{‰}$). As this group represented only one measurement site, the variability within the group was due to seasonal evolution.

The hydrochemical signature of the water from the ground moraine differed from the other glacial and periglacial landforms, especially in water temperature and EC. The water temperature was both distinctly higher ($5.7 \pm 2^\circ\text{C}$) and fluctuated more. The EC ($171.4 \pm 6.3\mu\text{S/cm}$) was notably lower than for the previously discussed landforms and remained rather constant over time and space. The $\delta^2\text{H}$ values ($-90.8 \pm 2.7\text{‰VSMOW}$) were comparable to those recorded in the rock glacier discharge, while the deuterium excess was lower ($10.5 \pm 0.4\text{‰}$).

The lake and its corresponding outflow were characterized by even warmer water ($9.5 \pm 3^\circ\text{C}$) and large temperature fluctuations between July and October. Both the EC ($170.2 \pm 24\mu\text{S/cm}$) and the stable isotope composition ($\delta^2\text{H}$ of $-90.5 \pm 4\text{‰VSMOW}$) were similar to the ground moraine. However, the lake outflow differed from the ground moraine through its negative peak in deuterium excess ($9.9 \pm 0.5\text{‰}$), which occurred at all measurement sites of the lake outflow during a warm period in mid-August, and in October for certain locations (see Figure 24, e, f, q).

The group classified as <exfiltrating hillslope water> encompasses all streams emerging from hillslopes within the catchments and thus represented the most hydrochemically diverse group. It was characterized by both significant spatial and temporal heterogeneity. Water temperature fluctuated strongly within the streams over the season, but at the same time, the variability between the different locations was high as well, with some sources staying below 4°C at all times (Figure 24, d), while the fluctuations of others were more pronounced. The EC within the exfiltrating hillslope water seemed to form two groups: one group with lower EC around $40\mu\text{S/cm}$, and another one with higher values

between 200 and 300 $\mu\text{S}/\text{cm}$. A high spatial and temporal variability was also found for the stable isotope composition, with both the most depleted (-106.5‰ VSMOW) and the least depleted (-82.1‰ VSMOW) stream water. Furthermore, three clusters of deuterium excess were identified:

- rather low deuterium excess around 9.8‰
- intermediate deuterium excess around 11‰
- values comparable to those of the rock glaciers and scree slope around 12‰

Generally, there was a tendency for higher deuterium excess in streams with a higher EC, except for one stream in Val Champagna (Figure 24, b), which had a high deuterium excess but low EC.

The hydrochemical signatures of streams below a confluence of different sources reflected their mixed characteristics, with intermediate mean values and a high intra-group variability in all the measured variables. While the variability in water temperature was primarily driven by seasonal evolution, similar to the trend in the lake outflow, the variability in EC, $\delta^2\text{H}$, and deuterium excess was rather due to spatial differences between the measurement sites.

The measured values of rain and snow samples are visualized in Figure 26. While EC was consistently low across all precipitation events, $\delta^2\text{H}$ varied considerably and was the least negative compared to all the other sources. Furthermore, deuterium excess was highest in snow samples with a mean of 19.3 ± 1.3 ‰ and highly variable in rain water, with the lowest value of 5.9‰. However, it should be noted that the precipitation samples might have been subject to kinetic fractionation during the collection process.

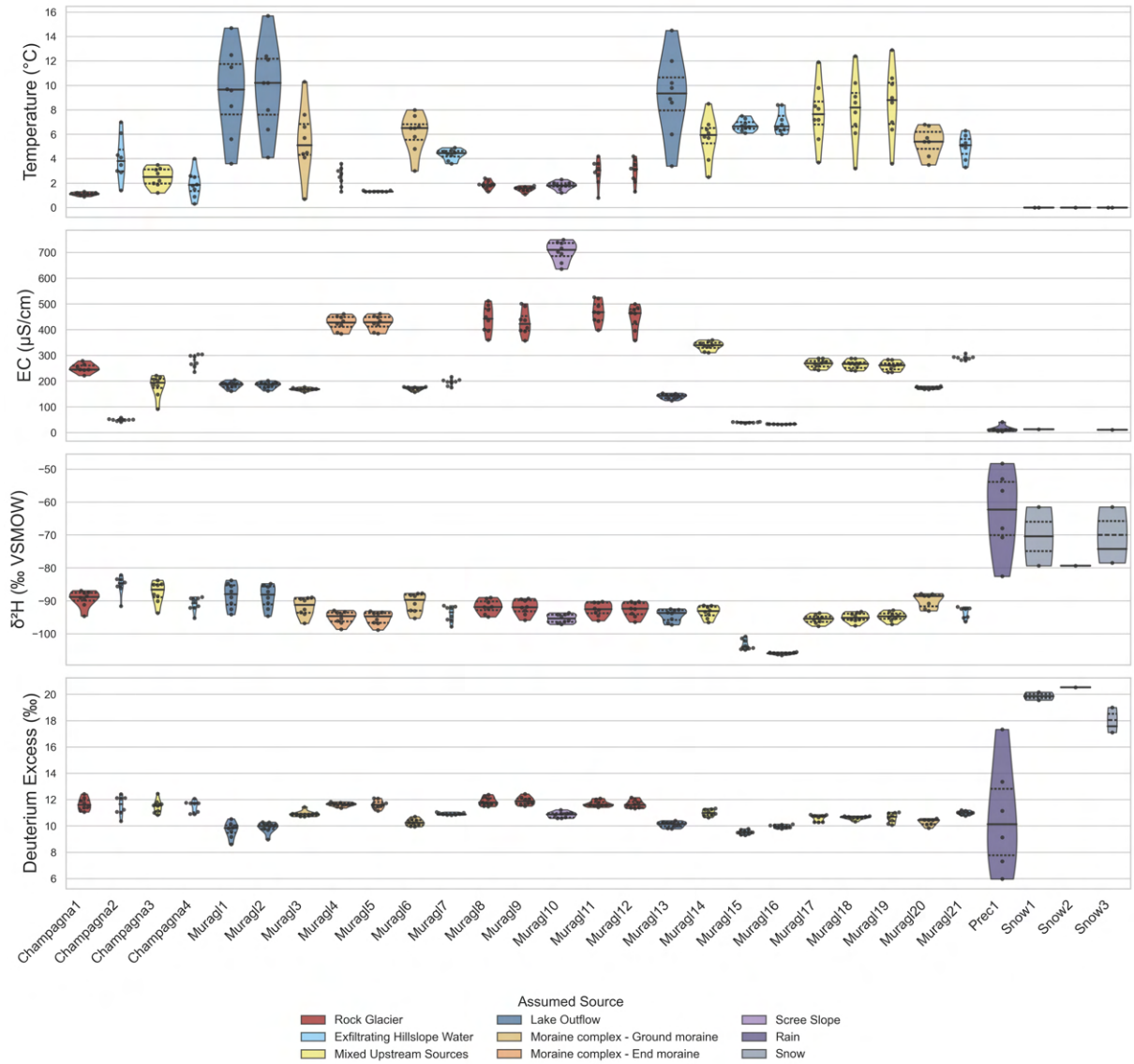


Figure 26: Violin plots of water temperature, EC, and stable water isotope composition for all measurement sites.

The significance of the observed hydrochemical differences for the different sources based on the Kruskal-Wallis test, followed by Dunn's post-hoc pairwise comparisons, is given in Figure 27. These analyses indicated that the scree slope, rock glaciers, and the end moraine were not significantly distinguishable from each other for any of the measured variables ($p > 0.05$), except for the rock glaciers and the end moraine based on $\delta^2\text{H}$ ($p = 0.035$).

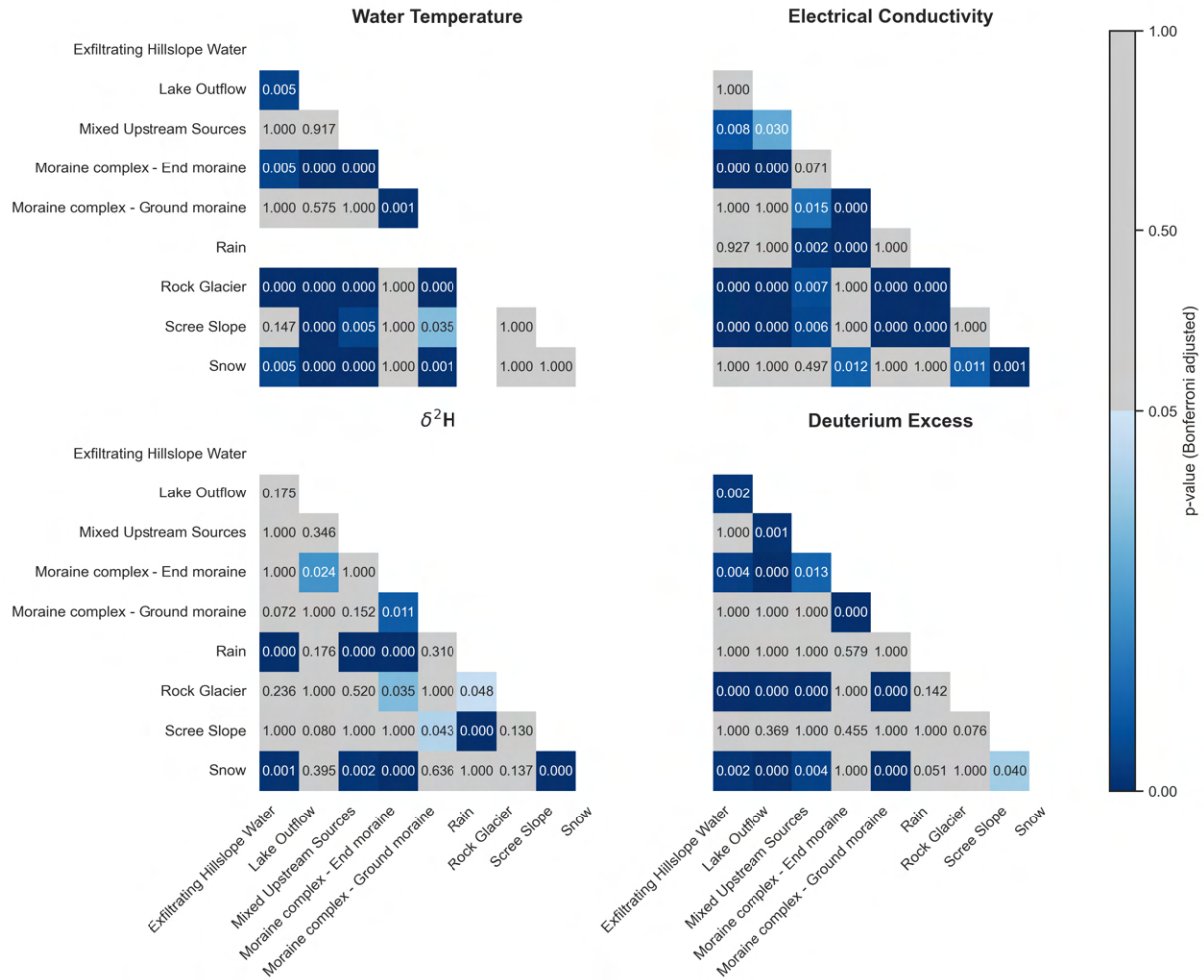


Figure 27: Assessment of Statistical significance of the EC, water temperature, $\delta^{18}\text{O}$ and deuterium excess between the different water sources and periglacial landforms based on a Dunn's Test, following a Kruskal-Wallis test.

However, multiple variables successfully distinguished between the ground moraine and the other glacial and periglacial landforms:

- Both water temperature and EC differed significantly between the water from the ground moraine and the comparably colder discharge from the end moraine, rock glaciers, and scree slopes with a higher EC.
- While the lower deuterium excess of the ground moraine additionally differed significantly from the end moraine and rock glacier with a higher deuterium excess, this was not the case for the scree slope.

Thus, among the glacial and periglacial landforms, only the ground moraine could be distinguished from the other groups.

To distinguish between the glacial and periglacial landforms and the lake outflow and exfiltrating hillslope, multiple variables could be used, except for the ground moraine:

- Both water temperature and EC differed significantly between the lake outflow and the colder and solute-enriched water from the end moraine, rock glacier, and scree slope.
- Exfiltrating hillslope water and water from the glacial and periglacial landforms differed significantly in temperature and EC, except for the scree slope, which could not be distinguished from exfiltrating hillslope water based on water temperature.
- Discharge from the ground moraine did not differ significantly from either exfiltrating hillslope water or lake outflow for any of the measured variables.

Finally, a significant difference in deuterium excess was observed between the higher values of the end moraine and rock glacier, compared to the lower values of the ground moraine, lake outflow, and exfiltrating hillslope water.

In summary, the rock glacier, scree slope, and end moraine were hydrochemically not distinguishable from each other based on the measured variables. However, they could be distinguished from discharge from the lake outflow, exfiltrating hillslope water, and the ground moraine by their colder water, higher EC, and higher deuterium excess.

5.1.3 Isotopic Composition Relative to Precipitation

The samples are plotted in the dual isotope space, together with the Global Meteoric Waterline (GMWL) in Figure 28. Rain samples were generally consistent with the less depleted modeled summer precipitation by Piso.AI (Nelson et al., 2021) and mostly plotted on the GMWL. Snow samples tended to be slightly more depleted and were characterized by a higher deuterium excess. Some samples from the exfiltrating hillslope water plotted close to the modeled winter precipitation. The majority of the other samples plotted between the modeled summer and winter precipitation and slightly above the GMWL (Figure 29).

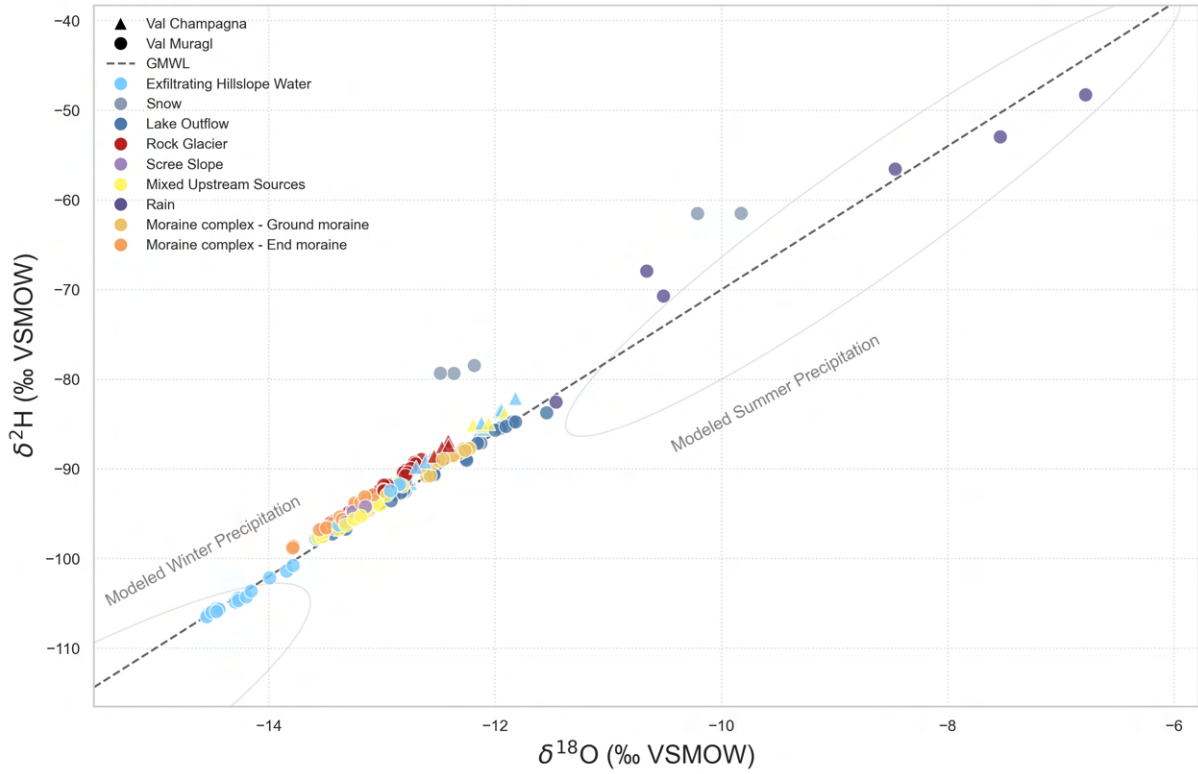


Figure 28: Dual isotope plot for the samples from different sources (color), the valleys (shape), and the GMWL. The ellipses indicate the typical composition of summer and winter precipitation according to Piso-AI (Nelson et al., 2021). For a zoomed-in version of the figure, see Figure 29

As already observed from the violin plots (Figure 25), the samples from the rock glaciers and the end moraine were both characterized by a slightly higher deuterium excess. Within this group, the end moraine samples tended to be slightly more depleted than discharge from the rock glaciers. Spatially, the samples from the rock glacier in Val Muragl (Figure 28, circles) were slightly more depleted than in Val Champagna (triangles).

Exfiltrating hillslope water and scree slope discharge had an intermediate deuterium excess, while the range was wider for the hillslope water (-106 to -82‰ VSMOW). The isotopic signature of the scree slope resembled that of the end moraine. Lake water and the majority of the samples from the ground moraine aligned closely with the GMWL. Although the isotopic composition varied between -12 and -13.5‰ VSMOW for the lake water, it was generally slightly less depleted for the ground moraine. For the lake outflow, the values became more negative further downstream, but this trend was influenced by additional water inputs along the flow path.

The elevation of the sampling sites did not seem to be a primary driver of the isotopic signature of the water; in fact, samples from higher elevations were generally less depleted

(see Appendix Figure 56). Although a seasonal shift towards less depleted water was visible in some sources, it did not explain the overall variation in the isotopic composition of the water samples.

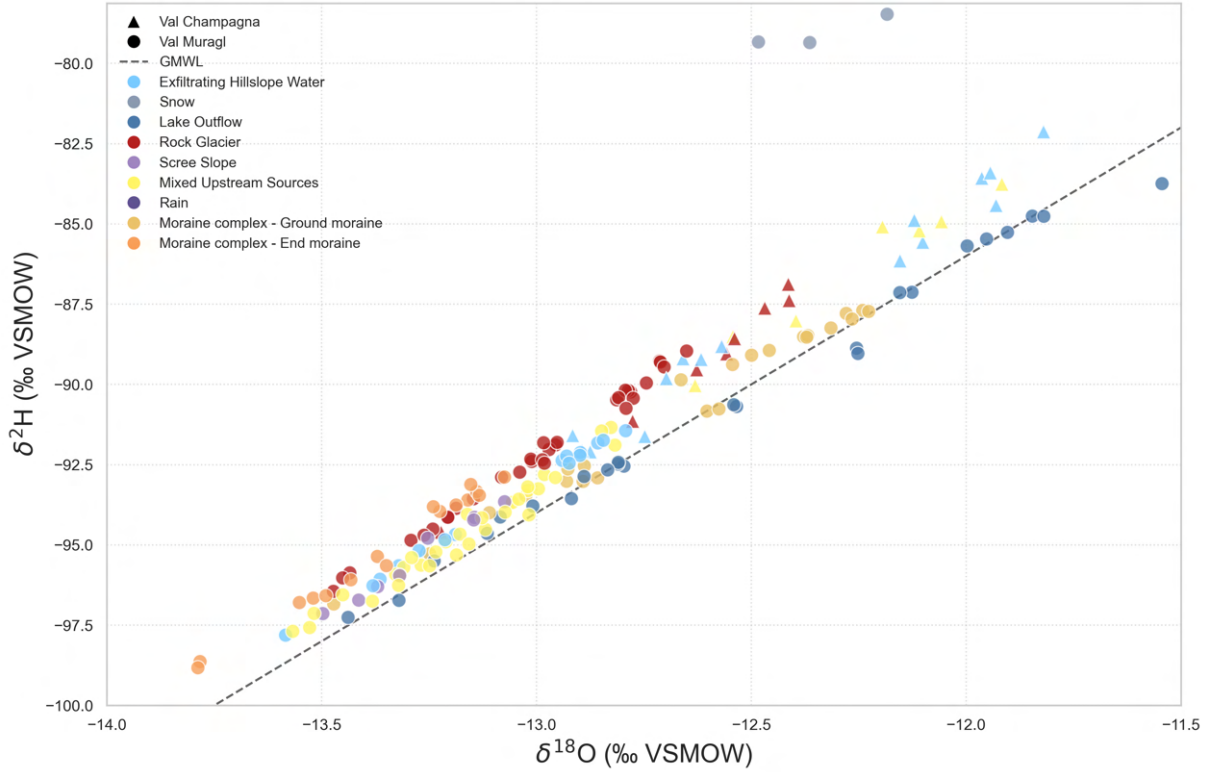


Figure 29: Dual isotope plot for the samples from different sources (color), the valleys (shape), and the GMWL - zoomed to the cluster with the most samples.

5.1.4 Classification of the Water Samples Based on All Water Quality Parameters

In Figure 30, the relationship between water temperature, EC, $\delta^2\text{H}$, and deuterium excess is shown. A distinct fingerprint was visible for the end moraine and the rock glacier, which were indistinguishable from each other, but clearly separated from other sources due to their low water temperature ($< 4^\circ\text{C}$), high EC, and high deuterium excess ($> 11\text{‰}$). The scree slope discharge was another unique cluster defined by its high EC and low temperature; however, its isotopic signature did not provide a clear distinction from other sources. The lake outflow and ground moraine were characterized by similar values across all variables, making them difficult to distinguish based on these variables alone. Exfiltrating hillslope water appeared to fall into two classes: one characterized by very low EC, low deuterium excess, and more negative $\delta^2\text{H}$ values, and another group with intermediate values in all of these variables. Water temperature did not seem to be a reliable indicator to distinguish between different classes of exfiltrating hillslope water.

The scatterplots also suggested that the valley from which the samples originated had a large effect on the water quality, since the water quality characteristics of the samples from Val Champagna (triangles) often differed strongly from those in Val Muragl (circles). While samples from Val Champagna had intermediate EC and low water temperature, they had a high deuterium excess and were isotopically less depleted than those in Val Muragl. Consequently, the clusters that could be identified mainly based on water temperature, EC, and deuterium excess, seemed to be specific for each valley.

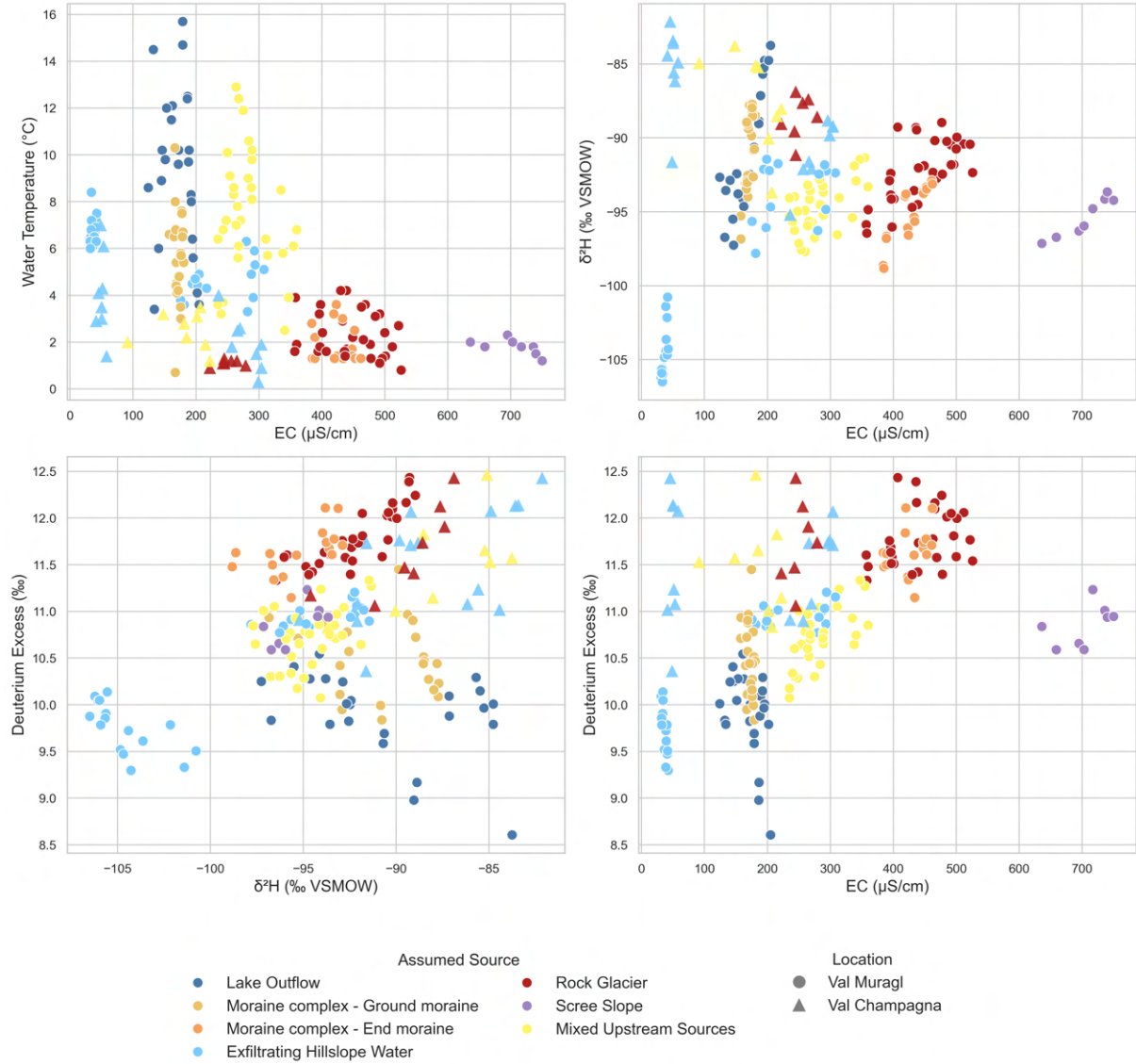


Figure 30: Relationship between water temperature, EC, $\delta^{18}\text{O}$, and deuterium excess for different water sources and landforms. Samples from Val Champagna are marked with a triangle, samples from Val Muragl with a circle.

5.1.5 Principal Component and Cluster Analysis

Statistical analysis has revealed significant differences between water sources for multiple variables (Figure 27). To analyze the variance and effect of multiple variables collectively, a Principal Component Analysis (PCA) was applied.

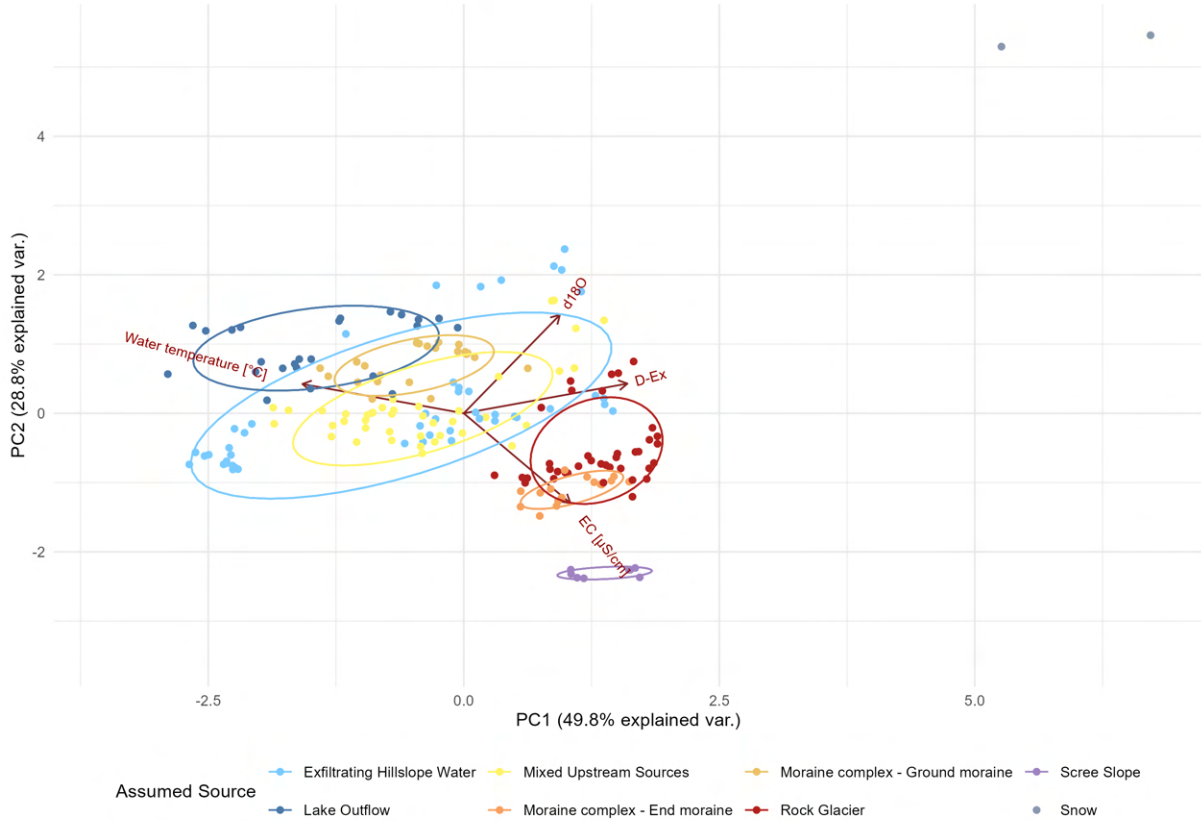


Figure 31: Principal Component Analysis plot based on water temperature, EC, $\delta^{18}\text{O}$ and deuterium excess with the different samples colored by their source. The length of the arrow represents the contribution of each parameter to the principal components.

Principal Component 1 (PC1) and Principal Component 2 (PC2) together could describe 78.6% of the total variance within the dataset, and thus a plot of PC1 and PC2 could reliably represent the majority of the variance (Figure 31). PC1 explained nearly half (49.8%) of the variance, while PC2 explained an additional 28.8% of the total variance.

Table 9 shows the loadings of the principal components. PC1 depended largely on water temperature (-0.595) and deuterium excess (0.604), and to a lesser degree also on EC (0.394), and $\delta^{18}\text{O}$ (0.355) (Table 9). It highlighted the inverse relationship between water temperature and deuterium excess and separated warmer water with a low deuterium excess on the left side of the plot from colder water with high deuterium excess on the right side. PC2 depended largely on $\delta^{18}\text{O}$ (0.705) and EC (-0.644), underscoring the

differences between isotopically more depleted water with high EC at the bottom of the plot and less depleted water with lower EC at the top (Figure 31).

Table 9: Statistical parameters of PCA with scaling parameters and loadings of the different principal components.

Variable	Center	Scale	PC1	PC2	PC3	PC4
EC [$\mu\text{S}/\text{cm}$]	270,59	159,59	0,394	-0,644	-0,645	-0,122
Water temperature [$^{\circ}\text{C}$]	4,89	3,31	-0,595	0,210	-0,454	-0,629
$\delta^{18}\text{O}$	-12,97	0,65	0,355	0,705	-0,542	0,290
Deuterium excess	11,00	1,11	0,604	0,213	0,291	-0,711
Standard deviation	-	-	1,411	1,074	0,708	0,595
Proportion of Variance	-	-	49,8%	28,8%	12,5%	8,9%

The ellipses in Figure 31 show the 68% confidence interval, which indicates a clustering of the different sources. Water from the scree slope was defined by a high EC compared to the rest of the dataset, while water from rock glaciers and the end moraine were both characterized by a high EC and high deuterium excess. Water from the lake outflow and the ground moraine was characterized by higher water temperatures and a tendency for less negative $\delta^{18}\text{O}$ values. Exfiltrating hillslope water and mixed upstream sources were close to the mean of the dataset.

Overlapping clusters indicate similar hydrochemical signatures among the sources, while a clear separation between clusters demonstrates distinct differences. While water from the scree slope, rock glacier, and end moraine differed from the other sources, the rock glacier and end moraine signatures remained indistinguishable from one another, even when using all chemical data together. Similarly, exfiltrating hillslope water, mixed upstream sources, and water from the ground moraine had comparable chemical signatures.

A k-means cluster analysis can give further insight into the similarity between the groups. In this case, the 199 water samples were partitioned into four clusters, which explain a total of 63.8% of the total variance, as shown in Figure 32 and Table 10.

Table 10: K-means Cluster Summary: Sample Size (n), Within-Cluster Sum of Squares (WC SS), and Center (Original and Standardized)

Clus.	n	WC SS	EC [$\mu\text{S}/\text{cm}$]		Temp [$^{\circ}\text{C}$]		$d^{18}\text{O}$		D-Ex	
			Orig.	Std.	Orig.	Std.	Orig.	Std.	Orig.	Std.
1	76	107.36	212.73	-0.363	3.79	-0.332	-12.61	0.548	11.01	0.014
2	56	44.30	477.38	1.296	2.13	-0.834	-13.14	-0.260	11.61	0.550
3	65	131.44	168.04	-0.643	8.70	1.153	-13.33	-0.556	10.22	-0.701
4	2	3.97	11.75	-1.622	0.00	-1.478	-10.02	4.518	18.64	6.865

Total Variance Explained: 63.8%

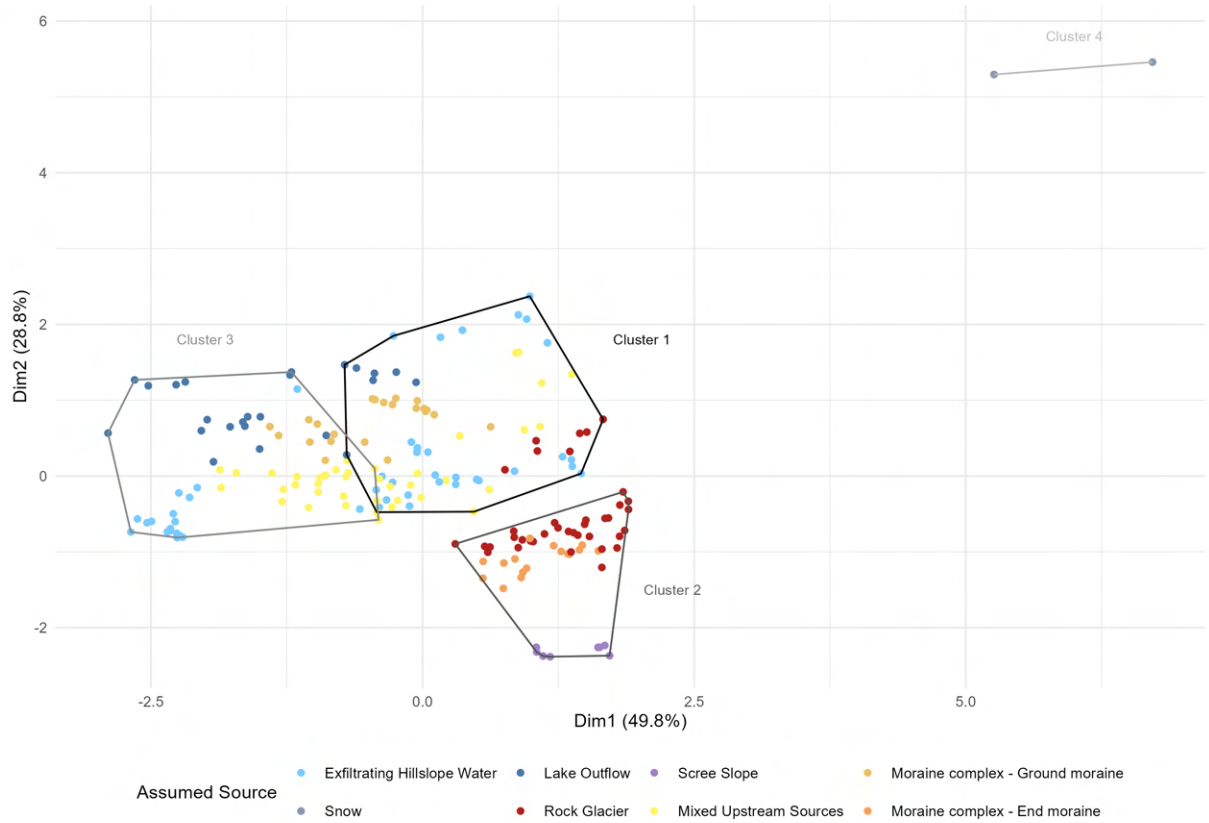


Figure 32: K-means Clustering using Water temperature, EC, $\delta^{18}\text{O}$ and Deuterium Excess.

To analyze how well the clusters represented the different water sources, Table 11 shows for each source, what percentage of water samples fell within each cluster.

- Cluster 1 ($n = 76$): This group was characterized by moderate values across all measured parameters. However, a high within-cluster sum of squares (WC SS = 107) also indicated a high diversity within this group, as noted in Table 10. This

cluster captured a large variety of sources, including a mix of exfiltrating hillslope water, lake outflow, and water from the ground moraine, alongside samples from the Champagna rock glacier.

- Cluster 2 ($n = 56$): This second cluster was defined by a high EC ($477 \mu\text{S}/\text{cm}$), low water temperature (2.1°C), and a slightly higher deuterium excess (11.6‰). It encompassed all of the samples from the scree slope and the end moraine, and the majority of rock glacier samples (82.1%).
- Cluster 3 ($n = 65$): The samples within this cluster had a higher water temperature (8.7°C), a lower EC ($168 \mu\text{S}/\text{cm}$), the lowest deuterium excess (10.2‰), and were isotopically most depleted. However, the diversity of the water samples was also high within this group ($\text{WC SS} = 131.44$). Furthermore, the sources of these water samples overlapped strongly with cluster 1, with both containing samples from exfiltrating hillslope water, lake outflows, and water from the ground moraine.
- Cluster 4 ($n = 2$): The fourth cluster only contained two water samples, with a low temperature (0°C), the lowest EC ($12 \mu\text{S}/\text{cm}$), a high deuterium excess (18.6‰), and was isotopically least depleted (-10‰VSMOW). All snow samples fell within this cluster, making snow distinctively different from the other samples.

Thus, snow samples were clearly distinguishable based on their water chemistry. Furthermore, water from the scree slope and the end moraine, as well as most rock glacier samples, were distinguishable due to their high EC and deuterium excess, as well as low water temperatures. However, this was not the case for rock glacier samples from Val Champagna, which fell into cluster 1 and thus remained indistinguishable from other water sources. Since water samples from the lake outflow, exfiltrating hillslope water, and the ground moraine fell in both cluster 1 and 3, and had a similar signature, they were not distinguishable from each other based on the measured variables.

Table 11: Percentage of Streams from different Sources in each cluster based on K-means clustering (and total count).

Assumed source	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Exfiltrating Hillslope Water	62% (29)	0% (0)	38% (18)	0% (0)
Lake Outflow	29% (7)	0% (0)	71% (17)	0% (0)
Mixed Upstream Sources	48% (19)	0% (0)	53% (21)	0% (0)
Moraine complex - Ground	61% (14)	0% (0)	39% (9)	0% (0)
Moraine complex - End	0% (0)	100% (16)	0% (0)	0% (0)
Rock Glacier	18% (7)	82% (32)	0% (0)	0% (0)
Scree Slope	0% (0)	100% (8)	0% (0)	0% (0)
Snow	0% (0)	0% (0)	0% (0)	100% (2)
Total Samples (n=199)	76	56	65	2

5.1.6 Permafrost Influence on Stream Characteristics

To evaluate whether the simulated permafrost occurrence could explain the differences in hydrochemistry between the stream monitoring sites, sampling sites were grouped according to whether the majority of the catchment area fell within the zone of probable, possible, or improbable permafrost occurrence according to the SLF permafrost map (Kenner et al., 2019; SLF, 2025). Streams with confluences from both permafrost and non-permafrost areas were classified as “Mixed”.

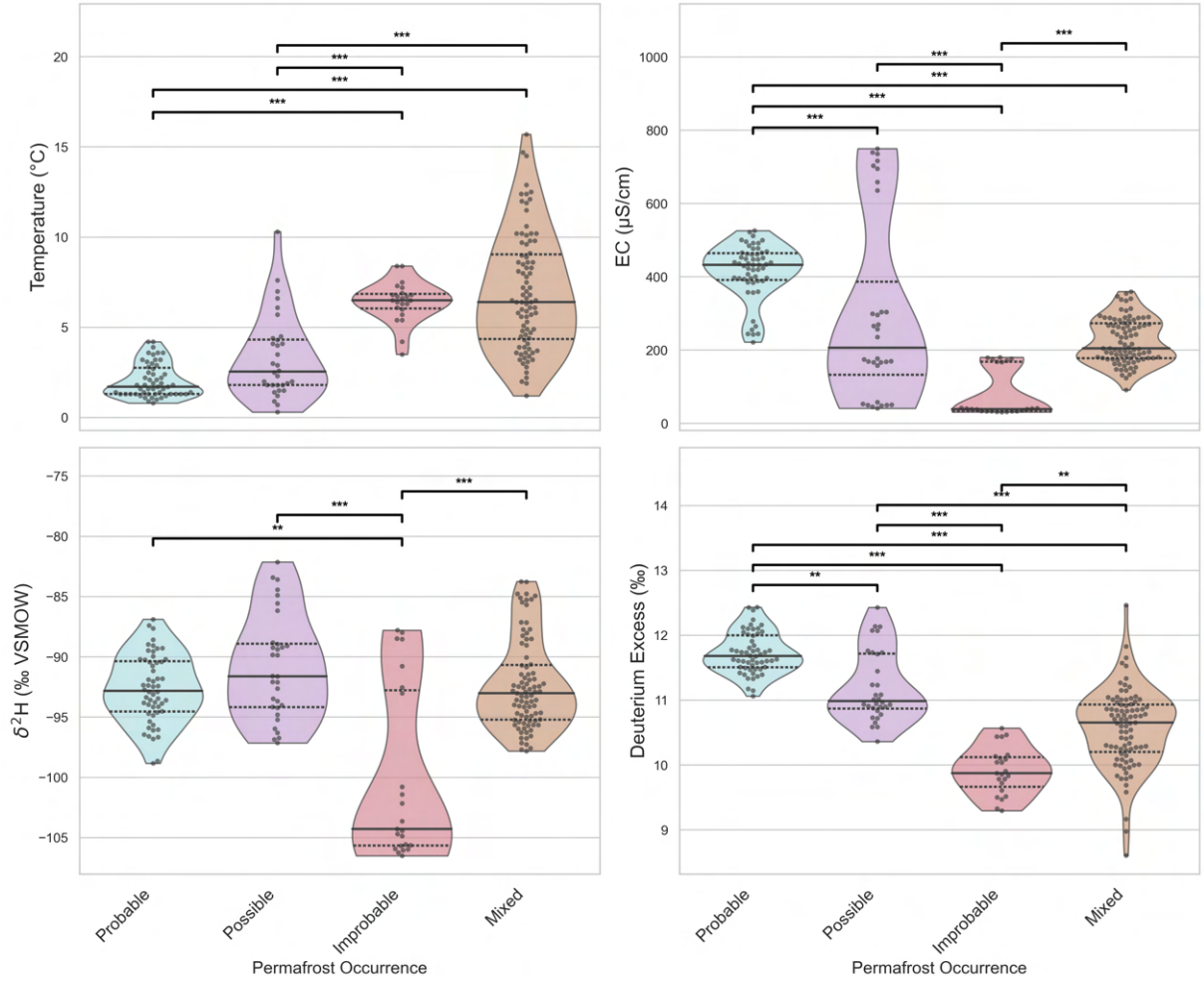


Figure 33: Water temperature, EC, and isotope composition of measurement sites with different permafrost occurrence in the catchment. The results of Dunn's post-hoc test and p-values are indicated with the following symbols: *** < 0.001, ** < 0.01, * < 0.05.

There were distinct hydrochemical and isotopic differences between streams based on the permafrost occurrence within their catchment (Figure 33). The patterns generally followed a gradient of lower water temperature, higher EC, and higher deuterium excess with an increased probability of permafrost. Streams with probable permafrost occurrence in their catchment were characterized by low water temperature ($2.0 \pm 0.9^\circ\text{C}$), and high values for both EC ($416 \pm 76 \mu\text{S}/\text{cm}$) and deuterium excess ($11.7 \pm 0.3\text{‰}$) (Table 12). Variability within water temperature for the different groups was mainly due to spatial differences between the streams. For the other variables, a seasonal evolution was observable, with rising EC and $\delta^2\text{H}$ and a peak in deuterium excess mid-September (see Appendix Figure 58), except for one stream with a lower EC throughout the season.

Catchments classified with possible permafrost were characterized by a greater heterogeneity across all variables. Water temperature ranged from 0.3°C up to 10.3°C , EC

spanned from 41 to 750 $\mu\text{S}/\text{cm}$, and deuterium excess was intermediate to high (10.4 to 12.5‰). This high variability was attributed to both the temporal variation between July and October and considerable spatial differences between sampling locations, especially for EC. The seasonal evolution of deuterium excess was characterized by the same peak in mid-September as for the streams with probable permafrost in their catchment.

Where permafrost was improbable, streams were generally warmer ($6.4 \pm 1.1^\circ\text{C}$) and had the lowest deuterium excess ($9.9 \pm 0.4\text{‰}$), aligning closely to the GMWL. Notably, this was the only group with more negative $\delta^2\text{H}$ values ($-100.1 \pm 7.2\text{‰VSMOW}$) in some streams; all other groups remained comparable to each other. EC within this group was split into two clusters: one with low EC and another with values up to 180 $\mu\text{S}/\text{cm}$. Variability here was dominated by spatial differences between the streams, while most values remained more or less stable over the season.

Streams that contained a mixture of tributaries with and without permafrost in their catchment had intermediate values for all variables and large heterogeneity, both due to seasonal evolution and large differences between individual streams.

When comparing the groups with each other, the results of the Dunn's test revealed significant hydrochemical and isotopic differences based on the permafrost occurrence, primarily due to water temperature, EC, and deuterium excess. Streams with probable permafrost in their catchment were significantly different from other groups due to their higher EC and deuterium excess values, and colder water, except for streams with possible permafrost influence, which had a similar water temperature. Samples from catchments where permafrost is possible had intermediate values, but were nevertheless significantly colder and had a higher deuterium excess than streams with improbable permafrost or mixed conditions. Streams with improbable permafrost were distinguishable due to their warmer temperature, lower EC, and lower deuterium excess. Notably, they were also characterized by a significantly lower $\delta^2\text{H}$ compared to all other groups.

Table 12: Mean $\pm$ Standard Deviation of the hydrochemical measurements grouped based on the modeled permafrost occurrence.

Permafrost Occurrence	Temp. [$^\circ\text{C}$] (Mean $\pm$ SD)	EC [$\mu\text{S}/\text{cm}$] (Mean $\pm$ SD)	$\delta^2\text{H}$ [‰] (Mean $\pm$ SD)	d-excess [‰] (Mean $\pm$ SD)
Improbable	6.4 ± 1.1	78 ± 65	-100.1 ± 7.2	9.9 ± 0.4
Mixed	7.0 ± 3.3	225 ± 61	-92.3 ± 3.7	10.6 ± 0.6
Possible	3.3 ± 2.3	301 ± 252	-90.8 ± 4.3	11.2 ± 0.5
Probable	2.0 ± 0.9	416 ± 76	-92.6 ± 2.8	11.7 ± 0.3

The previously described differences in deuterium excess (Figure 33) are highlighted in Figure 34, as well, with a higher deuterium excess in streams with probable permafrost in their catchment, while streams with improbable permafrost or mixed conditions plotted closer to the GMWL. Nevertheless, the deuterium excess was still considerably smaller than for the snow samples.

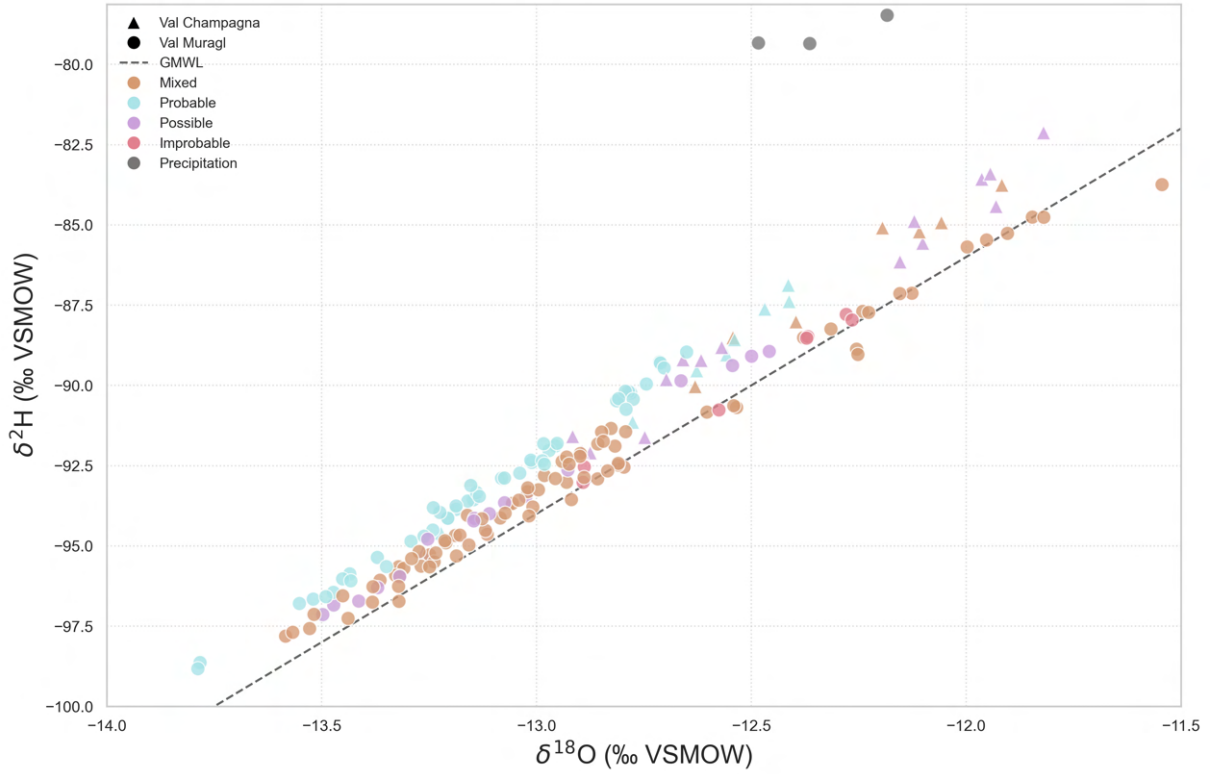


Figure 34: Dual isotope plot for all samples with modeled permafrost occurrence within the catchment as colors, valleys marked as shapes, and the GMWL, zoomed to the cluster of intermediate values.

The relationships between water temperature, EC, $\delta^2\text{H}$, and deuterium excess are shown in Figure 35. These variables revealed distinct clusters for streams influenced by probable permafrost within the catchment, mainly defined by high EC, low water temperatures, and high deuterium excess. In contrast, streams with possible permafrost within their catchment were scattered widely, and there were no distinct or isolated clusters observable. Streams likely not influenced by permafrost were characterized by two signatures: one group was characterized by warm water temperature, low EC, and deuterium excess, and more negative $\delta^2\text{H}$ values. However, a second group showed no distinct signature and was indistinguishable from mixed streams.

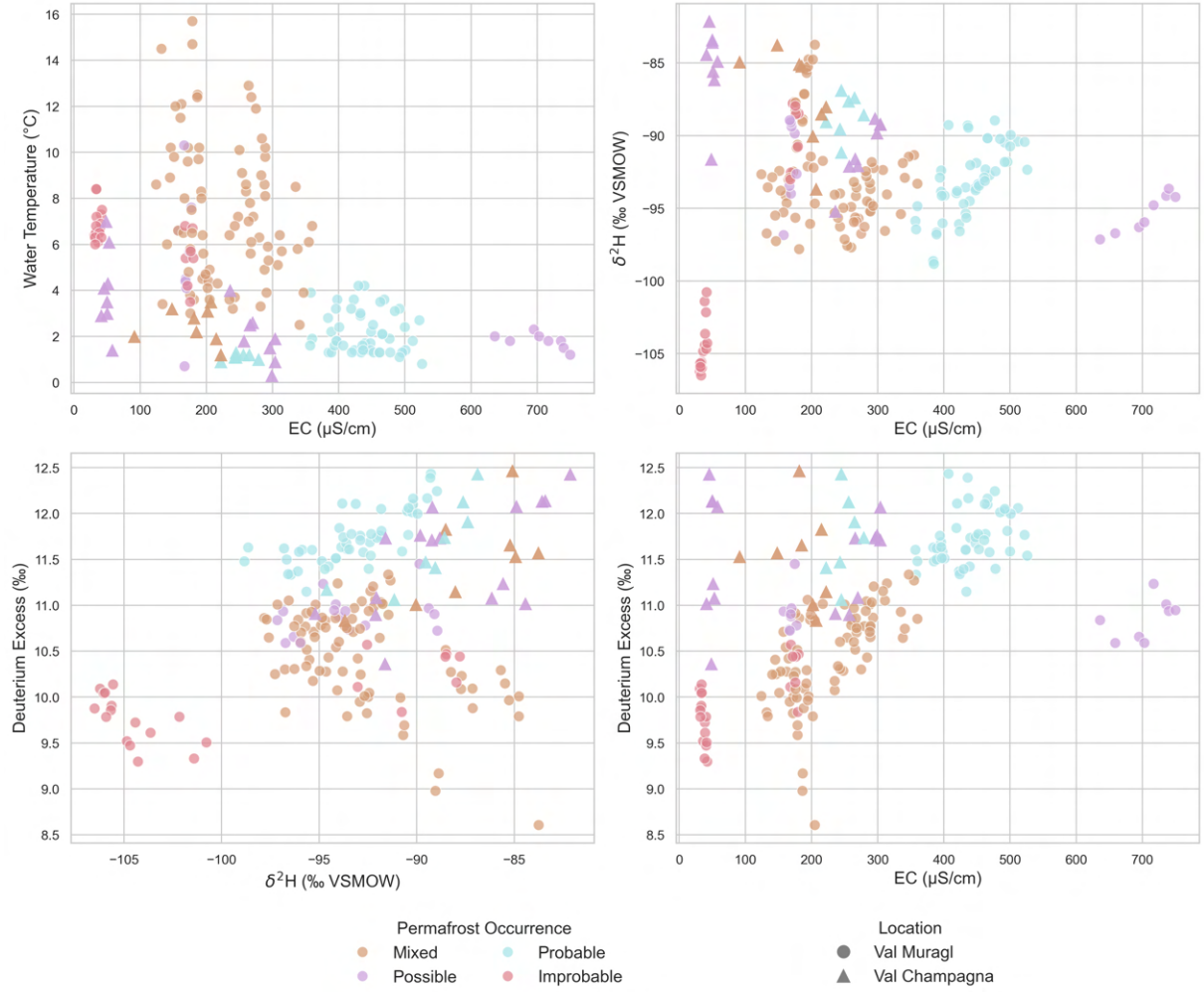


Figure 35: Relationship between water temperature, EC, and stable water isotope composition for catchments with possible, probable, improbable, and mixed permafrost occurrence for Val Champagna (triangles) and Val Muragl (circles).

The K-means cluster analysis, colored by permafrost occurrence, is shown in Figure 36. The percentage of water samples of each permafrost occurrence that fall within a certain cluster is indicated in Table 13.

Similar to the clusters of the different sources, samples of precipitation were clearly distinguishable in cluster 4. The majority of streams with probable permafrost (87%) in their catchment fell within cluster 3, characterized by high EC and deuterium excess, as well as low water temperatures. However, streams with possible permafrost (63%) were spread across three clusters, with the majority of samples in cluster 1. This further included samples from streams within both improbable, possible, and mixed permafrost occurrences. Samples from streams with improbable permafrost (78%) in their catchment had a tendency to plot within cluster 3, together with samples of mixed streams (49%). Thus, samples from improbable and possible permafrost occurrences, as well as

mixed streams, were not distinguishable from each other based on these variables, while a majority of samples from probable permafrost had a distinct signature.

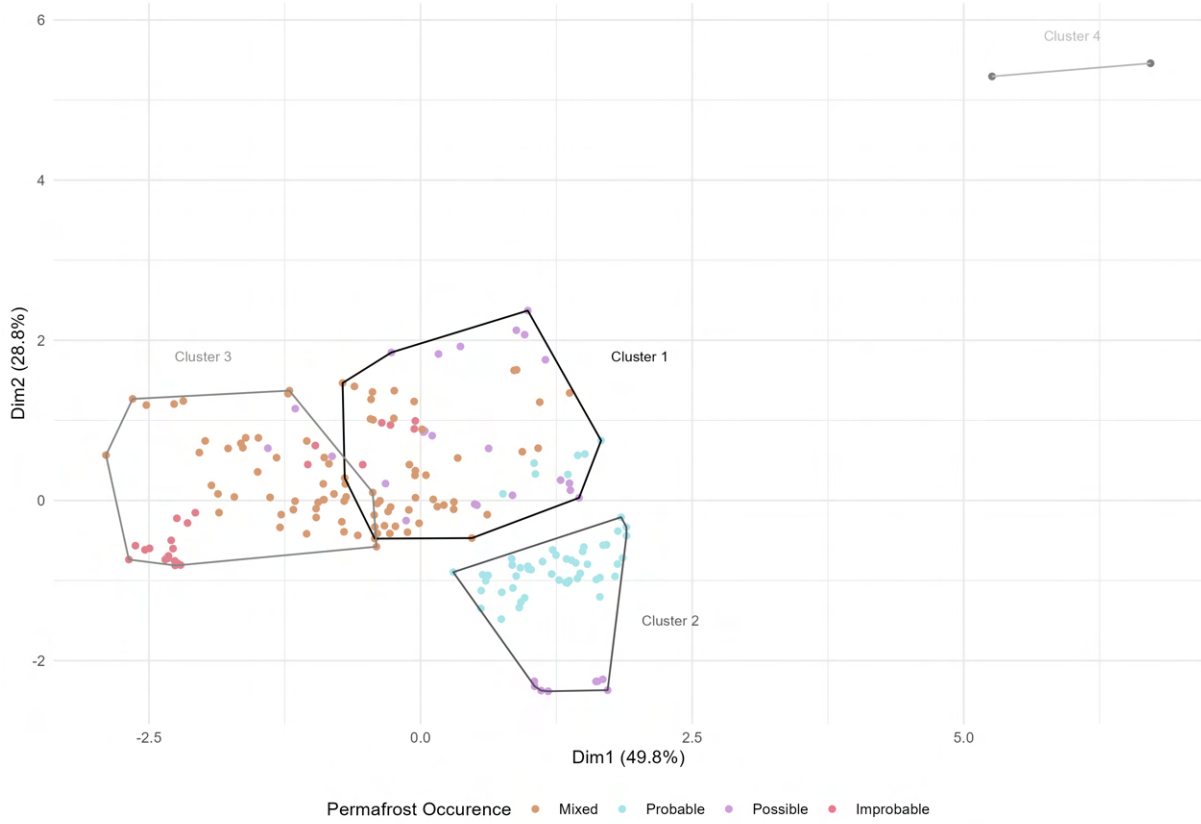


Figure 36: PCA results, with samples colored according to K-means Clustering based on Water temperature, EC, $\delta^{18}\text{O}$ and Deuterium Excess.

Table 13: Percentage of Streams with different Permafrost Occurrence across the four clusters based on K-means Clustering (and total count).

Permafrost Occurrence	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Improbable	22% (5)	0% (0)	78% (18)	0% (0)
Possible	63% (20)	25% (8)	13% (4)	0% (0)
Probable	13% (7)	87% (48)	0% (0)	0% (0)
Mixed	51% (44)	0% (0)	49% (43)	0% (0)
Precipitation	0% (0)	0% (0)	0% (0)	100% (2)
Total Samples (n=199)	76	56	65	2

5.2 Temporal Variability in Physical and Chemical Water Characteristics of Different Landforms

The temporal variability in physical and chemical water characteristics was measured with continuous measurements of water temperature, EC, and water pressure between mid-July and mid-October 2025. Data was taken at four locations: two active rock glacier discharge points, the end moraine of the former Muragl glacier, and a downstream site where all glacial and periglacial features within the catchment were mixed.

5.2.1 Seasonal Variability

The seasonal variability was assessed by investigating patterns observed over the summer months. Figure 37 presents precipitation and air temperature at the Bernina pass corrected to the elevation of the Muragl rock glacier using a lapse rate of $0.65^{\circ}\text{C}/100\text{ m}$. Furthermore, water temperature, EC, and water level in the discharge are displayed at four locations.

Air Temperature peaked at 22°C in August and dropped to -4.3°C in October, as detailed in Table 14. While an overall cooling trend was observable between August and October, there was a high variability within this trend. Furthermore, the diurnal temperature range of air temperature varied between 1°C and 12°C within the measured period. This daily amplitude was higher on dry days compared to rainy days. Because the air temperature was calculated for the Muragl rock glacier at 2478m a.s.l., it does not reflect the temperature variation across the catchment, but can nevertheless illustrate how the air temperature evolved throughout the season.

Precipitation between mid-July and mid-October 2025 was episodic, with events of varying intensity. There were three extended dry periods: The first period lasted from August 3rd to 14th, accompanied by high air temperatures. The second one occurred between the 15th and 21st of September, again with warm conditions. A colder, but dry period with snow in the catchment started on September 29th and continued until the end of the measurement period (October 18th 2025), only interrupted by a small snowfall event on October 4th.

Table 14: Summary of weather conditions between July and October 2025 with air temperature and precipitation measured at the Bernina pass (2260 m a.s.l.) and adjusted to an elevation of 2478m a.s.l.

Parameter	Mean	Minimum	Maximum
Air Temperature (°C)	7.7	-4.3	22.4
Daily Amplitude of Air Temperature (°C)	7.0	1.1	12.6
Daily Sum of Precipitation (mm)	4.7	0	97

Water temperature for the rock glaciers remained consistently low, staying below 2.4°C for the Muragl rock glacier and 1.4°C for the Champagna rock glacier (Table 15). The diurnal temperature fluctuation was larger for the Muragl than for the Champagna rock glacier, with a daily amplitude reaching up to 1.4°C and 0.6°C, respectively. While the diurnal variation was larger during dry periods for both sites, the responses on rainy days differed. The diurnal signal dropped to nearly 0°C for the Champagna rock glacier, but remained observable at the Muragl rock glacier. EC generally increased between July and October at both rock glaciers, even though absolute values were higher in the discharge of the Muragl rock glacier. Both rock glaciers experienced a sharp decrease in EC following major precipitation events. A unique feature of the Muragl rock glacier is the brief EC peak, immediately before the usual drop after precipitation (e.g., on 22.09.2025 in Figure 37). Furthermore, the EC decreased slightly during the prolonged dry periods in August and October for the Muragl rock glacier. Diurnal EC fluctuations were observed at both locations; however, while this diurnal fluctuation was most pronounced during the warm and dry periods at the Champagna rock glacier, it maintained a consistent amplitude throughout the summer season at the Muragl rock glacier.

On a seasonal scale, there was an inverse relationship between the EC and water level for both rock glaciers. Despite a slight overall decrease in water level over the season, rapid, short-term increases occurred after precipitation events, followed by a slow decline to the pre-event water level. The water became isotopically less depleted until mid-September, after which it became more depleted again. An exception was a local peak of less depleted $\delta^2\text{H}$ water at the end of July for both rock glaciers.

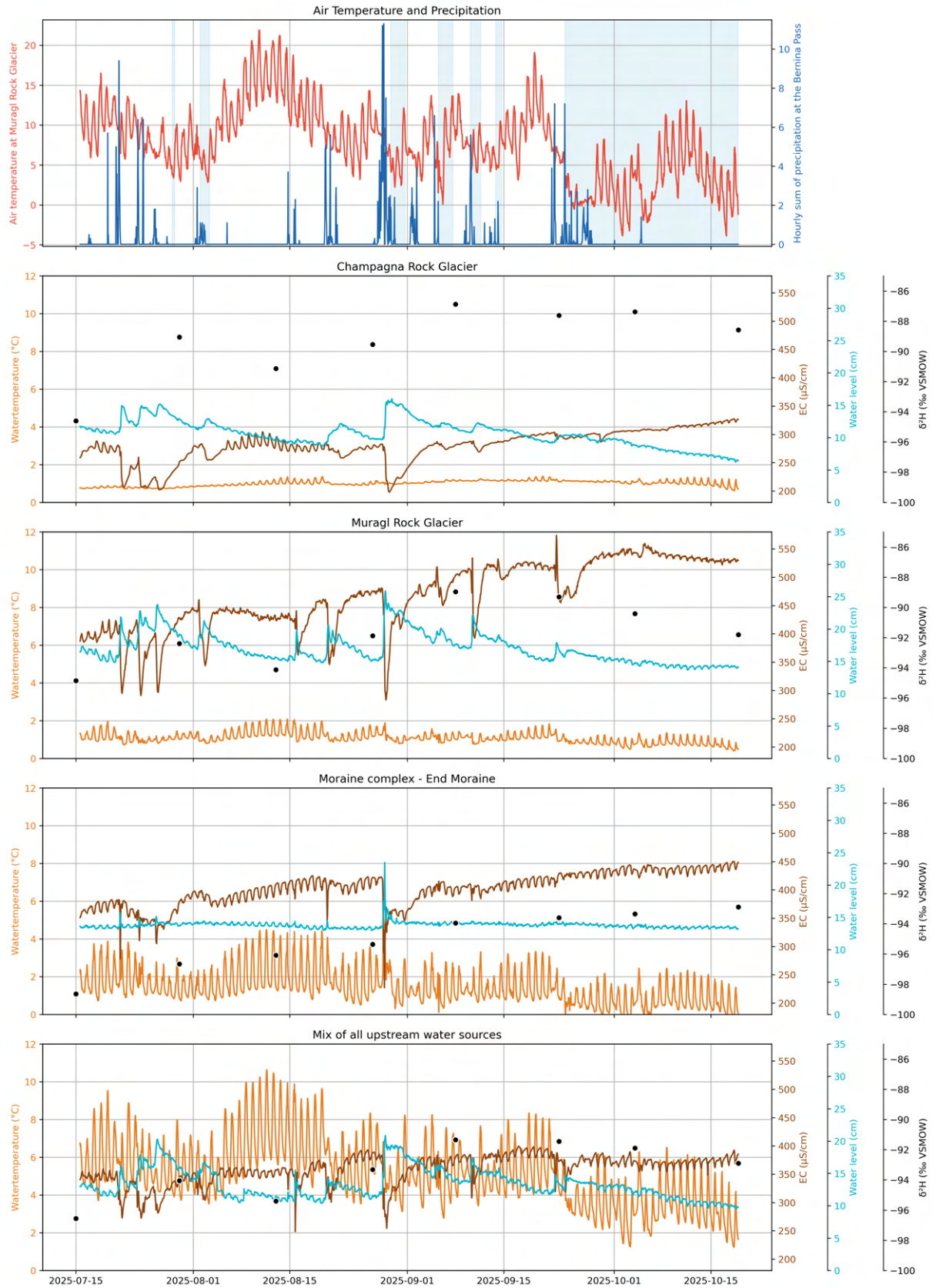


Figure 37: Time series of water temperature, EC, $\delta^2\text{H}$ and deuterium excess at the Champagna and Muragl rock glacier, the end moraine and the downstream mixing site. The first subplot shows corrected air temperature and precipitation (MeteoSchweiz, 2025), with periods during which snow was present in the catchment indicated by a blue shading.

The temporal variation in water temperature and EC were similar for the end moraine of the former Muragl glacier as for the rock glaciers, but the amplitude and reaction times differed. While water temperature remained rather stable throughout the season, mostly staying below 4°C, the diurnal variability was more pronounced with an amplitude of around 3°C on warm and dry days. There was one peak event with a water temperature of 6°C in late August, at the same time as a heavy precipitation event. However, these warmer water temperatures and higher diurnal amplitudes were due to the distance between the point of emergence and the measurement station. A temperature sensor within the same stream at the point of discharge remained constantly below 1.3°C, while the diurnal amplitude stayed generally below 0.1°C. The EC increased throughout the season from 350 to 450 $\mu\text{S}/\text{cm}$, with very distinct, but short-lived negative spikes followed by a quick recovery during precipitation events. Occasionally, the EC decreased for multiple days after longer periods of rainfall. Clear diurnal patterns of EC were seen throughout the whole season. Water level remained stable throughout the summer season, with a few peaks in water level during precipitation events. The water level increased sharply and quickly, but also recovered quickly to its stable water levels. Stable water isotope measurements indicated a steady enrichment between July and October.

The mixed downstream river, consisting of streams from different upstream sources and landforms, had a generally similar pattern to that of the rock glaciers. EC rose slightly from 350 to 370 $\mu\text{S}/\text{cm}$ throughout the summer, while precipitation events triggered EC drops and water level peaks. $\delta^2\text{H}$ values followed an identical seasonal trend as the rock glaciers, but with overall more negative values. In contrast, water temperature differed and followed the fluctuations of air temperature; it reached a maximum of above 10°C in August and a minimum of 1.2°C in October. The diurnal fluctuation of water temperature was large throughout the summer season, with amplitudes reaching up to 5.2°C.

Table 15: Summary statistics for water temperature, EC, and water level and $\delta^2\text{H}$ for the different landforms.

Landform	Temp. (°C)		EC ($\mu\text{S}/\text{cm}$)		Water Level (cm)		$\delta^2\text{H}$ (‰)	
	Min	Max	Min	Max	Min	Max	Min	Max
Muragl rock glacier	0.4	2.4	278	575	13.6	26.1	-94.8	-89.0
Champagna rock glacier	0.6	1.4	198	327	6.1	16.2	-94.6	-86.9
End moraine	-0.4	5.9	219	451	12.9	24.0	-98.6	-92.9
Mix of all upstream sources	1.2	10.7	233	401	9.4	21.2	-96.6	-91.3

5.2.2 Diurnal Variability

While the seasonal trends were comparable between the different sites, the diurnal patterns in water temperature, EC, and water level differed more strongly between the measurement sites and landforms. Figure 38 shows the time series for a warm and dry period in August for the Champagna and Muragl rock glacier, the end moraine of the former Muragl glacier, and a downstream location where all upstream sources mixed.

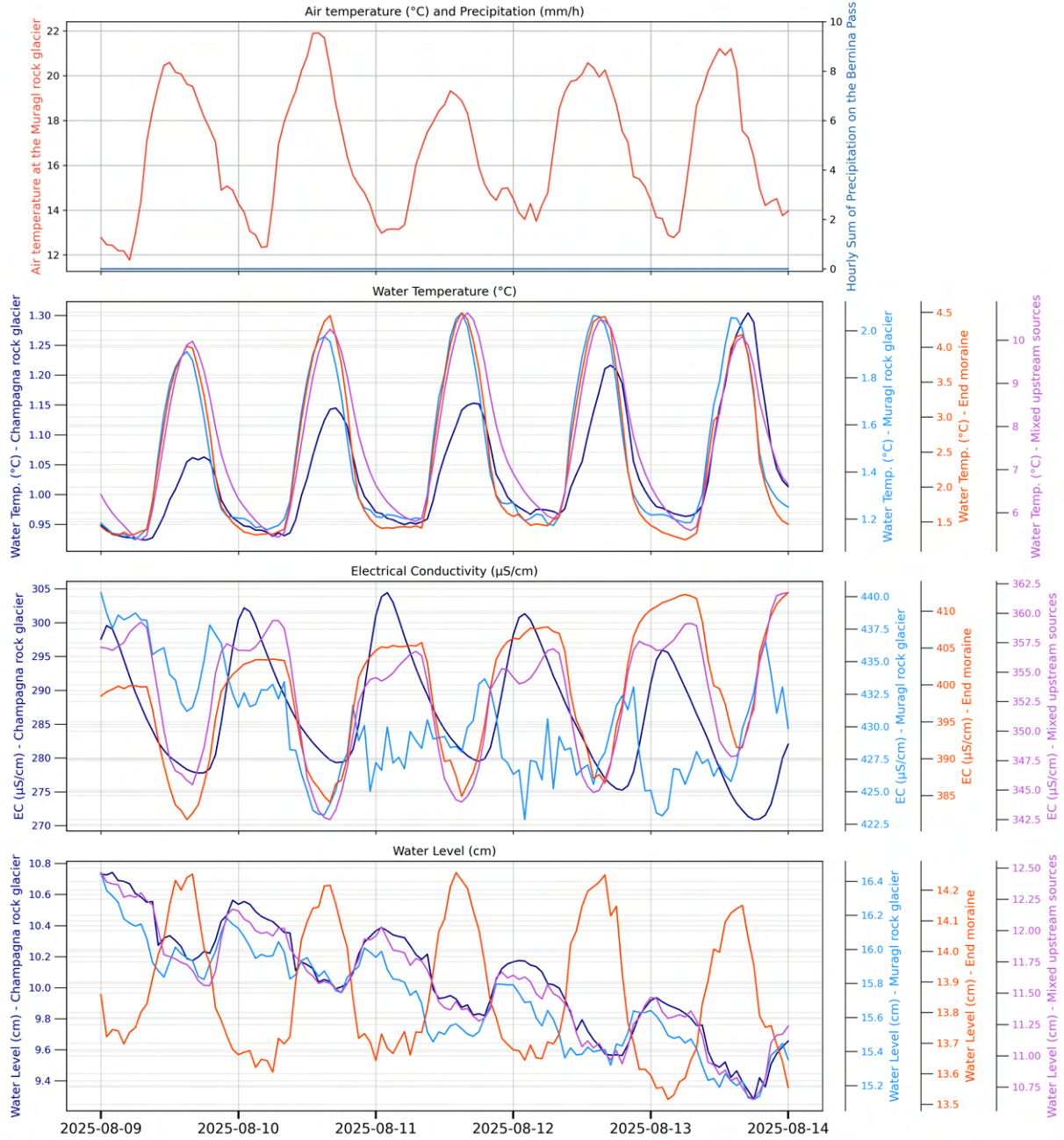


Figure 38: Time series of water temperature, EC, and water level during a warm and dry period in August 2025 for four different locations: the Champagna and Muragl rock glacier, the end moraine, and a downstream mixing location.

During this prolonged dry period, all monitored locations had diurnal variation in water temperature, with peaks in the late afternoon, closely coupled with air temperature. While the daily amplitude for air temperature reached nearly 10°C, the amplitude of water temperature varied by site, ranging from 0.3°C at the Champagna rock glacier up to 4°C at the stream with mixed upstream sources. The water level declined over this dry period, with the exception of the end moraine, where discharge remained steady. Although absolute EC differs across locations, the daily amplitude in EC of about 20 $\mu\text{S}/\text{cm}$ was comparable for all sites. Since the daily fluctuations of water level were small compared to the measurement uncertainty at all locations, with values ranging from 4 to 8 mm, the data must be interpreted with caution.

For both rock glaciers, EC and water level peaked approximately simultaneously, therefore indicating a direct relationship between these variables. Peaks were reached before midnight for the Muragl rock glacier, and shortly after midnight at the Champagna rock glacier. Diurnal minima for both variables were recorded late in the afternoon, soon after peak water temperature. However, due to the noise of the sensor at the Muragl rock glacier, this pattern is more difficult to detect than for the Champagna site.

At the end moraine, an opposite pattern with an inverse relationship between EC and water level was recorded. EC reached a plateau after midnight, coinciding with the diurnal water level minimum. The EC minimum occurred simultaneously with the highest discharge, which also aligns with the daily maximum in water temperature.

The mixed downstream location was characterized by a more complex pattern with two daily peaks of EC and water level: one before midnight and another at approximately 06:00 in the morning. While the second peak was more pronounced for the EC, a more distinct peak in discharge was recorded around midnight. The daily minima for both EC and water level occurred in late afternoon, indicating the same direct relationship between EC and water level as in the rock glaciers.

Table 16: Diurnal timing characteristics for the hydrological and chemical variations during a warm and dry period in August.

Variable	Rock glaciers		End moraine		Downstream mixing	
	Peak	Min	Peak	Min	Peak	Min
Water Temp	15:00	06:00	15:00	06:00	15:00	06:00
EC	01:00 / 20:00*	18:00 / 14:00*	00:00–07:00	15:00	07:00	15:00
Water Level	23:00–01:00	17:00–18:00	15:00	04:00	24:00	18:00
Relation	Direct (WL/EC)		Inverse (WL/EC)		Direct (WL/EC)	

*Variation noted between Champagna and Muragl stations.

When comparing these daily patterns with another dry, but colder period in October, a slightly different pattern is seen (Figure 39). The overall patterns for air and water temperature remained the same as during the warm and dry period, with a maximum in the late afternoon. For EC and water level, all sites had a similar pattern with a direct relationship between EC and water level. A minimum in EC and water level was reached in late afternoon, simultaneously with peak water temperature for all locations. Both a peak EC and discharge occur around 07:00 in the morning; however, a plateau in water level could be observed for the Champagna rock glacier between 18:00 and 07:00 in the morning. Thus, the diurnal pattern of the end moraine shifted from an inverse pattern in August to a more direct pattern in October, although it remained slightly shifted in timing.

Table 17: Timing characteristics for the hydrological and chemical variations across different measurement stations during a cold and dry period in October.

Variable	Rock glaciers		End moraine		Downstream mixing	
	Peak	Min	Peak	Min	Peak	Min
Water Temp	15:00	07:00	15:00	07:00	15:00	07:00
EC	07:00–09:00	15:00	07:00	15:00	08:00	15:00
Water Level	00:00–09:00	16:00–17:00	11:00	19:00	03:00–06:00	15:00
Relation	Direct (WL/EC)		Shifted (WL/EC)		Direct (WL/EC)	

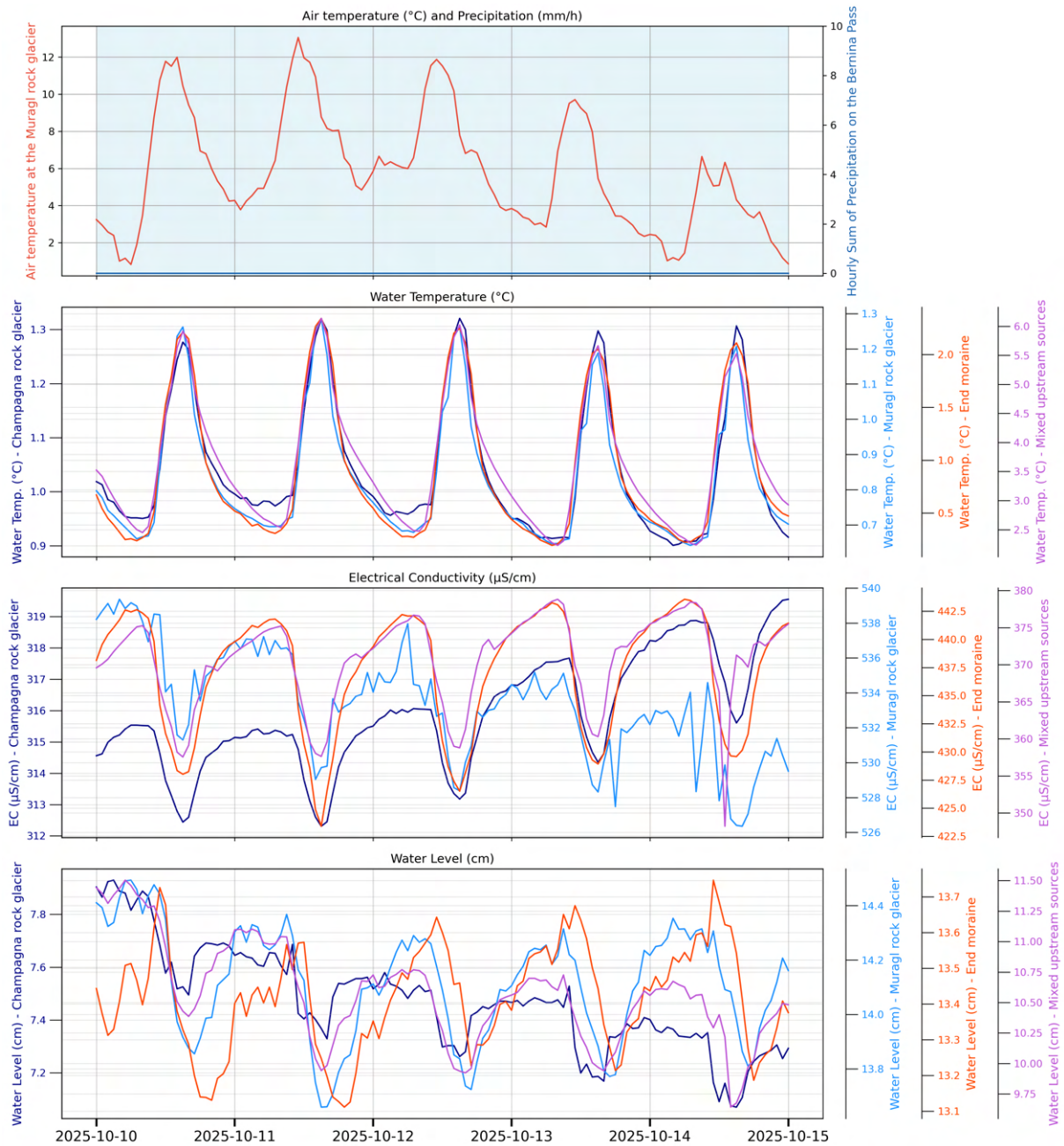


Figure 39: Time series of water temperature, EC, and water level during a cold and dry period in October 2025 for four different locations: the Champagne and Muragl rock glacier, the end moraine, and a downstream mixing location.

This change in pattern from August to October, and the relationship between the different variables, can best be seen when comparing two time periods directly, as illustrated in Figure 40.

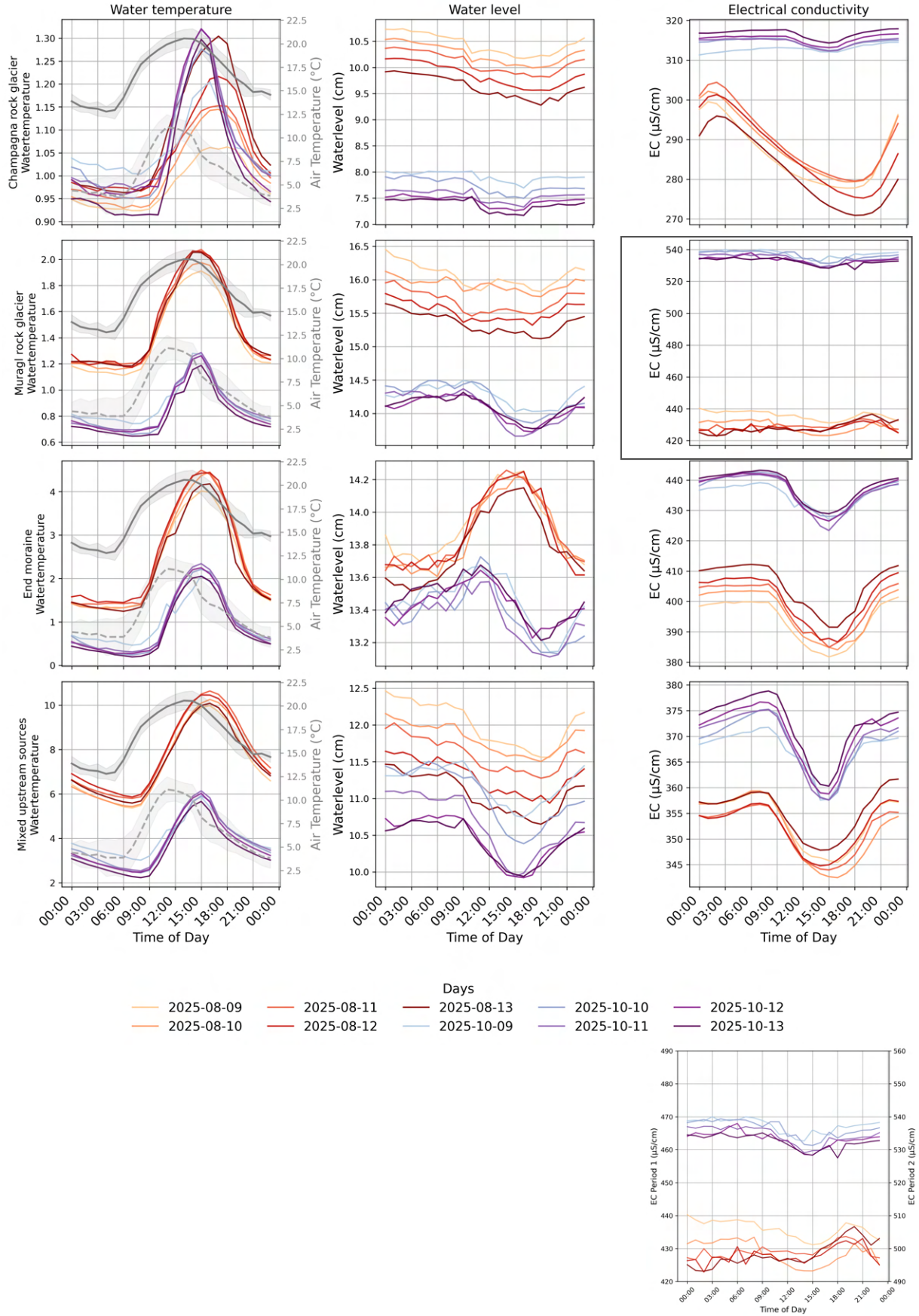


Figure 40: Diurnal cycles of water temperature, EC, and water level during two periods at four different locations. The extra box shows the diurnal cycle of EC for the Muragl rock glacier with two different y-axes.

The relationship between air and water temperature revealed a consistent time lag, with peak water temperature several hours behind a peak in air temperature. While the water temperature decreased at most sites in October alongside colder air temperatures, the Champagna rock glacier was an exception, with consistently low temperatures during both periods.

For both rock glaciers, the general diurnal pattern, characterized by an afternoon minimum in water level and EC, remained constant throughout the season (Table 18). However, the amplitude of the diurnal oscillations varied between the periods. In August, both rock glaciers had continuous water level fluctuations throughout the day. By October, the water levels remained relatively steady, with only a decrease between 12:00 and 18:00. This seasonal shift was even more pronounced for the EC signal of the Champagna rock glacier. In August, EC changed by nearly $30\mu\text{S}/\text{cm}$ over the course of a day, with a peak at 01:00 and a minimum at 18:00. By October, this pattern stabilized, with EC remaining relatively constant except for a minor drop at the same time as the water level drop. For the Muragl rock glacier, the substantial increase in absolute EC between August and October masks the diurnal patterns. For a better visualization, Figure 40 shows the same periods, but with two separate y-axes for EC. This graph confirms that for the Muragl rock glacier, there was no distinct seasonal shift, as observed at Champagna. Instead, its diurnal pattern remained consistent in amplitude and phase throughout the season.

The amplitude and timing of the water level variations for the end moraine varied seasonally. In August, the water level peaked at 15:00; however, by October, this maximum occurred earlier in the morning, followed by a discharge minimum at 18:00. This shift led to a daily signature in October that resembled the diurnal patterns observed in the rock glaciers more closely. In contrast, the diurnal EC pattern remained relatively stable at the end moraine across the summer season, with only a slight reduction in amplitude in October. Thus, the change from an inverse relationship to a more direct relationship between water level and EC was caused by a seasonal shift in water level rather than changes in EC patterns.

The downstream location with mixed sources had the most stable diurnal pattern. For both water level and EC, the timing and amplitude remained the same throughout the season.

Table 18: Diurnal timing of minimum values during dry periods in August and October.

Parameter	Period	Champagna Rock Glacier	Muragl Rock Glacier	End Moraine	Downstream Mixing
Min Water Level	August	18:00	10:00 - 18:00	03:00	18:00
	October	15:00	16:00	18:00	15:00
Minimum EC	August	18:00	15:00	15:00	14:00
	October	15:00	15:00	15:00	14:00

The response of the discharge to precipitation events differed between the measurement sites, both in response time and magnitude, as well as in recovery time after an event. In Figure 41, the measured parameters of the different locations are shown during a rainy period in July 2025.

The discharge of both rock glaciers was characterized by a similar response to precipitation events. Initially, a significant rise in water level occurred, followed by a short peak in EC, before a strong decrease in EC. Minimum EC was reached approximately two hours after the peak water level, indicating a time lag between maximum discharge and EC dilution. The response time at the Champagna rock glacier was slightly longer than for the Muragl rock glacier. Due to its location in the neighboring valley, it may be possible that air masses and precipitation arrived later; however, the simultaneous beginning of the EC drop suggests that this is not the main reason.

The magnitude of the EC and water level responses varied for each precipitation event; for the July event shown in Figure 41, EC dropped by $70\mu\text{S}/\text{cm}$ at the Champagna rock glacier and $120\mu\text{S}/\text{cm}$ at the Muragl rock glacier, while water level rose by 4 cm and 7 cm, respectively. Full recovery to pre-event values could take several days.

In contrast, the discharge of the end moraine responded much more rapidly. Although the initial reaction occurred at the same time as for the rock glaciers, the time to reach the minimum EC and peak water level was significantly shorter than for the rock glaciers. For the precipitation event in July, the water level peaked within just two hours and recovered at a similar time. In contrast to the rock glaciers and the stream with mixed upstream sources, the EC minimum and peak water level occurred at the same time. A similar magnitude of EC decrease of about $100\mu\text{S}/\text{cm}$ was achieved, but a smaller water level rise of about 2 cm. Furthermore, precipitation at this site occasionally induced a peak in water temperature, which briefly deviated from its usual daily pattern.

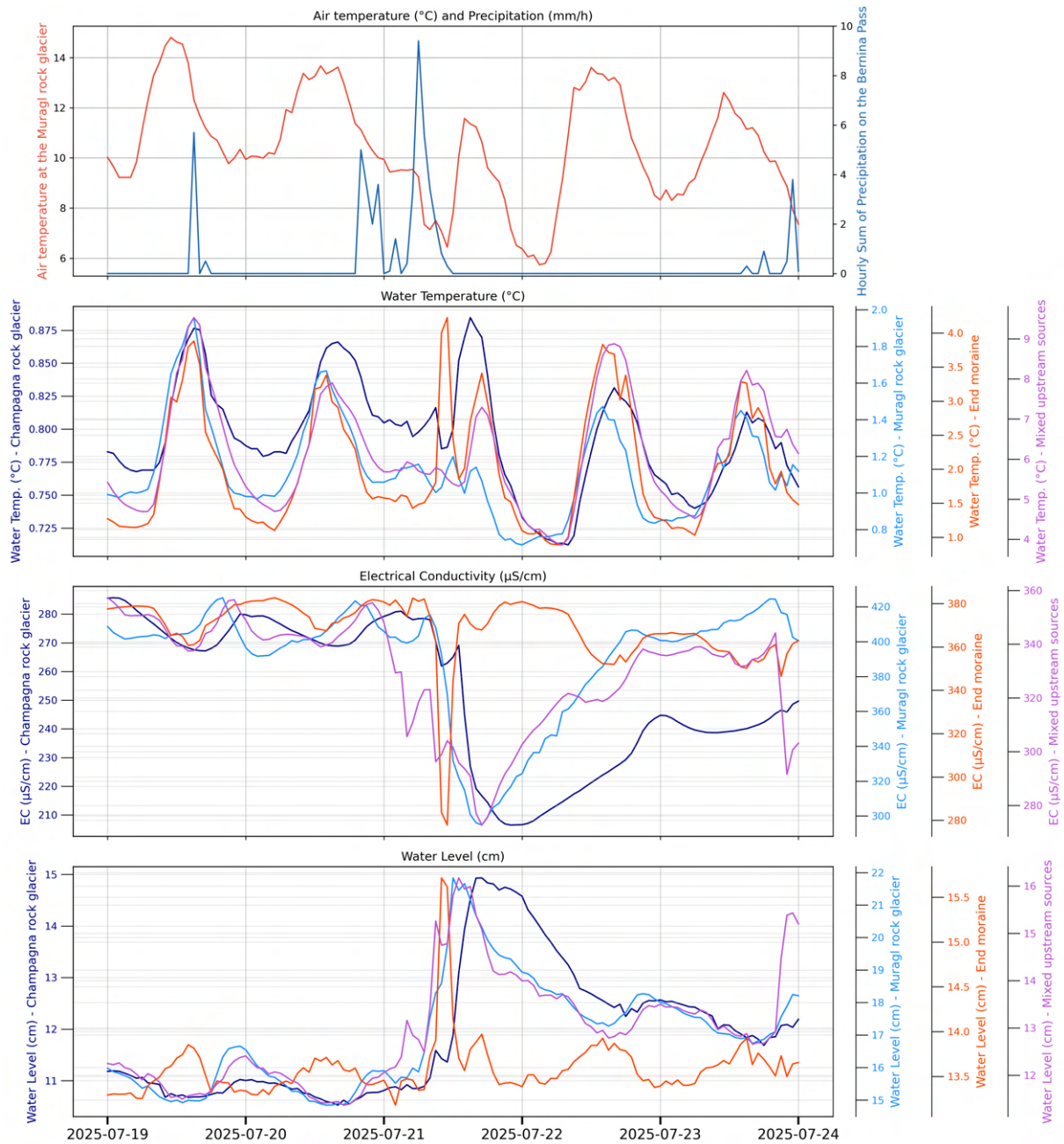


Figure 41: Time series of water temperature, EC, and water level during a warm and wet period in July 2025 for four different locations: the Champagna and Muragl rock glacier, the end moraine, and a downstream mixing location.

The downstream sampling location, which included water from different sources, was characterized by a complex response with multiple peaks in water level and minima in EC, each followed by a short recovery. The initial reaction occurred at the onset of precipitation, a second pulse coincided with the peak at the end moraine, and the third and largest peak coincided with the maximum discharge and minimum EC at the Muragl rock glacier. The change in signal at the downstream location started hours before the individual landforms, and also seemed to react to smaller amounts of precipitation; however,

the minimum was reached at approximately the same time as the minimum of the Muragl rock glacier. The recovery time was also similar to that of the rock glacier.

While these general patterns (Table 19) were consistent across major precipitation events, both the response and recovery time, as well as the magnitude of the reaction, were event-specific. Results for another precipitation event in September are shown in the Appendix in Figure 59. Compared to the precipitation event in July, the peak in EC before the drop for both rock glaciers was slightly more pronounced, while the overall response pattern remained the same.

Table 19: Summary of the hydrological response characteristics to precipitation events

Parameter	Champagna Rock Glacier	Muragl Rock Glacier	End Moraine	Downstream Mixing
Response time of EC	several hours	several hours	few hours	multiple drops
Response time of Water level	several hours	several hours	few hours	several hours
Recovery time (EC & Water level)	> day	> day	few hours	multiple recoveries
Relationship: EC – Water level (WL)	peak WL a few hours before minimum EC	peak WL a few hours before minimum EC	peak WL and minimum EC coincide	peak WL a few hours before minimum EC

5.3 Hydrochemical Evolution from Periglacial Sources to Downstream River Systems

The hydrochemistry of an Alpine catchment is a reflection of the diverse sources from which they originate. In the Muragl catchment, the surface water is influenced by its contributing sources that each have a distinct geochemical signature. The evolution of hydrochemical and isotopic signatures along the Ova da Muragl is assessed to reveal how water inputs from different landforms shape the character of the stream. To quantify the influence of periglacial landforms on the catchment, the contribution of different areas is evaluated.

5.3.1 Changes of Water Chemistry Along its Path Downstream

To evaluate the influence of different water inputs on the main stream, water temperature, EC, and stable water isotope composition were recorded along its flow path. The measurement sites along Ova da Muragl are indicated in the map on Figure 42.

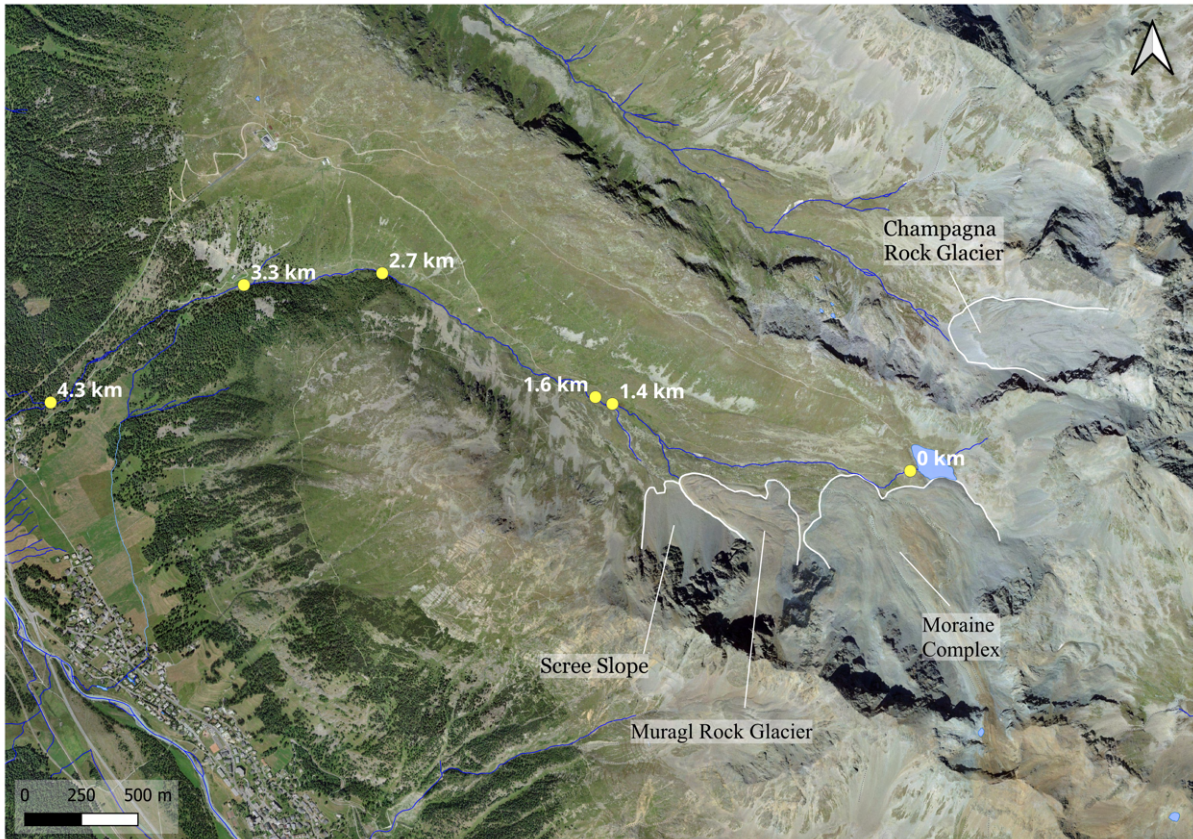


Figure 42: Measurement sites along the Ova Muragl in Val Muragl. The labels indicate the distance of the measurement point to the lake outflow on the downstream path.

The downstream evolution of the Ova da Muragl starts at the outlet of Lake Muragl (0 km), which provides the initial baseline of the hydrochemical and isotopic signature. As the water moves downstream, the influence of lateral inputs from different geomorphological landforms is reflected in shifts of the water signatures, as illustrated in Figure 43. Absolute values of the different variables are displayed in Figure 44.

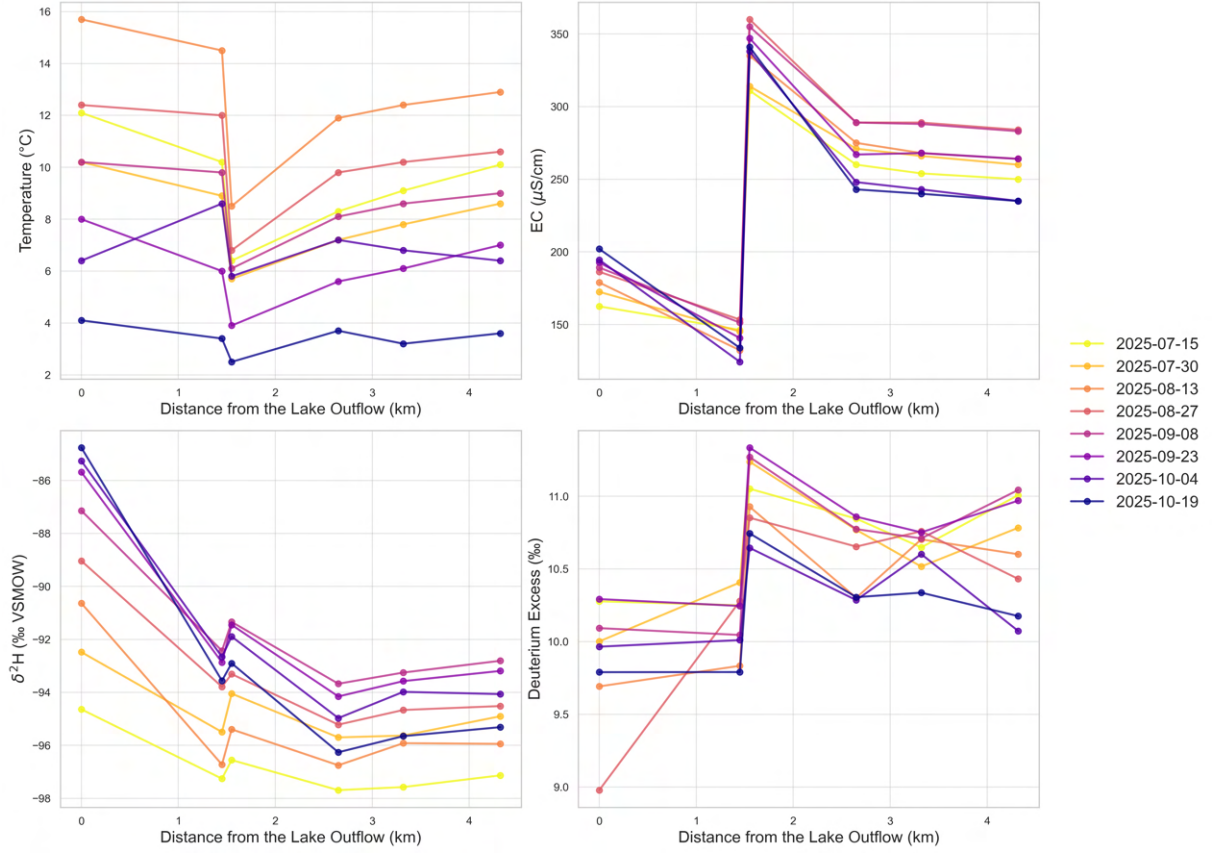


Figure 43: Changes of water temperature, EC, $\delta^2\text{H}$, and deuterium excess along a downstream river over time. Colors represent measurements at different times between July and October 2025.

- At the lake outlet, the water was characterized by a high seasonal variability in water temperatures, starting from 12°C in July, rising to almost 16°C in August, before dropping to 4°C in October. Parallel to thermal shifts, EC at the lake outflow followed a steady upward trend from 162 $\mu\text{S}/\text{cm}$ in July to 202 $\mu\text{S}/\text{cm}$ in October. The stable isotope signature underwent an enrichment throughout the summer season, with a more depleted signal of -94.6‰ VSMOW in July to -84.8‰ VSMOW in October. Deuterium excess remained relatively stable, fluctuating between 9.8 and 10.3 ‰, except for one outlier at 9.0‰.
- Moving 1.4 km downstream from the lake output, the Ova da Muragl receives input from the ground moraine and end moraine. As the water moved downstream, a slight decrease in water temperature was observed, accompanied by a more pronounced reduction in EC. The absolute EC at this measurement point remained relatively stable between July and mid-September (146 - 151 $\mu\text{S}/\text{cm}$), before it decreased towards October (134 $\mu\text{S}/\text{cm}$). The water at this site was distinctly more depleted in heavy isotopes than at the lake outflow, but underwent the same enrichment trend from July (-97.3‰ VSMOW) to October (-93.6‰ VSMOW). The deuterium excess

remained similar to that of the lake outflow with little fluctuations throughout the season. When comparing these changes in the main stream to the specific signatures of the ground moraine and end moraine outflow, the decrease in temperature and more negative $\delta^2\text{H}$ values were consistent with the measured outflow from those landforms. However, while the main stream underwent a decrease in EC along its path, both the ground and end moraine were characterized by a higher EC, and thus, the discharge from the moraine complex can not explain this observed dilution. Thus, an additional, unmeasured water source likely contributed to this section of the main stream.

- The subsequent monitoring site is located within a short distance of 200 m downstream, but the water signature changed due to the influence of the incoming discharge from the Muragl rock glacier and the neighboring scree slope. In August, the stream temperature decreased about 6°C over this 200 m distance. Simultaneously, the EC drastically increased. This enrichment became increasingly pronounced as the season progressed, with increases between 150 and 200 $\mu\text{S}/\text{cm}$. The seasonal pattern of EC was similar to that at the previous measurement location, with peak EC at the end of August. $\delta^2\text{H}$ values were slightly less negative than those recorded 200 m upstream, with the least negative delta values in September. Thus, the seasonal pattern changed from a continuous enrichment during the season to an enrichment from July (-96.6‰ VSMOW) to September (-91.3‰ VSMOW), followed by a slight depletion until October (-92.9‰ VSMOW). Deuterium excess underwent an abrupt increase to values between 10.7‰ and 11.3‰. This is consistent with values from the Muragl rock glacier and the scree slope, which had a high EC (360 - 750 $\mu\text{S}/\text{cm}$), constantly low water temperature (<2.5°C), a higher deuterium excess (>10.6 ‰), and the same seasonal pattern with the least depleted values in September.
- At the measurement site 2.7 km downstream from the lake, no further water inputs from any glacial or periglacial landform were expected. Water temperature increased again, with peak water temperature in August (11.9°C). EC decreased on its path downstream, with a seasonal trend with a peak EC in August (289 $\mu\text{S}/\text{cm}$). $\delta^2\text{H}$ values showed the same pattern as the last measurement station, with -97.7‰ in July, the least depleted water in September with -93.7‰, and -96.3‰ in October. Deuterium excess decreased compared to the previous measurement station, with no clear seasonal trend. These downstream trends are consistent with the higher water temperature, lower $\delta^2\text{H}$ values, distinctly lower EC, and a lower deuterium excess of the exfiltrating hillslope water.
- These trends continue further downstream towards the measurement sites at 3.3 km and 4.3 km: Water temperature continued to increase, except for the two mea-

measurements in October, where snow was present in the catchment. EC remained relatively stable along the main stream with only a slight decrease and a peak in August (289 $\mu\text{S}/\text{cm}$). $\delta^2\text{H}$ values are slightly less negative downstream and were least negative in September, while deuterium excess fluctuated strongly. For the exfiltrating hillslope water, two streams were sampled at two different elevations. In comparison with each other, the stream at the lower elevation had a higher water temperature, except for October, a lower EC, higher deuterium excess, and lower $\delta^2\text{H}$ values. Assuming that the change of these two values is representative of the change in exfiltrating hillslope water over different elevations, this change would be consistent with the temperature and EC changes within the main stream, but not for the less negative $\delta^2\text{H}$ values.

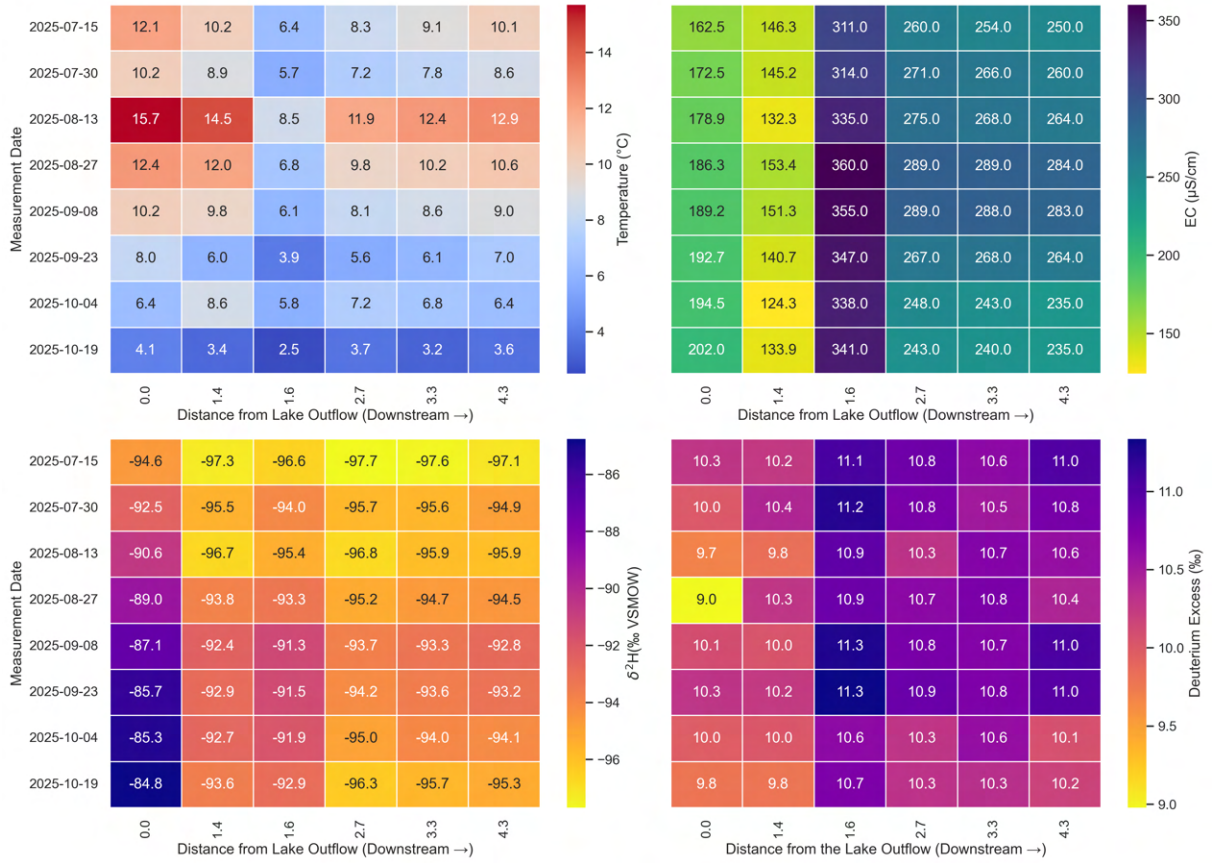


Figure 44: Heat maps depicting the water temperature, EC, $\delta^2\text{H}$, and deuterium excess for different locations along a downstream river at different times.

5.3.2 Contribution of the Discharge of Sub-Catchments and Landforms to the Main Stream

To estimate the relative contribution of different sub-catchments, a mixing analysis based on $\delta^2\text{H}$ was performed. Two streams and their mixing were investigated: one stream emerging from the lake, the moraine complex, and the surrounding Alpine meadows (yellow, Muragl13). The other stream originates from the Muragl rock glacier and the neighboring scree slope (orange, Muragl11), as illustrated in Figure 45.

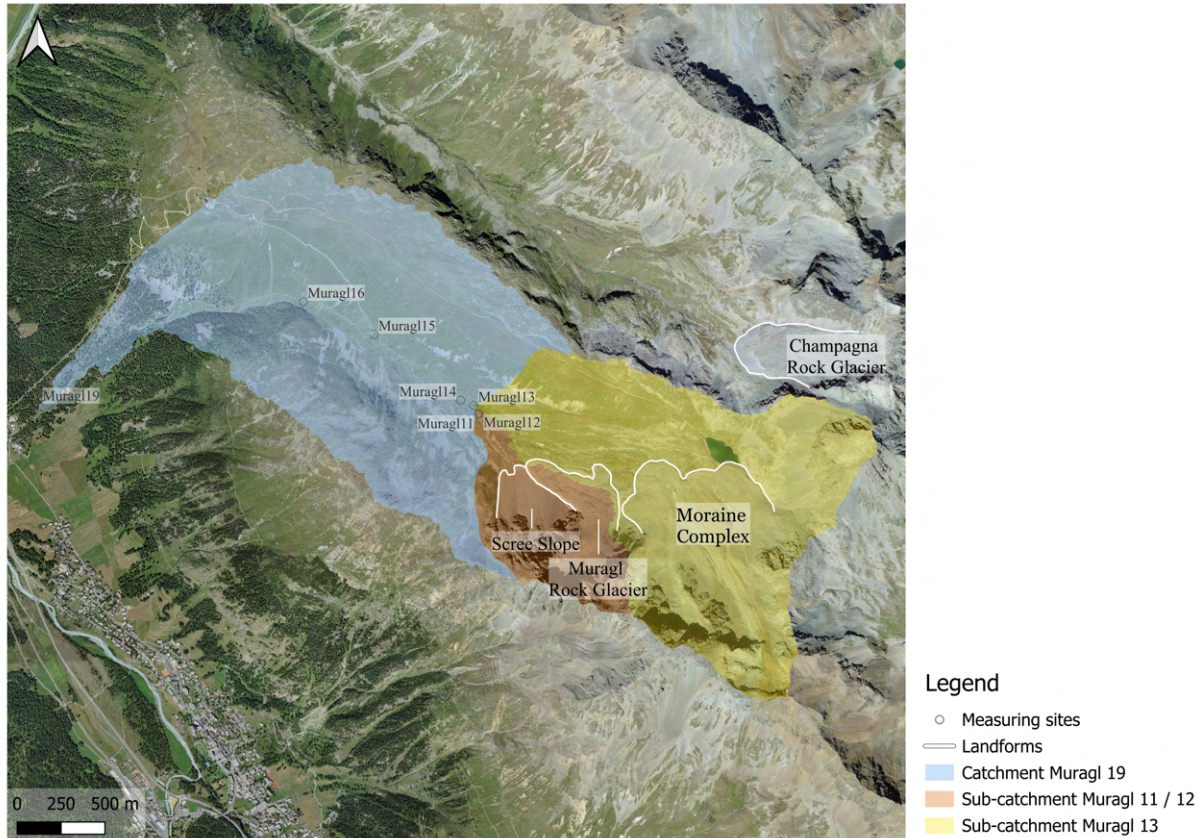


Figure 45: Map showing the location of the sub-catchments of Muragl 11 / 12 and 13 and their contribution to the catchment outlet (Muragl19).

As detailed in Table 20, the sub-catchment containing the Muragl rock glacier and the scree slope only accounted for 25% of the area at the confluence of the two sub-catchments (Muragl11 and Muragl13 in Figure 45). Despite its smaller extent, it had an important influence on the hydrology of the main river by contributing between 35% and 75% of the total discharge, based on the mixing model using $\delta^2\text{H}$ (Figure 46). In contrast, the Muragl13 sub-catchment, which included the moraine complex and the lake outflow, was three times larger in area but provided only 25% - 65% of the discharge according to the mixing model.

However, the same mixing calculation, but with a measuring location a few meters downstream (Muragl12), after the inflow of a small stream of exfiltrating hillslope water, resulted in a contribution of 33% - 88%. While the $\delta^2\text{H}$ values between the two sampling points deviated only by up to 0.4‰ depending on the sampling day, this minor difference resulted in a shift in the calculated contribution of up to 29%. This underscores the high sensitivity to small changes in the isotopic signature, where small uncertainties in the laboratory analysis can strongly influence the calculated contribution. Furthermore, it must be noted that the calculation of the sub-catchment area is based on the DEM and thus the topographic catchment, but does not account for potential subsurface flows from different sub-catchments. Nevertheless, while the absolute contribution varied, the mixing calculation with both Muragl11 and Muragl12 indicated that the discharge from the Muragl rock glacier and the scree slope contributes the majority of discharge on most sampling days, despite their smaller area.

Table 20: Area of different sub-catchments and their contribution to the total discharge according to the mixing model based on $\delta^2\text{H}$. Colors refer to those used in Figure 45.

Sub-catchment	Water sources	Color	Area [km ²]	Area [%]	Discharge [%]
Muragl14	Total catchment	Orange + Yellow	2.28	100	100
Muragl11	Muragl Rock glacier and Scree slope	Orange	0.57	25	35 – 75
Muragl13	Moraine Complex, Lake, Meadows	Yellow	2.23	75	25 – 65

The relative contribution of the sources varied seasonally. The contribution of the Muragl rock glacier and the scree slope was highest in July and August, accounting for the majority of the discharge. From late August through October, their contribution decreased, representing approximately a third to half of the discharge.

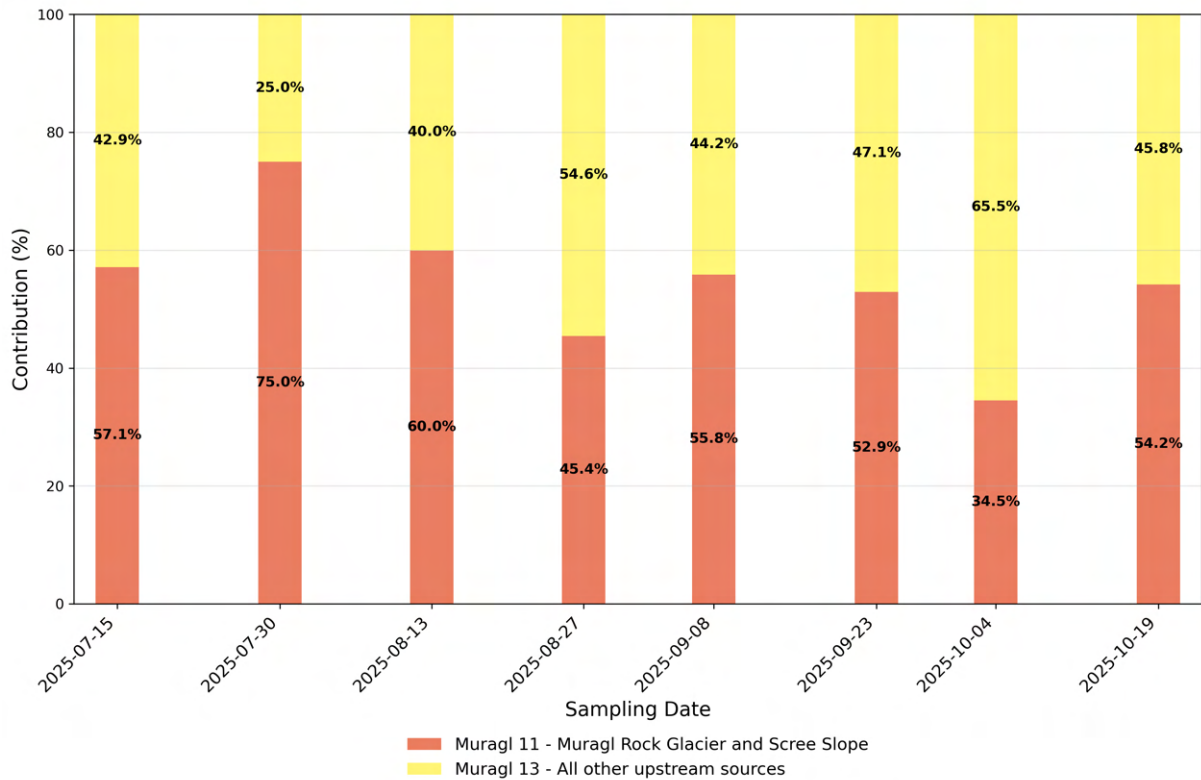


Figure 46: Contribution of the Muragl rock glacier and the scree slope (Muragl11) and the moraine complex and lake (Muragl13) to their junction (Muragl14) based on the mixing calculation using $\delta^2\text{H}$.

Following the same approach, the input of exfiltrating hillslope water (Muragl16) to the main river, Ova da Muragl, was evaluated. To calculate its contribution, it was assumed that after the mixing of the previously described streams (Muragl12 and Muragl13), the main water input was due to exfiltrating hillslope water, and that no other major water sources enter the stream.

Even though the measurement point is almost at the outlet of the catchment, the contribution of the upper part of the catchment was still substantial. While the sub-catchment of the Muragl rock glacier and the scree slope only occupied about 10% of the total area, it still contributed 29 - 70% of the total discharge at the basin outlet, whereas the discharge from the moraine complex and the lake outflow accounted for the second-highest amount with 23 - 55%, as shown in Table 21. The input of exfiltrating hillslope water was comparably smaller, with a contribution of 5 - 19% of the discharge.

This estimate was tested by repeating the calculation with the second measurement of exfiltrating hillslope water at a slightly higher elevation (Muragl15). For most sampling days, similar results were achieved. Even though the isotopic signatures between the two sampling locations of exfiltrating hillslope water deviated by up to 3.5‰ in $\delta^2\text{H}$, the

resulting impact on the calculated contribution was relatively small, with approximately 4% between July and September. In October, however, the deviation was slightly higher with differences up to 5.1‰ in $\delta^2\text{H}$, which led to differences in the calculated contribution of up to 12%. Despite these uncertainties, both calculations agreed on the importance of the upper part of the catchment, including the glacial and periglacial landforms, in shaping the discharge of this river system.

Table 21: Area of different sub-catchments and their contribution to the total discharge according to the mixing model based on $\delta^2\text{H}$.

Sub-catchment	Landforms / water sources	Color	Area [km ²]	Area [%]	Discharge [%]
Muragl19	Total catchment	–	5.74	100	100
Muragl11	Muragl Rock glacier and Scree slope	Orange	0.57	9.9	29 – 70
Muragl13	Moraine Complex, Lake, Meadows	Yellow	2.23	38.8	23 – 55
Muragl16	Surface runoff	Blue	2.94	51.3	5 – 19

Although the contribution of the upper part of the catchment to the total discharge remained high throughout the summer season, its relative importance decreased, while the input of exfiltrating hillslope water to the total discharge increased from July to October, reaching nearly 20% (or 30% for the second measurement of exfiltrating hillslope water), as indicated in Figure 47.

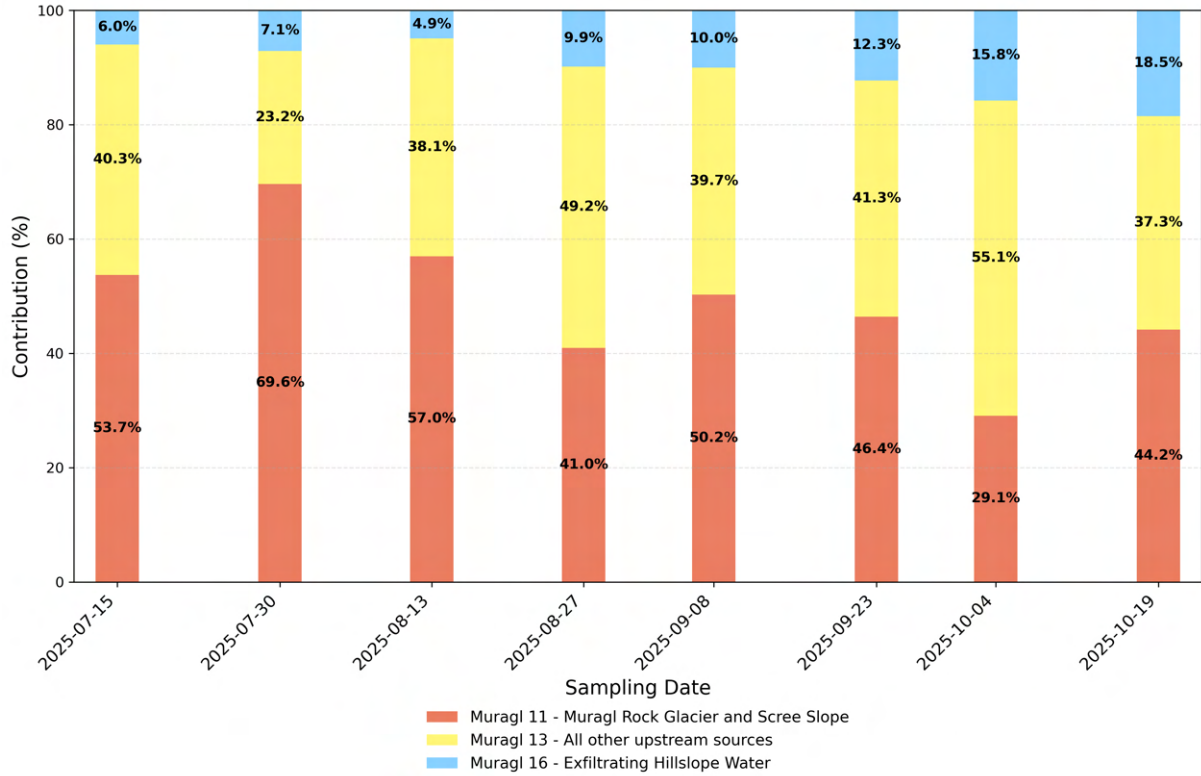


Figure 47: Results of the mixing calculation for the contribution of the Muragl rock glacier and the scree slope (Muragl11), the moraine complex and lake (Muragl13), and exfiltrating hillslope water (Muragl16) to the measurement station at the catchment outlet (Muragl19).

In summary, the highest contributions originated from the upper part of the catchment, based on the mixing calculations using $\delta^2\text{H}$. The majority of discharge was generated by the rock glacier and the neighboring scree slope, followed by the sub-catchment comprising the moraine complex, the lake, and the surrounding meadows. In contrast, the lower part of the catchment, without any glacial and periglacial landforms, contributed a smaller amount of the total runoff. These calculated contributions are, however, subject to substantial uncertainties due to potential inflow of unknown sources, the high sensitivity to small shifts in the isotopic signature of water sources, and the potential subsurface connectivity between the different landforms. Such groundwater flow paths might lead to more integrated landforms than the discrete boundaries of the DEM suggest.

6 Discussion

6.1 Spatial Variability in Hydrochemistry

6.1.1 Hydrochemical Variability Across Glacial and Periglacial Landforms

The spatial distribution of physical and chemical water properties within the Muragl and Champagna catchments demonstrates the high variability in the water quality signature of different streams and how it depends on the water source, the type of periglacial and glacial landforms along the flow path, and whether permafrost is present within the catchment. This suggests that landforms, such as rock glaciers or moraine complexes, are more than just transit points for groundwater or precipitation, but that they actively alter their discharge and water quality (Munroe & Handwerger, 2023b). Figure 48 illustrates the different hydrochemistry between the landforms and water sources.

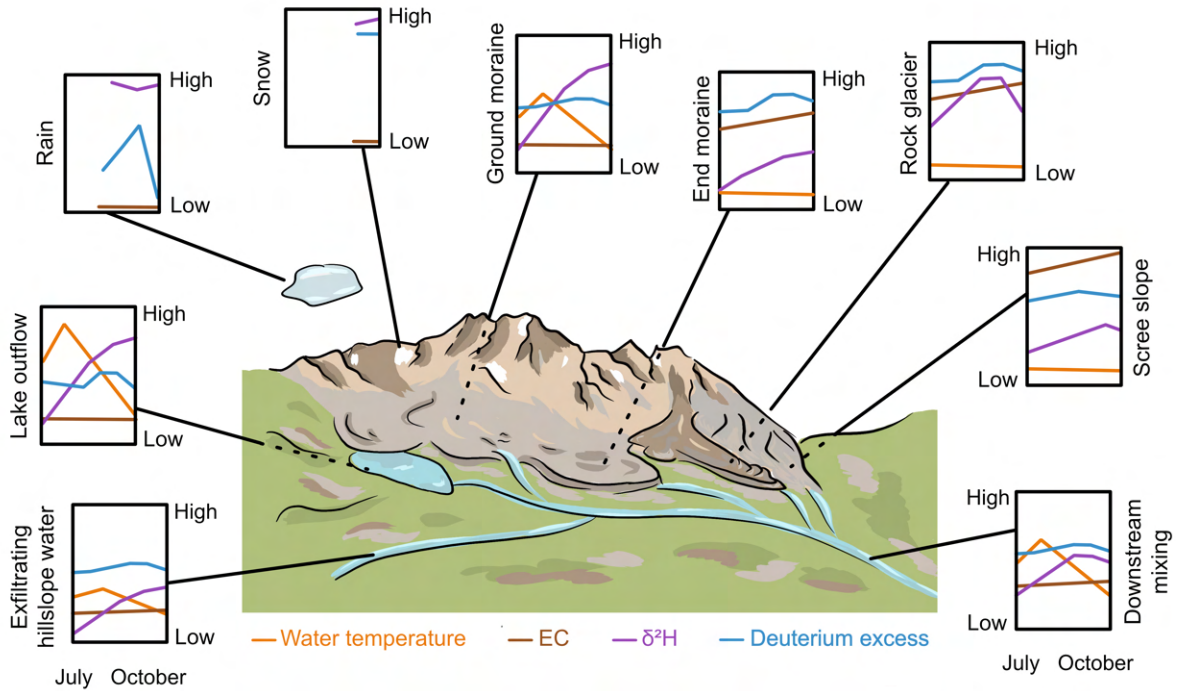


Figure 48: Sketch of the spatial and temporal variability of the physical and chemical water properties of different water sources and landforms within the Muragl catchment (own Figure).

Outflow from both rock glaciers was characterized by elevated EC, consistently low water temperature, and a high deuterium excess. The high concentration of solutes within the discharge of rock glaciers is likely driven by the large surface area of minerals in contact with ice and water, which promotes chemical weathering (Brighenti et al., 2024; Colombo et al., 2018a; Jones et al., 2019; Munroe, 2018), together with the release of

solute-enriched ice melt through thawing permafrost (Bearzot et al., 2023; Brighenti et al., 2024; Colombo et al., 2018b), and the long residence time of the water within the landforms (Brighenti et al., 2026). However, significant differences exist between the rock glaciers in the two catchments, with lower EC for the discharge of the Champagna rock glacier. Nevertheless, both findings fall within the ranges of EC reported for rock glacier discharge in the literature: from $50\mu\text{S}/\text{cm}$ at the Murtèl rock glacier (Amschwand et al., 2025), up to $1000\mu\text{S}/\text{cm}$ in Austria (Delpero et al., 2025) and $1200\mu\text{S}/\text{cm}$ in the Andes (Crespo et al., 2017). This disparity is assumed to be due to the local lithology within the catchments (Brighenti et al., 2021a, 2024; Crespo et al., 2017; Munroe & Handwerger, 2023b). The local geological setting controls the type of minerals and chemical weathering, which in turn determines the resulting concentration of dissolved ions and trace elements in the discharge (Brighenti et al., 2026). Comparing the lithology of the two neighboring catchments showed that the Champagna catchment is dominated by augen gneiss, an orthogneiss primarily composed of quartz, plagioclase, and K-feldspar, with a minor biotite content of approximately 5%. In contrast, the Muragl catchment consists mainly of biotite gneiss, a paragneiss composed of plagioclase and quartz, and a higher biotite content ranging from 5% to 30% (Peters, 2005). Generally, biotite is more susceptible to chemical weathering compared to plagioclase or quartz (Regmi et al., 2014; Springman et al., 2012). Brighenti et al. (2024) showed that both rock glacier status and lithology are the most important drivers to explain solute export within rock glacier discharge. For intact rock glacier springs with paragneiss as the main lithology, 91% had poor water quality (Brighenti et al., 2024). The distinct differences in EC within the Muragl catchment indicate that EC could serve as a tracer to distinguish between different landforms and water sources within the catchment, since there seems to be a trend of higher EC for the rock glacier, end moraine, and scree slope compared to other water sources. However, the absolute values remain incomparable across the two catchments, even though the catchments are in close spatial proximity. Similarly, Carturan et al. (2016) reported a large spatial variability of EC, from below $100\mu\text{S}/\text{cm}$ to over $500\mu\text{S}/\text{cm}$ within a 36 km^2 catchment in the Eastern Italian Alps, which they attributed to geological and topo-climatic factors rather than permafrost or rock glacier occurrence. Thus, EC might be an indicator for determining water sources within the catchment, but they can not be compared between the catchments. Nevertheless, this heterogeneity within and between catchments also highlights the benefits of analyzing different streams within a catchment, since it can help to put the hydrochemistry within the discharge of a landform into context.

The constantly low water temperatures below 2°C for both rock glacier springs match the literature (Amschwand et al., 2025; Brighenti et al., 2019, 2021a; Moradi et al., 2024; Munroe & Handwerger, 2023a), and are likely due to the contact of water with permafrost within the rock glacier (Bearzot et al., 2023; Brighenti et al., 2026; Munroe & Handwerger, 2023a). This is further supported by the elevated deuterium excess in rock glacier discharge compared to other streams, which is attributed to meltwater of ice that has been subject to fractionation during multiple freeze-thaw cycles (Colombo et al., 2018a; Delpero et al., 2025; Munroe & Handwerger, 2023a, 2023b). In rock glacier discharge, mean deuterium excess values between 12 and 14.3‰ were described by Colombo et al. (2018a) in the Italian Alps, gradually increasing values from 10 to 16‰ over the summer season by Munroe and Handwerger (2023b) in Utah, and higher δD -excess in perennial rock glacier ice and supra-permafrost runoff than in seasonal ice by Delpero et al. (2025). In the ice of the Muragl rock glacier, similar or even higher deuterium excess values were recorded as for the discharge (Personal communication with Annegret Udke, WSL, 2026), indicating that the ice within the Muragl rock glacier could have undergone such freeze-thaw cycles as well. Furthermore, a peak in deuterium excess was observed in mid-September for most glacial and periglacial landforms, which is assumed to be the seasonal window of permafrost thawing (Delpero et al., 2025).

The water draining from the end moraine had an overall similar signature as that for the rock glaciers, except for a slightly more depleted stable water isotope composition. The cold water supports the assumption of ice embedded within the landform (Brighenti et al., 2026). Together with the high deuterium excess, this supports the findings of an existing ice core through geophysical assessments by Kneisel and Kaeab (2007). One hypothesis for the slightly more depleted stable isotope composition compared to the rock glacier might be the origin of the ice. Crespo et al. (2017) reported more depleted isotope signatures in the discharge of glaciers than in the discharge of rock glaciers in the Andes. Another explanation might be the recharge elevation, since precipitation at higher elevation is typically more isotopically depleted due to the preferential rainout of heavy isotopes (Beria et al., 2018). As the end moraine is situated at a slightly higher elevation than the rock glacier, it might consequently be recharged with more depleted precipitation. However, the differences in isotope signature found in this thesis were small, and based on the measured variables, the water from these two landforms can not be distinguished from each other.

The water from the scree slope had an even higher EC than the neighboring Muragl rock glacier. Its water temperature below 2.3°C indicates that the water was in contact with cold conditions within the slope (Bearzot et al., 2023; Brighenti et al., 2026). The

possibility of permafrost mainly at the lower section of a scree slope has been reported by different studies (Rogger et al., 2017; Scapozza et al., 2011). It is assumed that the existence of a permafrost body in scree slopes is likely due to a chimney effect of air circulation within the coarse talus slope, leading to a cooling of the ground in the lower part of the slope (Rogger et al., 2017). If permafrost is present, it is assumed that the overall storage capacity within the scree slope might be reduced, and infiltration of precipitation and snow melt could be limited by the permafrost table (Rogger et al., 2017). However, this is challenged by the comparably high EC, constant discharge from the scree slope throughout the summer, and a stable isotope composition between the modeled winter and summer precipitation. Hayashi (2020) reports that while coarse material enabling rapid groundwater flow usually dominates, a capacity to store groundwater within scree slopes sufficiently long to allow for rock-water interaction can not be excluded. It is assumed that water could be stored in bedrock depressions filled by fine sediments, which can be released slowly (Hayashi, 2020). This aligns with findings by Scapozza et al. (2011), reporting that unfrozen sediment or bedrock is possible underneath a permafrost body within a talus slope (Scapozza et al., 2011). Similarly, Brighenti et al. (2023) found well-mixed water of different ages within the discharge of a scree slope, suggesting that relatively deep subsurface flow paths must exist within the scree slope. Since the spring from the scree slope did not dry out throughout the season, this could be an indication of the storage of groundwater with a slow release. Nevertheless, further examinations would be necessary to confirm a potential permafrost body within the scree slope and to explain the significantly higher EC.

While the discharge from the lake outflow and the ground moraine are spatially close to the ice-cored end moraine, their signatures differ significantly. Their water temperature varied strongly between July and October, reflecting the influence of seasonal air temperature patterns. Similarly, Brighenti et al. (2026) found water strongly influenced by incoming radiation with a water temperature of up to 12°C in a stream from a pro-glacial area in the Eastern Italian Alps, with strong daily and seasonal fluctuations, even though a glacier still exists in the upper part of the catchment (Brighenti et al., 2026). On the contrary, the opposite was found by Brighenti et al., 2019, with constantly low water temperatures in a moraine discharge below a glacier, which was attributed to the buffering of atmospheric temperatures through the coarse blocky deposits (Brighenti et al., 2019). Since there are no visible remnants of the former Muragl glacier, the influence of solar radiation might be even stronger in the Muragl glacier forefield. This supports the assumption of permafrost-free glacial till within the glacier forefield (Kneisel & Kaeab, 2007; Kneisel et al., 2000). The intermediate EC and a stable isotope composition that lies between winter and summer precipitation suggest a contribution of different components (Bearzot

et al., 2023). Together with an observed discharge throughout summer, it could indicate the existence of a deeper and slower groundwater system within the ground moraine, as has been found in other studies (Arnoux et al., 2020). Especially where permafrost is absent, it is assumed that water can infiltrate down to the bedrock and groundwater can flow at greater depth (Rogger et al., 2017). While the samples from the ground moraine plotted slightly above that of the global meteoric water line, that of the lake outflow was close to or slightly below, especially during the warmest period in August. This could indicate that some kinetic evaporation occurs from the lake surface. Furthermore, while no surface water inputs were observed in the field, Hayashi (2020) emphasizes that Alpine lakes can be part of a groundwater system, especially when bordered by talus slopes or moraines (Hayashi, 2020). A potential influence of the neighboring push moraine next to the lake can not be confirmed with the measured data; however, it can not be rejected either. Scapozza et al. (2019) reported that an input of meltwater into an Alpine lake can alter its chemical composition, especially in late summer. Similarly, Schreder et al. (2023) showed that the increase in EC, sulfate, and ion concentrations throughout the summer season was larger for lakes influenced by rock glaciers than in mountain lakes without rock glacier influence (Schreder et al., 2023).

Springs emerging from a slope without a clearly defined landform origin were considered exfiltrating hillslope water. However, the large variability indicates that different types of water sources are included in this group. Both streams emerging from the south-facing slope at lower elevation in the Muragl catchment had a constantly low EC and intermediate water temperature, but more depleted water, which is within the range of modeled winter precipitation (Nelson et al., 2021). This suggests that this groundwater system is mainly fed by snowmelt or winter precipitation (Munroe & Handwerger, 2023a); however, without a high amount of dissolved minerals within the water. Intermediate water temperatures are likely due to the buffering of thermal extremes in groundwater (Roesky & Hayashi, 2022). For the other streams, grouped as exfiltrating hillslope water, the isotopic signature lies between the modeled winter and summer precipitation, with low to intermediate EC and variable water temperature. These streams might represent different groundwater flows or more shallow subsurface flows.

The isotope signature for all landforms, including rock glaciers, end moraine, ground moraine, and lake outflow, lies between the modeled summer and winter precipitation (Nelson et al., 2021). This suggests similar recharge sources and reflects mixing of precipitation throughout the hydrological year (Bearzot et al., 2023; Munroe, 2018). Since all samples were taken on days with negligible precipitation, I hypothesize that the samples represent slower groundwater flows beneath the landforms. Only two streams of exfiltrat-

ing hillslope water were isotopically closer to winter precipitation, while rain resembled summer precipitation (Nelson et al., 2021). Due to the similar isotopic fingerprints for most of the samples, the water sources are indistinguishable from each other based on isotopes alone.

Between July and September, all locations underwent an enrichment in stable water isotopes, likely due to a decreasing influence of snowmelt, while the influence of summer precipitation increased (Amschwand et al., 2025; Colombo et al., 2018a; Munroe & Handwerger, 2023a, 2023b). Noticeable is the seasonal evolution in stable water isotopes, with a continuous enrichment in the landforms at higher elevation, while the measurement sites at an elevation of the rock glacier and below underwent a depletion in October. One reason for this change in pattern could be the snow in the catchment from mid-September on, which remained in the upper parts of the catchment until October. However, it is possible that it melted in the lower parts of the catchments, which could potentially have led to this more depleted isotope signal. While the isotope signature of the snow melt is not compatible with this observed depletion, the isotopic signature was only measured at one location, and therefore it can not be excluded that it was spatially variable throughout the catchment.

Both rain and snow samples had a stable isotope composition that was consistent with the summer precipitation modeled by Piso.AI (Nelson et al., 2021), and were more enriched in heavy stable isotopes than the other water sources. This is consistent with findings by other studies (Bearzot et al., 2023; Brighenti et al., 2023; Delpero et al., 2025). Despite fitting within this modeled range, the values fluctuated strongly during the summer season, which is attributed to the variable origin of air masses and temperature of the cloud formation (Delpero et al., 2025). Notably, snow samples had a higher deuterium excess, whereas rain samples tended to cluster around the global meteoric water line. The higher deuterium excess in late summer snow could be due to kinetic fractionation during the formation of ice crystals, progressive metamorphism throughout summer, and repeated thawing and freezing cycles (Brighenti et al., 2023; Delpero et al., 2025). Although there was no evidence of fractionation for the rain samples, as the samples plot close to the GMWL, it can not be excluded that the isotope signature was altered due to the sampling method, with potential evaporation from the bottle, since the water was only emptied every other week.

6.1.2 Impact of Permafrost Presence on Catchment-Scale Water Quality

The comparison of water temperature, EC, and stable isotope composition across streams with varying permafrost probabilities shows that water chemistry is governed not only by geomorphological origin but also by the presence of underlying permafrost. Naturally, these categories overlap, since permafrost is a defining feature of landforms like rock glaciers. However, it can give an indication of whether the presence of permafrost acts as a key driver for the observed chemical signatures and whether these signatures could be used to determine the presence of permafrost.

Overall, significant differences were found between streams with different permafrost likelihood for water temperature, EC, and deuterium excess. EC tended to be higher in streams influenced by permafrost, even though exceptions to this trend were observed, especially for samples across different catchments. A reason for this finding could be enhanced chemical weathering due to the contact of ice with freshly exposed minerals (Brighenti et al., 2024; Colombo et al., 2018a; Del Siro et al., 2023; Jones et al., 2019). However, Carturan et al. (2016) emphasizes that EC can not be used as a tracer of permafrost occurrence, due to overlapping EC between springs with probable and improbable permafrost, their seasonal evolution, and the dilution after precipitation events. Carturan et al. (2016) suggests that the large spatial variability in EC is rather due to topo-climatic and geologic factors, as well as their recharge from different water sources. Furthermore, different flowpaths and their variable contribution over time, varying residence time, and the activity of rock glaciers can explain the high variability also between different rock glacier discharge (Carturan et al., 2016). Nevertheless, they do not exclude the possibility of using EC for the investigation of small catchments with comparable conditions at a seasonal scale (Carturan et al., 2016), as is the case in this thesis. While the EC gradually increased for both rock glaciers over the summer season, this rise was not significantly greater than for other water sources. Different results were obtained by Carturan et al. (2016) and Bearzot et al. (2023), reporting a more remarkable increase in EC in springs with probable permafrost or from rock glacier discharge than in unaffected springs.

Stable isotope composition was comparable for streams with different permafrost occurrence, which confirms findings by Carturan et al. (2016), who concluded that the isotope signature can not be used to distinguish between streams of different permafrost likelihood due to its large temporal variability and response to rainfall events. Furthermore, a gradual enrichment in heavy stable isotopes was found within all streams between July and October. This aligns with a trend of enrichment of heavy stable water isotopes during the summer in rock glacier discharge found by different studies, which is often attributed to changing water sources from snow melt to a rising contribution of ground-

water and summer precipitation (Amschwand et al., 2025; Colombo et al., 2018a; Munroe & Handwerger, 2023a, 2023b). However, this phenomenon occurs across all water sources and in streams with likely no influence of permafrost within the Muragl and Champagna catchment. Thus, I hypothesize that this does not reflect an influence of melting ice. Furthermore, deuterium excess was significantly higher in streams with a probable permafrost likelihood. Other studies have attributed this to the process of thawing and refreezing of water (Colombo et al., 2018a; Delpero et al., 2025; Munroe & Handwerger, 2023a, 2023b).

Finally, significant differences were found between the water temperature of streams with probable or possible permafrost occurrence within their catchment compared to those with improbable permafrost. For this thesis, the potential influence of permafrost in a catchment was determined using a map of modeled permafrost likelihood by the SLF and catchment boundaries based on a DEM to group the streams into probable, possible, or improbable permafrost likelihood. However, since both the modeled permafrost distribution and the calculation of the watershed boundaries based on the DEM contain uncertainties, this already influences whether significant differences between the permafrost occurrences can be found. Another way to investigate the presence of permafrost is to analyze the water temperature within the discharge of the different landforms in late summer (Carturan et al., 2024). This approach is based on the principle that spring water influenced by permafrost is usually colder than water from unaffected sources (Carturan et al., 2024) and undergoes little seasonal and inter-annual variability (Carturan et al., 2016). Typically, an upper threshold of 0.9 - 1.1°C indicates probable permafrost, while temperatures between 1.8 - 2.2°C suggest possible permafrost conditions (Carturan et al., 2024). However, a source of uncertainty is the distance between the permafrost body and the measurement point. Since water temperature is not a conservative tracer, it is subject to changes through heat exchange with unfrozen sediment, input of warmer water sources, or warmer groundwater paths that are not in direct contact with permafrost (Carturan et al., 2016; Carturan et al., 2024). Carturan et al. (2024) indicates that water temperature can be modified even within a few tens of meters downstream (Carturan et al., 2016). This could lead to a false-negative classification of permafrost presence (Carturan et al., 2024). For this thesis, the automatic stations required a deep enough water level to function correctly. Consequently, the stations were placed several meters downstream from the initial point of emergence of a spring. To quantify the changes in water temperature, a continuous temperature logger was additionally placed at the primary discharge point of the end moraine. At the source, temperatures remained stable between 1.15-1.25°C, with a minimal diurnal amplitude (<0.1°C). Approximately 25 meters downstream, the same stream had fluctuations between 0°C and 5°C, with diurnal amplitudes of up to 3°C. This represents a shift in water temperature of +4°C to -1°C over just 25 meters,

highlighting that the proximity to the emergence point is critical to assess the occurrence of ice correctly, and that these thresholds can only be applied if the sensor is close enough to the emergence of the spring.

For the Muragl rock glacier, with confirmed permafrost within, water temperatures between 1.3 and 2.4 °C were measured throughout the season at approximately 28 meters distance from its first emergence. According to the above-mentioned threshold, this would result in a classification of probable permafrost based only on water temperature in late summer, which is the ideal measurement window suggested by Carturan et al. (2024). Similarly, Carturan et al. (2024) found water temperatures of up to 3.5°C downstream of active rock glaciers, suggesting that the upper limit of spring-water temperature might be higher for possible and probable permafrost. This is why I suggest that if multiple measurements are made throughout the summer, the classification of permafrost likelihood should not only be based on one measurement in late summer, but rather on the assessment of the stability of water temperature throughout the summer season.

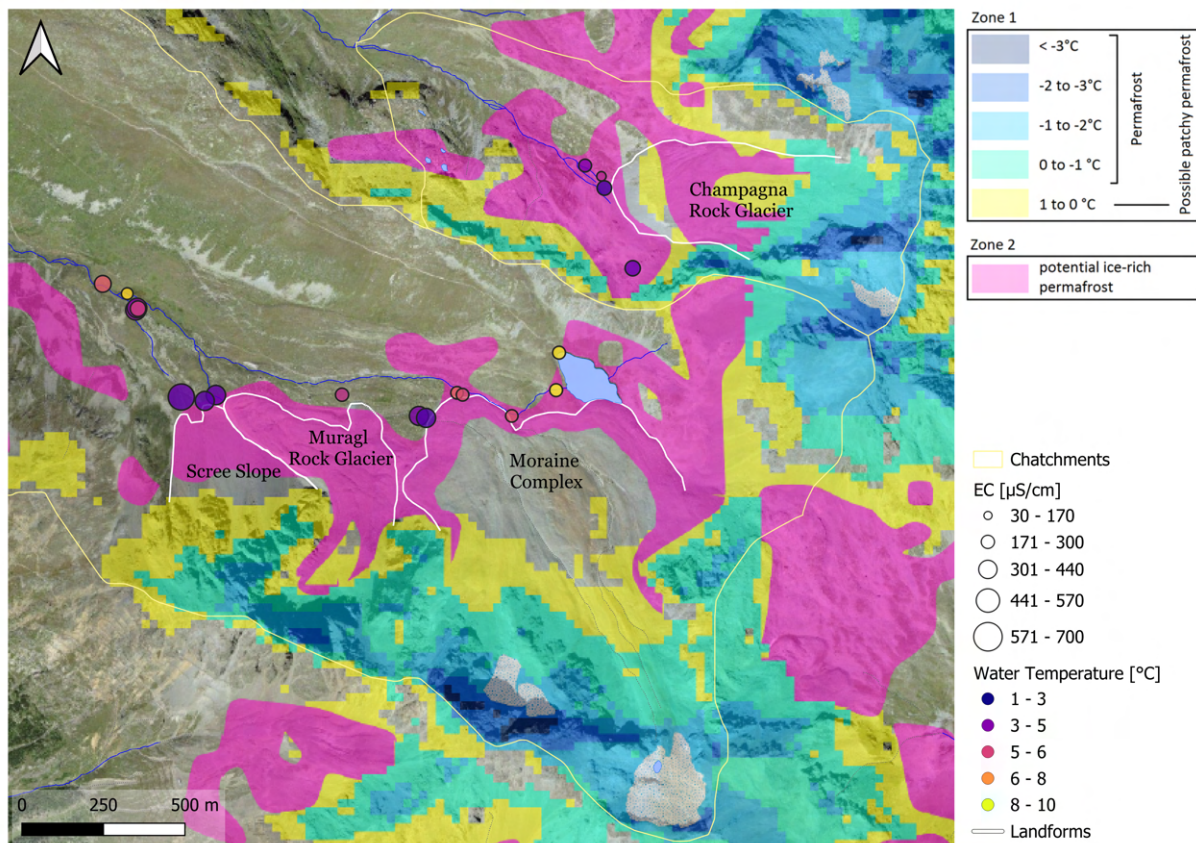


Figure 49: Combination of the permafrost map by SLF and the measured water temperature and EC within the streams (Kenner et al., 2019; SLF, 2025).

A comparison of the classification through the permafrost map with the water temperature within the stream overall confirms the general patterns within the permafrost map, as illustrated in Figure 49. The water temperatures are constantly low in front of both rock glaciers, but also in the discharge of the scree slope, all marked with ice-rich permafrost on the map. Different studies have found low temperatures from both active, inactive, and in certain cases even relict rock glaciers (Carturan et al., 2024; Winkler et al., 2016). A possible explanation for this observation might be that while relict rock glaciers are defined by the absence of internal ice, some relict rock glaciers may preserve isolated permafrost and ice patches far below the regional lower limit of discontinuous permafrost. Consequently, they might appear visually relict, but still contain patches of permafrost and thus should be classified as pseudo-relict (Carturan et al., 2024).

For the end and ground moraine, the measurements show a more nuanced image, with large differences between spatially nearby streams. While the margins of the moraine complex are marked with ice-rich permafrost, water temperature measurements confirm contact with cold conditions in the section of the end moraine close to the rock glacier. Further towards the lake, where the water emerges from the ground moraine, the water is warmer, and the temperature fluctuates more strongly throughout the summer season, suggesting no direct contact with permafrost. This supports findings by Kneisel et al. (2000) and Kneisel and Kaeaeb (2007), assuming either improbable permafrost occurrence, or possible shallow permafrost within the ground moraine that might undergo permafrost degradation (Kneisel & Kaeaeb, 2007; Kneisel et al., 2000).

The lake, which lies directly next to the push moraine, where an ice core was detected by previous geophysical methods by Kneisel and Kaeaeb (2007), has higher water temperatures with large seasonal fluctuations. However, similarly high water temperatures were also found by Colombo et al. (2018a) in a pond directly fed by a rock glacier and thus do not exclude permafrost occurrence in its catchment. In the Champagna catchment, continuously cold water was found both in the discharge of the rock glacier and in some, but not all, of the exfiltrating hillslope water. According to the map, all of these measurement stations lie within an ice-rich permafrost region. This underscores that, next to the thermal phenomena, the water source or its geomorphological origin should not be neglected for understanding the hydrochemistry within streams.

Since permafrost is a thermal phenomenon, the map does not distinguish between glacial or periglacial origin of the ice, but only if temperatures are cold enough that ice can exist. A comparison of the catchments of the streams with this map can therefore give an insight into a potential contact of water with cold conditions; however, it does

not differentiate between periglacial or glacial origin. A classification of the likelihood of permafrost within the catchment thus indicates a mixed signal of permafrost and glacial influence. To be able to determine the influence of geomorphological landforms on the downstream system, it seems reasonable to investigate both the thermal phenomena of permafrost and its influence on water chemistry, as well as the influence of geomorphological landforms in altering these variables.

6.2 Temporal Evolution of Hydrochemistry Throughout the Summer Season

The importance of geomorphological landforms on the storage and discharge pattern is further highlighted by the seasonal and diurnal patterns observed within its discharge. While seasonal trends are comparable between rock glaciers and the end moraine, the diurnal patterns differ.

6.2.1 Seasonal Variation in Water Quality as an Indicator of Alpine Water Sources

The seasonal trends of water temperature, EC, water level, and stable isotope composition can give insights into the changing water sources over the summer season, with varying contributions of melting snow, precipitation, melting rock glacier ice, and groundwater (Jones et al., 2019; Munroe & Handwerger, 2023a). The seasonal patterns between July and October 2025 for the discharge of the rock glaciers, end moraine, and the downstream location are summarized in Table 22.

Table 22: Summary of the seasonal variation in water temperature, EC, and water level of the rock glaciers, end moraine, and a downstream location between July and October 2025.

	Rock glaciers	End moraine	Downstream mixing
Water temperature	↔ stable and cold	↔ stable and cold	↑↓ variable
EC	↑ rising	↑ rising	↑ slightly rising
Water level	↓ decreasing	↔ stable	↓ slightly decreasing

Within the study area, both rock glaciers and the end moraine had comparable seasonal trends in water level, EC, and water temperature, typically attributed to a seasonal transition of dominant water sources (Jones et al., 2019). The highest discharge in rock glacier springs is usually measured during snow melt in spring and early summer (Bearzot et al., 2023; Brighenti et al., 2019; Geiger et al., 2014; Jones et al., 2019; Krainer &

Mostler, 2002; Wagner et al., 2021). This phenomenon could not be captured in this thesis due to the installation of the instruments after most of the snow had already melted. When starting the measurements in mid-July, only a few small snow patches were visible in the catchments. Nevertheless, the melting of remaining snow in shaded areas can not be excluded (Munroe & Handwerger, 2023a). From mid-July on, both rock glaciers had a similar trend of rising EC, decreasing water level, and an enrichment of stable water isotopes towards October. This pattern has been described in discharge of different rock glaciers (Amschwand et al., 2025; Bearzot et al., 2023; Brighenti et al., 2019; Carturan et al., 2016; Del Siro et al., 2023; Geiger et al., 2014; Krainer & Mostler, 2002; Louis et al., 2025; Munroe & Handwerger, 2023a; Reato et al., 2022; Thies et al., 2013; Wagner et al., 2021) and has been attributed to a changing contribution of different sources: while snow melt, with low EC and depleted in heavy isotopes, dominates in early summer, its influence declines over the summer season (Amschwand et al., 2025; Carturan et al., 2016; Colombo et al., 2018a; Del Siro et al., 2023; Jones et al., 2019; Louis et al., 2025; Munroe & Handwerger, 2023a; Wagner et al., 2021). The contribution of groundwater, with comparably higher EC and intermediate isotope signature, becomes more prominent in late summer (Brighenti et al., 2019; Colombo et al., 2018a; Geiger et al., 2014; Jones et al., 2019; Louis et al., 2025). However, the composition of groundwater itself can change through snow melt and rainwater that percolates and recharges deeper groundwater flow as well (Del Siro et al., 2023; Reato et al., 2022). This trend is interrupted by precipitation events, usually with rainwater containing low EC and being relatively enriched in heavy stable isotopes (Colombo et al., 2018a; Geiger et al., 2014; Jones et al., 2019; Louis et al., 2025). Furthermore, the influence of chemical weathering of freshly exposed minerals and the melt of solute-enriched ice in rock glaciers are possible reasons for the seasonal increase in EC (Brighenti et al., 2019; Del Siro et al., 2023; Delpero et al., 2025; Geiger et al., 2014; Jones et al., 2019; Munroe & Handwerger, 2023a; Reato et al., 2022). However, the contribution of ice melt from the rock glacier core is assumed to be small, since the active layer acts as a thermo-hydrological buffer that protects the ice core to a certain extent (Amschwand et al., 2025; Bearzot et al., 2023; Brighenti et al., 2026; Jones et al., 2019). Nevertheless, Seelig et al. (2026) proposed that preferential flow paths within the rock glacier might be able to transport heat deeper into the rock glacier, potentially enabling permafrost thaw and internal ice melt.

While some studies report the drying of rock glacier springs during the summer, except for high discharge during precipitation events (Amschwand et al., 2025; Geiger et al., 2014), this was not observed at the Champagna and Muragl rock glaciers. The observed constant baseflow during dry periods supports the assumption of different flow paths within the rock glacier, with a slow flow component sustaining baseflow over a longer

period, and a fast flow component that responds quickly to precipitation events and snow melt (Hayashi, 2020; Jones et al., 2019; Seelig et al., 2026; Wagner et al., 2020, 2021). The finding of a permeable unfrozen layer underneath the ice core of the Muragl rock glacier during the drilling of the 1999 boreholes (Springman et al., 2012) supports the presence of a slow flow component beneath the permafrost ice. This slow flow is assumed to have a longer residence time and take place in an area with a high storage capacity (Seelig et al., 2026), which would align with the measured stable water isotope composition between modeled winter and summer precipitation (Nelson et al., 2021).

The discharge from the end moraine was characterized by a similar pattern of rising EC and steady enrichment of heavy stable water isotopes throughout the season, interrupted by short periods of dilution after heavy precipitation events. As for the rock glacier discharge, Roy and Hayashi (2009) hypothesized that there is a change in the contribution of different water sources, from snow melt in the early melt season in shallow flow paths, to discharge dominated by a less responsive groundwater flow through and over the bedrock (Roy & Hayashi, 2009). The water level, in contrast, did not decline as observed in the rock glaciers but remained at stable levels throughout the summer season. Roy and Hayashi (2009) reports similar patterns, with a steady or even increasing flow during rain-free periods, and only short peaks in water level after precipitation events. However, the reported rising water levels could be influenced by glacial melt and a lake in the catchment (Roy & Hayashi, 2009), and thus these results may not be comparable to the conditions in the Muragl catchment, where no remnants of the Muragl glacier are visible. Similarly to the rock glaciers, McClymont et al. (2011) found a deeper groundwater flow over the bedrock underneath the moraine, combined with the possibility of flow through a network of fractures within the shallow bedrock when investigating the internal structure of an ice-cored moraine in the Canadian Rockies. Additionally, shallow flow on top of buried ice and bedrock was detected, leading to the assumption that melting snow or rainwater is confined to the top of the ice, leading to a shallow, fast-response flow system through the moraine (McClymont et al., 2011). Where there is no ice present in the moraine complex, it is hypothesized that melting snow and rain infiltrate to the base of the bedrock, where it flows within a saturated layer of sediment or potentially within fractured bedrock (Hayashi, 2020; McClymont et al., 2011). Thus, Hayashi (2020) concludes that the two-phase recession, with fast recession after snow melt and precipitation events, followed by a sustained discharge over a longer period, could be controlled by the internal structure of these landforms. Langston et al. (2011) and Hayashi (2020) further suggest that the saturated layer at the boundary between moraine and bedrock accounts for a large amount of groundwater, providing capacity for temporary storage that contributes to the baseflow of Alpine streams. Similarly, Brighenti et al. (2026) found a large amount

of runoff from moraine springs, which they attributed to groundwater pathways that store and slowly release water to river networks. Furthermore, these deeper groundwater flow pathways could have a different chemical signature than the shallow flow paths due to their longer residence time and opportunity to interact with rocks (Hayashi, 2020).

Overall, the seasonal evolution of water level, EC, and stable water isotope composition seems to be mainly influenced by a changing contribution of snowmelt, rainwater, ice melt, and groundwater (Amschwand et al., 2025; Jones et al., 2019). The continuous discharge and fast response after rainfall events support the assumption of different flow paths within the rock glaciers and the end moraine, with a deeper groundwater flow, sustaining baseflow over the summer season, and faster, more shallow flow on top of the ice (Hayashi, 2020; Jones et al., 2019; Langston et al., 2011; McClymont et al., 2011; Seelig et al., 2026; Wagner et al., 2021).

6.2.2 Diurnal Discharge Cycles as Indicators of Internal Structure

While the seasonal pattern is caused by different contributions of water sources, diurnal variations offer deeper insights into the short-term storage within different landforms (Jones et al., 2019). Within the Muragl catchment, different diurnal cycles were found for the rock glacier and the end moraine. Figure 50 shows an overview of the diurnal patterns during dry periods for each month between July and October for the different measurement locations.

The diurnal variability within rock glacier discharge is influenced by local weather conditions, the thermal conditions within the active layer, as well as physical mechanisms that determine the flow of meltwater through a rock glacier (Jones et al., 2019). The largest diurnal runoff cycles are usually found in the snow melt season, where the melting of snow leads to a peak discharge and minimum EC in the late evening due to the dilution of the discharge through snow melt (Brighenti et al., 2021a; Del Siro et al., 2023; Geiger et al., 2014; Jones et al., 2019; Louis et al., 2025; Wagner et al., 2021). Since the snow melt season occurred before the start of the measurements for this thesis, these diurnal cycles could not be recorded. After a peak of snow melt, it is assumed that the contribution of snow melt decreases, while the contribution from groundwater baseflow increases (Jones et al., 2019; Louis et al., 2025). Similarly to the snow melt season, multiple studies report an inverse diurnal relationship with a minimum in EC simultaneously with a peak in discharge, which is hypothesized to be due to a dilution effect of ice melt compared to higher EC of groundwater (Amschwand et al., 2025; Del Siro et al., 2023; Louis et al., 2025; Wagner et al., 2021). While it is assumed that the majority of melt during a warm summer period originates from the active layer (Amschwand et al., 2025; Brighenti et al.,

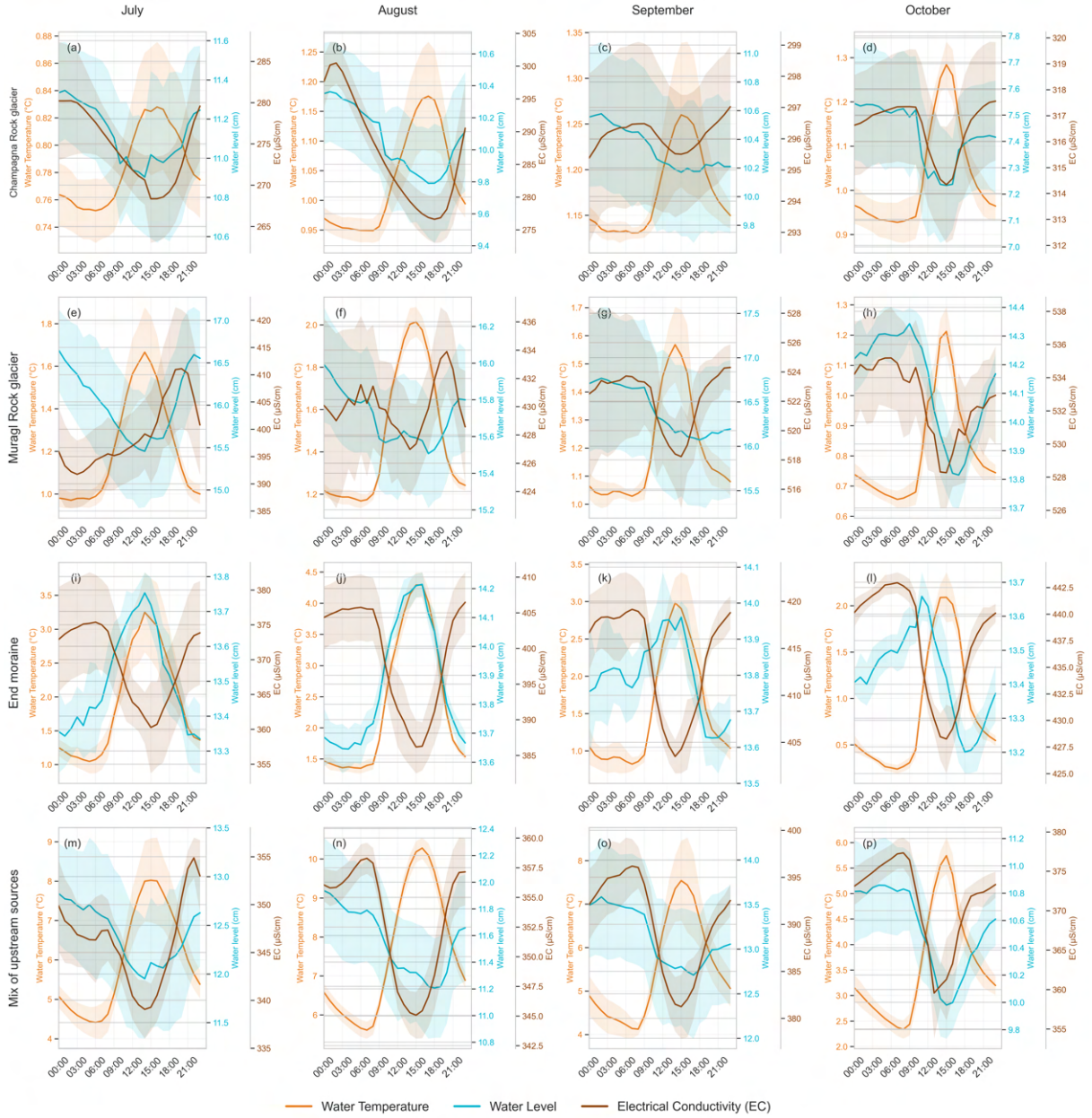


Figure 50: Diurnal pattern in water temperature, EC, and water level for both rock glaciers, the end moraine, and the downstream mixing location for the periods of 15.07.2025 - 19.07.2025, 09.08.2025 - 13.08.2025, 16.09.2025 - 20.09.2025, and 10.10.2025 - 15.10.2025. These periods were chosen based on the absence of precipitation during these days. The line represents the mean, and the shading represents the standard deviation. Note that y-axis scales are optimized for each subplot to highlight the relationship between variables; therefore, absolute magnitudes should not be compared directly across different plots.

2023; Louis et al., 2025), it is possible that, especially during late summer and fall, melt from the permafrost core could occur, even though it is assumed to contribute only a small amount of the total discharge of a rock glacier (Del Siro et al., 2023; Louis et al., 2025; Moradi et al., 2024). In contrast to these findings of previous studies (Amschwand et al., 2025; Del Siro et al., 2023; Louis et al., 2025; Wagner et al., 2021), a predominantly direct relationship between water level and EC was observed throughout the summer season in the Champagna rock glacier (Figure 50, a - d), and in September and October in the Muragl rock glacier (Figure 50, g - h). The time lag between peak water temperature and water level was approximately 7 - 10 hours in July and August, and is comparable to what is found in other studies (Del Siro et al., 2023; Krainer & Mostler, 2002). In September and October, it peaked at a similar time, but remained high for several hours (Figure 50, c - d and g - h). This time lag between peak temperature and water level is attributed to the longer flow paths in rock glaciers compared to other landforms (Colombo et al., 2018a).

A hypothesis for this simultaneous peak of EC and water level might be a high EC of the permafrost core, together with flow paths enabling solute transport within the rock glacier. While some studies report or assume low-EC ice within the permafrost ice, potentially leading to this dilution during peak discharge, different studies have measured a high EC of up to $1500\mu\text{S}/\text{cm}$ within the perennial rock glacier ice (Delpero et al., 2025; Nickus et al., 2023). The analysis of ice within the rock glacier collected during the drilling of the new boreholes in the Muragl rock glacier indicated a high EC, comparable to or slightly lower than the EC measured in the discharge (Personal Communication with Annegret Udke, WSL, 2026). Seasonal ice within the active layer is reported to have comparatively less solutes and an EC comparable to precipitation or snowmelt of $10 - 150\mu\text{S}/\text{cm}$ (Delpero et al., 2025). Nevertheless, Delpero et al. (2025) found a higher EC also within the supra-permafrost runoff (293 and $1027\mu\text{S}/\text{cm}$ for supra-permafrost runoff on two different rock glaciers in the Eastern Italian Alps, respectively). Thus, the positive correlation between discharge and EC may be explained by the melting of high-EC ice or supra-permafrost runoff, especially during late summer, when more melting is expected. The internal flow paths of the rock glacier could further influence these patterns. While a relatively massive ice core is assumed in some rock glaciers (Amschwand et al., 2025), others report a mixture of ice and debris, and potentially ice-free layers (Nickus et al., 2023). At the Muragl rock glacier, a large heterogeneity and a rather low ice content of $40 - 70\%$ with warm ice close to 0°C were found during the drilling of the 1999 boreholes (Arenson et al., 2002). The presence of water within the Muragl rock glacier (Hochstrasser, 2025) might indicate that the permafrost ice does not act as an aquitard, but that intra-permafrost flow is possible, which could potentially enhance the export of solutes, leading to a high EC. Different studies assume that preferential fast flow not only occurs on top

of the permafrost table, but might extend into the permafrost core, where it enables rapid internal flow (Seelig et al., 2026; Wagner et al., 2021). Furthermore, this aligns with findings by Mutter and Phillips (2012), describing the formation of a seasonal talik between June and October in the Rittigraben rock glacier, with a well-developed open drainage channel and presence of water flowing through the permafrost body. Consequently, the elevated EC in the discharge may result from melting and subsequent flushing out of solute-rich ice within the rock glacier. This hypothesis is further supported by the short EC peaks observed following precipitation events in the Muragl rock glacier, particularly from September onward. Similarly, Moradi et al. (2024) hypothesized that freezing and thawing within the sediment-ice mixture in the core of a rock glacier leads to enrichment of solutes within the ice. During warm periods, a water film with enriched solutes could form, which can be flushed out through snowmelt or precipitation (Moradi et al., 2024).

The role of permafrost depth and intactness on the hydrology of a rock glacier is further discussed by Bearzot et al. (2023). Applying dye tracer tests on two neighboring rock glacier lobes with different internal structures suggested more direct runoff on intact ice cores, while more water infiltrated into deep groundwater storage in rock glaciers characterized by low ice content and heterogeneous permafrost distribution (Bearzot et al., 2023). Thus, discontinuous permafrost can allow for water movement, increase hydraulic permeability, and support infiltration and recharging of groundwater (Amschwand et al., 2025). However, this potential infiltration might also suggest another hypothesis for the direct relationship between EC and discharge. The response of the groundwater system to melting snow or ice could lead to a pushing out of higher EC groundwater when melting occurs, or changes in the mixing of different groundwater components. Thus, the higher EC might not be caused by high EC in the melt water itself, but by a pushing out of high-EC groundwater through melting ice. These mechanisms have been discussed as potential reasons for a positive EC - discharge relationship in a moraine complex by Roy and Hayashi (2009). However, it must be noted that the circumstances within this catchment with a glacier, a lake, and a moraine complex are very different to that in the Muragl catchment. Similarly, Harrington et al., 2018 assumed that infiltration of surface water in an inactive rock glacier increases the hydraulic gradient, which leads to a displacement of deeper groundwater. The displacement of groundwater by infiltrating ice melt is further suggested by the declining EC during prolonged dry periods, particularly within the Muragl rock glacier. However, the current dataset remains insufficient to validate these hypotheses, and more extensive and longer observations would be needed, or direct measurements of the EC in supra-permafrost runoff.

Furthermore, Louis et al. (2025) suggests that the amplitude of diurnal EC variation might give insights into the intensity of dilution from the rock glacier melt (Louis et al., 2025). The higher amplitude of diurnal EC variation in the Champagna rock glacier during warm and dry periods between July and August (Figure 50, a - b), followed by smaller diurnal variations in September and October (Figure 50, c - d), could support such an interpretation. In the Muragl rock glacier, on the contrary, no trend in diurnal amplitude throughout the season was observable (Figure 50, e - h). Instead, the diurnal variation was similar throughout the summer season.

Still, there seems to be a seasonal evolution in the timing of the diurnal EC pattern in the Muragl rock glacier. There was a shift of the minima in EC from 03:00 in the morning in July (Figure 50, e), to two daily minima in August (Figure 50, f), to a more direct relationship of EC and water level with a minimum around 15:00 from September on (Figure 50, f - g). One hypothesis for this change in diurnal pattern throughout the season could be a changing contribution of different sources (Wagner et al., 2021), from a snow melt-dominated diurnal pattern with an inverse relationship between EC and water level, as found by Geiger et al. (2014) and Wagner et al. (2021), to a more groundwater or ice melt-dominated cycle in late summer. Another explanation could be a changing contribution or timing of discharge from shallow or deep flow paths, for instance, due to a thickening of the active layer. However, conflicting trends have been found concerning this time lag. Louis et al. (2025) reports a decreasing time lag over the summer season between diurnal maxima in air temperature and minima in EC, which they attributed to shorter flow paths due to a thickening of the active layer throughout the melt season, as well as more preferential flow paths that might be formed (Louis et al., 2025). However, other studies, in contrast, suggest that a progressive thawing of ice during the melt season could increase infiltration, leading to longer flow pathways within the rock glacier (Buchli et al., 2013; Del Siro et al., 2023). Since no measurements were conducted during the snow melt season, these hypotheses can not be confirmed. Future measurements, preferably throughout the whole year, could give insight into a potential change in diurnal patterns, which could indicate a contribution from different sources. Overall, it must be noted that due to the uncertainty of the sensor itself, as well as noisy measurements for the sensor in front of the Muragl rock glacier, an interpretation of this diurnal pattern is difficult.

Based on the assumption and interpretation of the observed seasonal and diurnal patterns of the rock glacier, a simplified conceptual model is presented in Figure 51. It is hypothesized that there are multiple flow paths: a deeper groundwater flow with a slower response time in the unfrozen till beneath the rock glacier and/or in fractured bedrock underneath, which maintains a baseflow throughout the summer season. Additionally,

a faster response through more shallow flow paths, with supra-permafrost flow above or within the active layer, and intra-permafrost flow (Jones et al., 2019) that could potentially be active during thawing on warm and dry days. These extensive, complex pathways likely delay response times. The relative importance of different water sources and flow paths might shift throughout the summer season. While snow melt dominates in early summer, rainwater and groundwater become more dominant towards late summer. Seasonal ice begins to melt and flow paths open, which brings meltwater in contact with weatherable minerals. On a diurnal scale, flushing of solute-rich melt water or the pushing out of groundwater through snow melt could occur during warm periods, leading to this positive EC - discharge relationship.

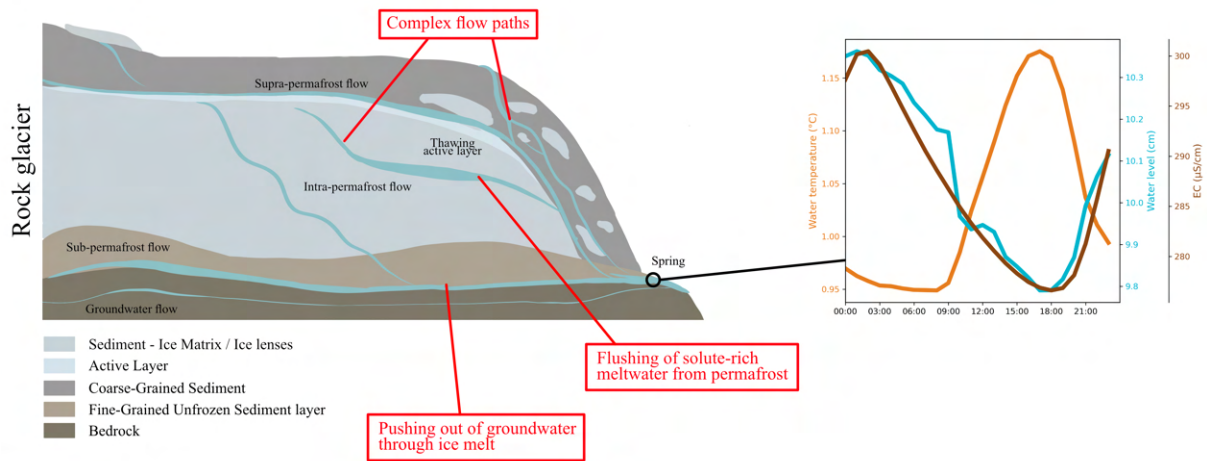


Figure 51: Sketch of a hypothetical model of the hydrological flow paths through the rock glacier on a warm and dry day in August (own Figure based on a Figure by Jones et al., 2019).

The end moraine had a different diurnal cycle, characterized by a water level peak in the afternoon and a corresponding minimum in EC from July through September (Figure 50, i - k). By October, the timing of the water level peak shifted to the late morning (Figure 50, l), whereas the timing of the EC minima remained consistent throughout the season. A potential explanation for the peak water level near-simultaneously with a peak in water temperature might be a shorter flow path and thus faster response time than in the rock glacier. A fast response of shallow groundwater flow over buried ice found by McClymont et al. (2011) within a moraine complex in the Canadian Rockies, which could support this hypothesis. Furthermore, the faster response may potentially be due to a more intact ice core, which could be supported by higher flow velocities found on continuous ice bodies (Bearzot et al., 2023; Hayashi, 2020). The inverse relationship between discharge and EC resembles those described for rock glaciers, which is attributed to the dilution of groundwater through melting ice (Amschwand et al., 2025; Del Siro

et al., 2023; Louis et al., 2025; Wagner et al., 2021). One hypothesis might be that the end moraine contains less solute-rich ice compared to the rock glaciers due to its origin from glacier ice. This hypothesis could be supported by less solute-rich water found in glacier discharge compared to rock glacier discharge (Crespo et al., 2017; Delpero et al., 2025; Jones et al., 2019). Alternatively, the melting may occur within seasonal ice, which is reported to contain less solutes (Delpero et al., 2025). However, to confirm this hypothesis, samples from the ice within the end moraine would be needed.

A simplified conceptual model of these interpretations is shown in Figure 52. The stable discharge over the season could be due to a constant deep groundwater flow with higher solute concentrations. Compared to the rock glacier, the shallow flow paths over the ice core might be shorter, and preferential flow on top of the ice might lead to a fast response time. Melting of ice with lower EC, either of the ice core itself or the seasonal ice, could lead to a dilution during peak discharge on a diurnal scale.

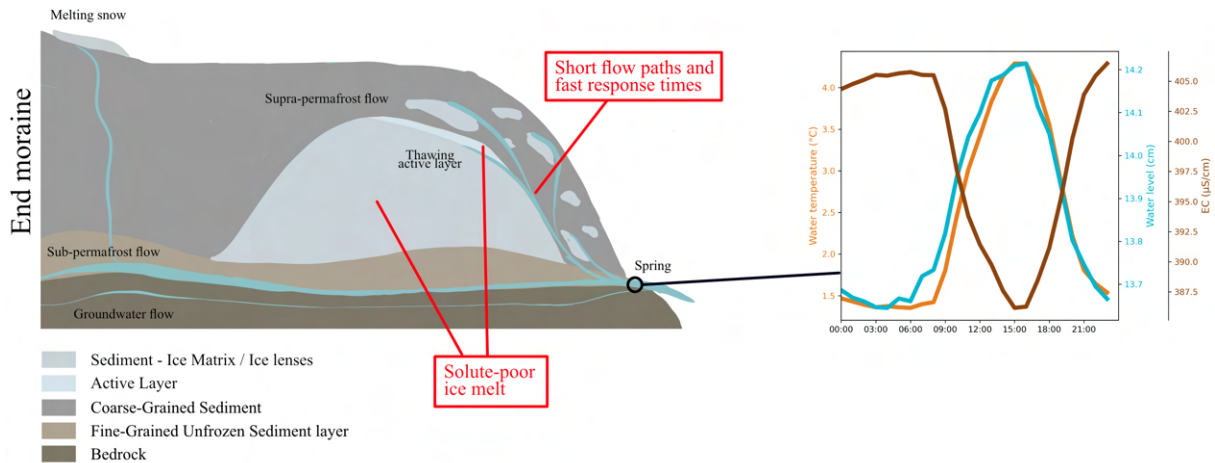


Figure 52: Sketch of a hypothetical model of the hydrological flow paths through the end moraine on a warm and dry day in August (own Figure).

Overall, it is hypothesized that the diurnal patterns might be governed by a complex interplay of internal system and flow paths (Bearzot et al., 2023; Hayashi, 2020), and that the response might be influenced by the extent of permafrost and total ice content within the landform (Bearzot et al., 2023), and potentially the origin of ice melt and with it the solute concentrations within the ice (Bearzot et al., 2023; Delpero et al., 2025). However, the interpretation of these patterns is subject to significant uncertainties and relies on several unverified assumptions. Consequently, more research would be needed to confirm the discussed hypotheses and to investigate the underlying mechanisms and processes. Nevertheless, the distinctly different diurnal patterns within the same catchment highlight the unique hydrological signatures of different landforms and highlight the necessity for more detailed investigations.

6.2.3 Responses to Precipitation Events

Not only the diurnal patterns during warm periods, but also the reaction of the landforms to precipitation events can give insights into the internal structure of a landform. Both rock glaciers, the end moraine, and the downstream location with different water sources were characterized by a similar response to precipitation events: a rising water level and a synchronous drop in EC. These reactions are illustrated in Table 23.

Table 23: Summary of the hydrological response of the rock glaciers, end moraine, and a downstream location to precipitation events.

	Rock glaciers	End moraine	Downstream mixing
Water temperature	$\leftrightarrow\downarrow$ Stable or decrease	$\uparrow$ Increase or decrease (rain/snow)	$\leftrightarrow\downarrow$ Stable or decrease
EC	$\downarrow$ Within multiple hours	$\downarrow$ Within a few hours	$\downarrow$ Multiple minima
Water level	$\uparrow$ Within multiple hours	$\uparrow$ Within a few hours	$\uparrow$ Multiple peaks

While the overall pattern is the same for all observed landforms, the response and recovery times differed between the landforms. Both rock glaciers were characterized by a time lag of multiple hours between the peak precipitation and peak discharge. A delay between the main precipitation event and discharge peak of rock glacier discharge was reported by various studies: between 6 hours to 1 days after rainfall events, and up to 3 days after snowfall by Colombo et al. (2018a), a few hours after a precipitation event by Krainer and Mostler (2002), or 2 - 9 hours for different streams leaving the same rock glacier by Geiger et al. (2014). Colombo et al. (2018a) suggests that these variable response times for different rock glaciers of hours to several days could be due to internal characteristics of these rock glaciers, such as the properties of internal ice, the composition of sediments, their hydraulic conductivity, or the thickness of the active layer. Compared to non-rock glacier catchments, the flood peaks tend to occur later in rock glacier discharge (Geiger et al., 2014). The rise in water level is accompanied by a drop in EC. The dilution effect of a stream through precipitation has been observed in different catchments with periglacial landforms and has been attributed to the influence of low EC rainwater (Amschwand et al., 2025; Carturan et al., 2016; Del Siro et al., 2023; Louis et al., 2025). However, the opposite reaction has been recorded as well in rock glacier ponds, with rising EC in the discharge of a rock glacier following rainfall events, which was assumed to be due to the export of solutes released by thawing of the internal sediment-ice matrix and subsequent

flushing out due to the rainwater (Brighenti et al., 2021a; Colombo et al., 2018a). The reaction of the EC occurred approximately two hours after a peak in water level. A potential explanation for the delayed response might be that EC is mainly affected by mixing of water with higher and lower solute content after an increase in spring discharge (Winkler et al., 2016), whereas the discharge depends on the pressure response (Beven, 2012; Michelin et al., 2023). Another indication of the previously discussed displacement of pre-event water could be the short peak in EC observed mainly in the Muragl rock glacier shortly after the onset of the dilution, followed by a steep drop in EC after precipitation events. A similar spike in EC after precipitation events was also briefly mentioned for the Murtèl rock glacier (Amschwand et al., 2025). Similarly, Colombo et al. (2018a) assumes that due to the intensification of water percolation through the rock glacier, the export of solutes could be enhanced. Thus, one hypothesis could be that the deepening of the active layer or thawing of perennial ice releases more solute-rich water, which is pushed out after precipitation events. The tendency for an increase in these peaks towards the end of the summer season for the Muragl rock glacier could support this hypothesis. The recovery time back to pre-event values can last over several days for both the water level and EC, which is comparable to time scales found by Geiger et al. (2014) who reported 15 - 40 hours until a normal baseflow is reached. Furthermore, for most precipitation events, a stable or even decrease in water temperature within the rock glacier discharge was recorded. Similar observations were made in the discharge of other rock glaciers, with stable or decreasing water temperatures after the infiltration of warm rainwater, even though the discharge increased strongly (Colombo et al., 2018a; Harrington et al., 2018; Krainer & Mostler, 2002). It is assumed that this export of cold water is due to the contact of water with melting ice within the rock glacier (Colombo et al., 2018a; Krainer & Mostler, 2002). However, it must be noted that the reactions, response, and recovery times vary for each precipitation event during the recorded period, depending on intensity and duration (Jones et al., 2019), but also if precipitation falls as snow or rain (Colombo et al., 2018a). Colombo et al. (2018a) noted that snowfall and subsequent melting of snow can significantly delay the discharge peaks (Colombo et al., 2018a). However, to confirm these patterns, a longer time span of measurements would be necessary, preferably over multiple years.

These inferences are summarized in a conceptual model of the hydrological flow paths and their response to precipitation events in Figure 53. It is assumed that the complex contributions from different flow paths lead to a delayed response to precipitation of multiple hours. A flushing out of solute-rich water on top or within the active layer, as well as within intra-permafrost flow, could lead to a peak in EC, followed by a dilution through rainwater. Afterwards, there is a slow return to groundwater baseflow.

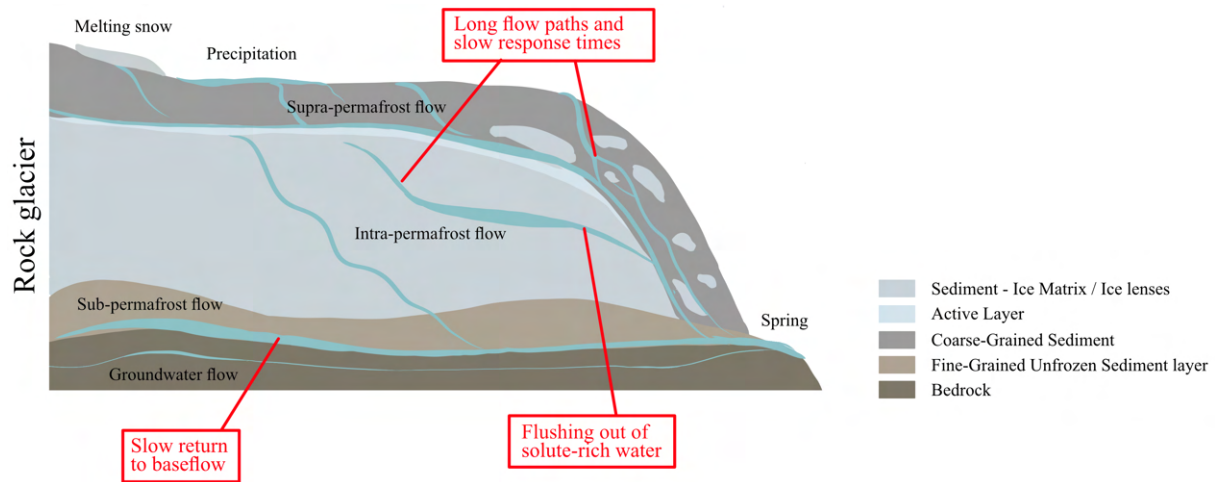


Figure 53: Sketch of a hypothetical model of the hydrological flow paths through a rock glacier and its response to a precipitation event (own Figure, based on a Figure by Jones et al., 2019).

The end moraine, in contrast, reacted more quickly with a short response time and a return to pre-event values within a few hours. This aligns with findings by Roy and Hayashi (2009), who measured a rapid increase of the water level with a delay of 3 to 6 hours from peak rain to peak groundwater discharge in a moraine complex in the Canadian Rockies, followed by a fast decline. This could support the previously discussed assumption of a contribution from shorter and shallower flow paths, and a higher direct surface-runoff component (Bearzot et al., 2023), before returning to its usual baseflow. Similarly, Roy and Hayashi (2009) hypothesized that this fast response to rainfall events could indicate rapid infiltration of rain and snow melt, suggesting a shallow subsurface flow system in this landform. They further assumed that the buried ice within the moraine might function like a funneling mechanism, rapidly directing percolating water towards the springs, especially since the water temperature was constantly below 1°C (Roy & Hayashi, 2009). This aligns with the assumption of the existence of preferential flow paths on top of the ice, leading to a fast response (Seelig et al., 2026). A flashy response with little delay after rainfall events has also been observed at the Murtèl rock glacier, where ice-rich permafrost limits the storage and retention of liquid water (Amschwand et al., 2025). Although the conditions of the end moraine are not directly comparable with those of a rock glacier, this might support the assumption that the ice core constrains flow to shallow, rapid pathways. Similarly, Bearzot et al. (2023) showed a faster response in a rock glacier with a more intact ice core compared to one with major unfrozen layers, which delayed runoff and led to a longer residence time (Bearzot et al., 2023). Another indication for a shorter flow path might be the simultaneous peak in water level with a minimum in EC, and an increase in water temperature at the same time during some, but not all, of the precipitation events.

The reaction of the discharge to precipitation events supports the previous findings and is shown in a simplified conceptual model in Figure 54. The ice core of the moraine could lead to fast, shallow flow with a short response time, which leads to a simultaneous water level rise and decline in EC through rainwater. Where no ice is present, the precipitation could infiltrate into the groundwater. The discharge then returns quickly to a stable groundwater baseflow.

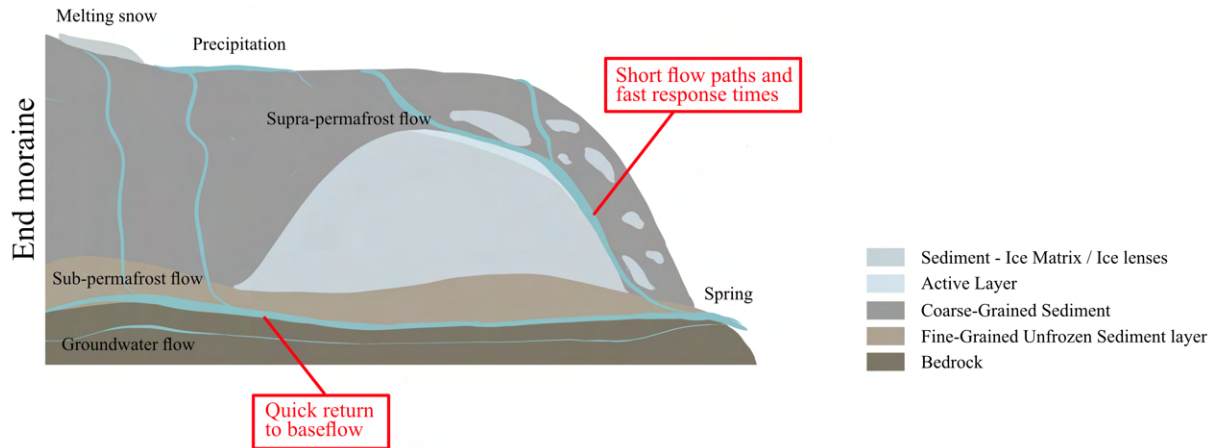


Figure 54: Sketch of a hypothetical model of the hydrological flow paths through an end moraine and its response to a precipitation event (own Figure).

Notably, the intensity of the rainfall event appears to be more important for the shift in hydrochemistry than the total duration of the rainfall, since high-intensity precipitation events seem to trigger a larger rise in water level and drop in EC. This observation is supported by Jones et al. (2019), who suggested that the stormflow of a catchment is rather determined by precipitation intensity than volume. At the Murtèl rock glacier, it was observed that low-intensity rainfall did not generate measurable discharge from the rock glacier, since the outflow seeps into the ground along its way (Amschwand et al., 2025). Brighenti et al. (2021a) identified a minimum rainfall threshold of 5 mm required to trigger a response in EC and water temperature of rock glacier discharge. An even higher threshold of 18 mm was found by Wagner et al. (2020). After reaching this threshold, a further increase in precipitation led to a roughly linear increase in event water (Wagner et al., 2020). Furthermore, Geiger et al. (2014) found that while the time to peak was longer in rock glacier catchments, the total percentage of water leaving the catchment was also higher for a rock glacier catchment compared to a non-rock glacier catchment, where a low amount of precipitation left the basin as surface runoff (Geiger et al., 2014). This higher runoff after high-intensity events is discussed to be due to the increased surface runoffs on impervious surfaces on rock glaciers (Bearzot et al., 2023; Geiger et al., 2014; Jones et al., 2019).

6.3 Synthesis of the Spatial and Temporal Patterns Within the Catchment

The integration of spatial and temporal data is essential to receive a holistic characterization of the hydrology within an Alpine catchment. Spatially, the variability in water temperature serves as a primary indication for identifying contact of water with permafrost (Brighenti et al., 2024; Colombo et al., 2018a; Jones et al., 2019; Munroe, 2018). Together with deuterium excess, which can potentially indicate freeze-thaw processes (Colombo et al., 2018a; Delpero et al., 2025; Munroe & Handwerger, 2023a, 2023b), it can be used as an indication of permafrost or glacial ice sources within the catchment. However, these variables alone are insufficient to distinguish between specific geomorphological landforms, as both buried glacial ice in end moraines and periglacial ice in rock glaciers had similarly cold discharge. Spatial EC distributions can further provide a proxy for residence time and mineral weathering (Hayashi, 2020; Louis et al., 2025), but are dependent on local lithology (Brighenti et al., 2026; Crespo et al., 2017; Munroe & Handwerger, 2023b). Thus, EC can give further insight into the water source or geomorphological origin, but is insufficient to distinguish between features with similar parent material. For instance, the end moraine and the rock glacier in the Muragl catchment were characterized by similar EC, water temperature, and isotopic signatures, and were distinguishable from the ground moraine based on these variables, but not from each other. Nevertheless, this thesis emphasizes the benefit of comparing multiple streams within a catchment to identify the distinct discharge behaviour of individual features and allowing for contextualizing their hydrological contribution within a broader catchment system.

The temporal evolution of the rock glaciers and the end moraine both indicate that these landforms influence the hydrological behavior more than simply transmitting water through them; their complex internal structure regulates not only water chemistry, but also the timing and magnitude of discharge (Bearzot et al., 2023). These patterns reflect the complex internal structure of a landform with different flow paths and changing water sources over time (Krainer & Mostler, 2002). While the end moraine and rock glacier had a similar temperature, EC, and isotopic signature, their storage and discharge patterns differed from each other. This suggests that the hydrological impact of a landform depends not merely on the presence of ice, but also on how this ice and the surrounding sediment govern storage and release mechanisms. Therefore, it is worth examining the water chemistry signature both with a focus on permafrost and its geomorphological origin, but also assessing the detailed temporal patterns to understand how different landforms store and release water. While the seasonal patterns seem to reflect the changing influence of different water sources (Jones et al., 2019), the varying diurnal cycles could emerge from many

different factors, such as internal flow paths (Bearzot et al., 2023; Hayashi, 2020), the ice content within the landform (Bearzot et al., 2023; Jones et al., 2019), or the origin of the meltwater (Bearzot et al., 2023; Delpero et al., 2025). Nevertheless, both rock glaciers and the end moraine seem to contain both deeper groundwater flows underneath the ice with a slower response time, and faster flow components, likely on top or within the ice (Hayashi, 2020). Further studies are necessary to validate these hypotheses and resolve the large uncertainties regarding internal structure, flow path, and processes within these landforms.

The storage behavior of periglacial landforms might evolve in the future as permafrost continues to degrade (Geiger et al., 2014; Jones et al., 2019; Rogger et al., 2017). Under degrading permafrost, there is likely a slightly increased runoff within rock glaciers due to the melting ice during the summer season (Geiger et al., 2014; Munroe, 2018; Rogger et al., 2017). After a transition of rock glaciers towards inactive and relict status, this could change (Geiger et al., 2014; Jones et al., 2019). Through the degradation of the ice core, the porosity could potentially increase, leading to a higher amount of snow melt and precipitation that is transmitted to the groundwater system (Brighenti et al., 2021b; Del Siro et al., 2023; Geiger et al., 2014; Jones et al., 2019; Munroe, 2018), potentially leading to a decrease in flood peaks (Geiger et al., 2014; Jones et al., 2019). The higher storage capacity could then maintain baseflow during summer periods (Geiger et al., 2014; Jones et al., 2019). This again could lead to a changing discharge pattern, which again influences the runoff cycle of the whole Alpine catchment (Jones et al., 2019). Thus, permafrost degradation would affect the amount of storage and the timing of water release, and the total amount of water leaving the catchment (Geiger et al., 2014; Jones et al., 2019).

Not only could the timing and amount of discharge change, but also its hydrochemistry. The constantly low water temperatures within the discharge of rock glaciers and other cold rocky landforms can provide habitats for cold-adapted species, acting as a climate refugia for aquatic and terrestrial biodiversity (Brighenti et al., 2021b; Harrington et al., 2017). It is assumed that with receding snow and ice, water temperatures will increase in Alpine catchments (Brighenti et al., 2021b). Due to their higher resilience to climate warming, rock glaciers and other cold landforms might be able to maintain a cold habitat even after a decline of glaciers and snowfields (Brighenti et al., 2021b; Harrington et al., 2017). Furthermore, Brighenti et al. (2024) reported that the solute concentration and the overall quality of water in the discharge of rock glacier springs are mainly influenced by the bedrock lithology and the occurrence of ice content within these landforms. Higher concentrations of major ions and trace elements were found in intact rock glaciers

compared to relict rock glaciers (Brighenti et al., 2024). They hypothesize that during warm and prolonged summers, the overall solute export from rock glaciers might increase, potentially leading to a decreasing water quality during permafrost degradation and ice loss. However, this impact might decrease after the final stages of permafrost degradation (Brighenti et al., 2024).

6.4 Influence of Periglacial and Glacial Landforms on Alpine Catchments

The findings in this thesis support the hypothesis of Hayashi (2020), that the groundwater storage within Alpine watersheds is not negligible, and that even regions with little soil and vegetation can have an influence on the storage and discharge characteristics in downstream river systems. In the Muragl and Champagna catchments, both rock glaciers and the end moraine maintained a steady baseflow even in prolonged dry periods with little recharge, indicating the presence of an Alpine aquifer with the ability to store substantial amounts of groundwater (Arnoux et al., 2021; Brighenti et al., 2023; Christensen et al., 2020; Cochand et al., 2019; Hayashi, 2020; Wagner et al., 2020). Especially, land cover consisting of coarse sediment increases the baseflow, highlighting the relevance of periglacial landforms as water reservoirs (Hayashi, 2020; Reato et al., 2022). This underscores the importance of such landforms not only for the landform itself, but for the discharge of the whole catchment. While different studies discussed the influence of periglacial and glacial landforms on the overall hydrology of the catchment (Bearzot et al., 2023; Brighenti et al., 2019; Hayashi, 2020; McClymont et al., 2011; Roy & Hayashi, 2009), comparisons are often complicated by diverse geomorphological features or the presence of a glacier within the catchment. Since the Muragl glacier lacks visible glacial remnants, it offers insights into an Alpine catchment, where glaciers no longer dominate the hydrological response. Within this context, permafrost and periglacial landforms play a growing role in shaping the hydrological response of Alpine catchments (Brighenti et al., 2019).

6.4.1 Hydrological Contribution of Periglacial and Glacial landforms to the Downstream River System

The contribution, distinct hydrochemical signature, as well as the discharge and storage characteristics of the periglacial and glacial landforms, affect the downstream river system within the Muragl catchment, as illustrated in Figure 55. Even though the rock glacier and the scree slope together only account for 10% of the area of the catchment, they contribute the majority of the total discharge on most measured days. A study by Brighenti et al. (2026) showed a high contribution of 43% from active rock glaciers to the catchment

outlet, making up a higher contribution than the glaciers, moraines, and scree slopes within their catchment. Similarly, Bearzot et al. (2023) reported a disproportionately large contribution of rock glacier discharge of up to 63% in late summer, despite draining only 39% of the area within the catchment (Bearzot et al., 2023). Harrington et al. (2018) observed that despite covering only 20% of the total catchment area, an inactive rock glacier contributed 30 - 50% of summer runoff, and provided nearly all of the discharge during winter months in the Canadian Rockies (Harrington et al., 2018). Similarly, Hood and Hayashi (2015) found a high storage capacity within depressions in a pro-glacial moraine when estimating the groundwater storage within an Alpine watershed, with lower storage volume in the talus slopes and meadows, despite occupying larger areas. In the Muragl catchment, the contribution of the rock glacier and the scree slope discharge is highest at the beginning of August, while the relative contribution of the lake and ground moraine, as well as the exfiltrating hillslope water, increases towards October. The majority of the remaining discharge emerged from the lake, the moraine complex, and the meadows around these landforms, while occupying approximately 40% of the catchment. The high sensitivity of the mixing model to small shifts in $\delta^2\text{H}$, as observed across different sampling sites of the rock glacier discharge and exfiltrating hillslope water, underscores the large uncertainties within these calculations. Nevertheless, the calculations agree on the dominant role of the upper part of the catchment, and thus highlight the relevance of periglacial and glacial landforms in shaping the discharge of this Alpine catchment. While the geological and geomorphological landforms often differ between catchments (Hood & Hayashi, 2015), these findings highlight the importance of such landforms as aquifers in Alpine catchments (Brighenti et al., 2023; Hayashi, 2020). Especially during baseflow periods, landforms such as rock glaciers play an important role due to their capability of storing and transmitting groundwater (Bearzot et al., 2023). Thus, while the contribution of perennial ice melt itself might be small in such periglacial landforms (Amschwand et al., 2025; Del Siro et al., 2023), their function as an aquifer is still highly relevant (Arenson et al., 2022; Hayashi, 2020).

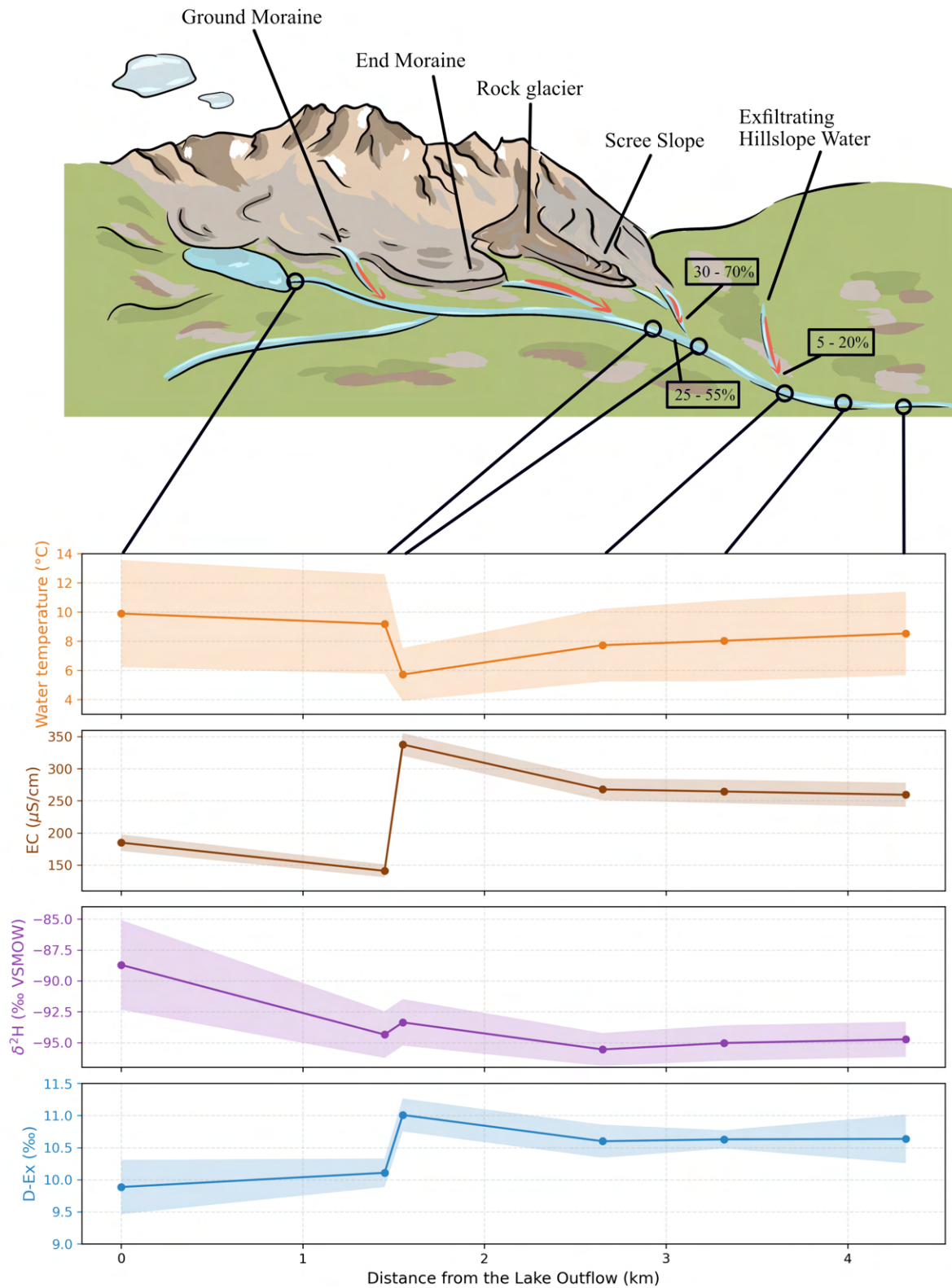


Figure 55: Sketch of the downstream mixing of water temperature, EC, and stable isotope composition, and the hydrochemical evolution along the Ova da Muragl with distance from the lake. The percentage contribution of different subcatchments in the sketch is shown in black font. Sketch is not up to scale. The lines represent the mean, while the shading indicates the standard deviation (own Figure).

6.4.2 Hydrochemical Contribution of Periglacial and Glacial Landforms to the Downstream River System

The importance of the periglacial landforms is not only visible in its contribution, but also through its influence on the hydrochemical characteristics of the Ova da Muragl. Similarly, Brighenti et al. (2023) found that rock glaciers and glaciers drive the isotopic and hydrochemical patterns along river systems. Since the discharge from the ground moraine is generally very similar to that of the lake outflow, no large change is expected through the input of this source. From the end moraine, a water input with a lower temperature, higher EC, more negative $\delta^2\text{H}$ values, and a higher deuterium excess is expected. Similarly, the influence of discharge from a moraine complex led to a decrease in temperature and an increase in EC after its confluence in a study by Brighenti et al. (2019). Within the Muragl catchment, the water cools down, and the water gets more depleted in heavy stable isotopes, and the EC decreases on the path downstream. Thus, another water source with low EC must enter the stream, for example, an input of exfiltrating hillslope water, which could further explain the substantial depletion in heavy stable water isotopes.

The next measurement station lies in a short distance, but underwent drastic changes in hydrochemistry, which align well with the input of water from the rock glaciers and the scree slope; the changes reflect the input of colder, slightly less depleted water with significantly higher EC and deuterium excess. The strong drop in water temperature of up to 6°C and an increase in EC of 150 to 200 $\mu\text{S}/\text{cm}$ within only approximately 200 m distance are likely due to both the significantly different properties of the water inflow, and the large contribution of this incoming branch. Similar influence of a rock glacier discharge on a downstream river system was found by (Brighenti et al., 2026), with a strong control of the rock glacier on water temperature, runoff, and water chemistry. They reported a decrease in water temperature of 2-4°C below the confluence (Brighenti et al., 2026), which aligns with a reported decrease in water temperature of up to 2.9°C by Bearzot et al. (2023) and an average decrease of 3.2°C in July and August by Harrington et al. (2017) after a confluence with rock glacier discharge. Moreover, Brighenti et al. (2019) demonstrated an increase in EC below the confluence of rock glacier discharge.

Not only do the absolute values of temperature and EC underscore the influence of the rock glacier, but also the seasonal and diurnal patterns. While the water temperature at downstream locations is influenced more by fluctuations in air temperature, the seasonal patterns in EC, water level, and stable isotope composition after the confluence generally follow those of the Muragl rock glacier. The reaction of the discharge at the downstream location to precipitation events reflects the influence from different water sources: an initial, almost instantaneous response with the onset of the precipitation suggests an in-

fluence of direct precipitation into the stream channel itself. This is followed by multiple peaks in water level and minima in EC, likely due to the arrival of diluted water from different landforms and water sources, such as the end moraine and the rock glacier, at slightly different times. The recovery time of multiple hours to days is similar to that of the Muragl rock glacier, which underscores that the delayed contribution of the Muragl rock glacier has a large influence on the hydrological signature of the downstream mixing location.

Further downstream of this measurement site, no further water input of any periglacial landform is expected. On its way to the next measurement station, the hydrochemistry recovers slightly from the drastic changes through the rock glacier discharge with a trend towards higher water temperatures, lower EC and deuterium excess, and more negative $\delta^2\text{H}$ values. This would align well with the assumption that there is an input of exfiltrating hillslope water into the stream, which is defined by these characteristics. Furthermore, environmental factors, particularly air temperature and the presence of snow, influence stream dynamics. Stream temperature generally increased towards the catchment outlet, unless snow was present in the catchment, which led to a cooling effect. Nevertheless, the influence of the rock glacier discharge can be detected even at the outlet of the catchment. The EC was still higher at the catchment's outlet than it was within the stream before the confluence with the rock glacier discharge. This aligns with Brighenti et al. (2026), emphasizing that a higher concentration of solutes and trace elements through the inflow of rock glacier discharge alters the water quality down to the basin outlet.

6.5 Limitations and Future Research

While this thesis provided a first insight into the hydrology of the Muragl and Champagna catchments, both the temporal scope and methodological limitations pose significant constraints and limit the interpretation of the findings.

The analysis of the diurnal water level patterns within these streams showed that the atmospheric correction and the morphology of the stream affect the accuracy of the data. To isolate the daily fluctuations in water pressure, the correction with air pressure is essential. Extrapolating the data from weather stations in neighboring valleys can lead to a temporal lag and discrepancies in the pressure and thus the water level. A local barometer in each valley is thus preferable if diurnal fluctuations are analyzed. Nevertheless, the extrapolation of the barometer data to different elevations introduces further sources of uncertainty. Furthermore, the stream morphology influences changes in water level. While natural stream channels do not follow a perfect rectangular geometry, the increase in water level is often accompanied by a lateral expansion across the streambed. Thus, an

increase in pressure can indicate a rise in water level, but does not provide information on the absolute discharge. To tackle this challenge, measurements of the discharge volume at different water levels would be beneficial to establish a stage-discharge relation and to quantify the contribution of different landforms to the total discharge. Moreover, the diurnal signals must be interpreted with caution, since in addition to the named challenges, the uncertainty of the barometer and water pressure sensors was often larger than the changes in diurnal water level and EC overall. This highlights the importance of a good placement within the stream, high-sensitivity equipment, ideally individual barometric measurements at each measurement station, and a cautious interpretation of the diurnal patterns.

Furthermore, while EC is a useful indicator of total dissolved solids, it is also strongly dependent on temperature. For this reason, the EC of water samples measured at different temperatures must be corrected to a standard temperature before interpretation (Hayashi, 2004). For the sensors installed in this thesis, this was applied automatically using a linear temperature compensation to 25°C (Keller Pressure, 2025b). In the cold discharge of the rock glaciers and the end moraine, this correction strongly influences the diurnal patterns of EC, thus even small errors in the measured temperature or EC could affect the observed pattern. In addition to the uncertainty of the sensor itself, this introduces another potential source of error into the interpretation of small-scale diurnal fluctuations in the corrected EC.

Moreover, the interpretation of the stable isotope composition is subject to several constraints. No measurements of the initial winter snowpack melt were available, since the sampling started in mid-July. Furthermore, rain was sampled only at one location and could not account for elevation gradients in the isotopic signature; however, Delpero et al. (2025) showed that such an elevation gradient can exist. Additionally, potential evaporation or freeze-thaw processes within the collector may have altered the isotopic signature of the precipitation. Finally, the sampling frequency within the discharge of the streams captured seasonal evolution between July and October, but failed to capture short-term phenomena, such as diurnal patterns during warm days or reactions to precipitation events. Further studies would benefit from automatic samplers in important streams to achieve a higher frequency in sampling, especially during dry periods, to track short-term hydrological shifts.

For this thesis, a short time scale of only the seasonal evolution between mid-July and mid-October in 2025 was captured. In the future, I suggest a year-round installation of the automatic measurement stations to capture data during the snow melt and winter

season. Monitoring these periods would reveal how the diurnal fluctuations evolve, which could potentially give insight into the seasonal shift in water sources within the Muragl and Champagna catchment. Moreover, discharge patterns in small catchments are inconsistent between years, which makes long-term predictions difficult (Geiger et al., 2014). For a comprehensive understanding, a multi-year monitoring would help to understand such inter-annual variability of the year. Additionally, the assessment of major ions and trace elements could give further insights into water quality and weathering processes (Brighenti et al., 2024).

The Muragl catchment is characterized by diverse geomorphological landforms. This introduces challenges for the interpretation of discharge patterns due to potential subsurface connectivity, but provides the opportunity to compare the dynamics of different landforms. In contrast, a catchment with fewer landforms that influence each other, such as Val Champagna, might provide a more constrained environment to assess the response of an individual landform, but fails to capture broader, catchment-scale processes. By investigating the discharge in both catchments, the benefits of both can be utilized. Furthermore, I suggest monitoring the seasonal and diurnal discharge of groundwater unaffected by permafrost, to ensure that, especially the diurnal patterns, are not due to other processes happening in the entire catchment, but due to processes affected by ice melt.

A next step in the research of rock glacier hydrology could be to correlate the observed discharge patterns with internal temperature and water pressure data within boreholes. This could help to bridge the gap between surface hydrological signals and the internal dynamics of the rock glacier. Such an approach would clarify the importance of different flow paths and the internal storage capacity within the rock glacier, and how the thickening of the active layer throughout the summer influences the chemistry of the runoff. Ultimately, linking the internal and external measurements could allow the development of a more robust conceptual model of the storage-discharge dynamics of rock glaciers.

7 Conclusions

The findings in this thesis demonstrate that glacial and periglacial landforms are important in determining hydrological and hydrochemical signatures within the Muragl and Champagne catchments. The distinct hydrochemical signatures of spatially close streams highlight the high degree of local variability in these Alpine catchments. The low water temperatures and elevated deuterium excess in the discharge of the rock glaciers, the end moraine, and the scree slope indicate contact with permafrost and ice that has potentially undergone multiple freeze-thaw cycles. Their high solute concentrations further suggest prolonged residence time and extensive interaction of minerals with ice and water. In contrast, the discharge from the lake outflow and the ground moraine was characterized by a larger variability in water temperature throughout the summer season and intermediate EC and deuterium excess, suggesting improbable permafrost occurrence within the ground moraine. This confirms patterns of permafrost distribution of the modeled map, with a lower likelihood of permafrost in the ground moraine, while supporting evidence for the presence of internal ice within the rock glaciers, the end moraine, and likely also the associated scree slope. Despite these hydrochemical contrasts, the isotope signature for all landforms, including rock glaciers, end moraine, ground moraine, and lake outflow, fell between the modeled summer and winter precipitation. This suggests similar recharge sources and reflects mixing of precipitation throughout the hydrological year.

The internal structures of periglacial and glacial landforms not only influence the water signature but also the timing and magnitude of water release. The constant and stable baseflow in the end moraine and both rock glaciers, with high EC and an isotopic composition between winter and summer precipitation, suggests slow groundwater flow underneath the ice. Fast responses to precipitation events indicate shallow supra-permafrost flow across both landforms and potentially intra-permafrost flow. The faster reaction and recovery time in the end moraine compared to the rock glaciers might reflect shorter flow paths, possibly due to a more intact ice core. Seasonal patterns, with stable water temperature, rising EC, and stable or decreasing water level, were likely dominated by a shifting contribution of different water sources: from snow melt in early summer, towards a higher relevance of rainwater and groundwater, and potentially melting of seasonal and perennial ice in late summer. Diurnal patterns observed during dry periods suggested melt processes within the rock glacier. The observed direct relationship between EC and water level in the rock glaciers indicates either a flushing out of solute-rich water through supra- or intra-permafrost flows, or the pushing out of solute-enriched groundwater through the melting of ice. The inverse relationship found for the end moraine might suggest dilution through ice melt. However, further research is needed to confirm these assumptions.

The discharge from these landforms impacted the downstream river system. A mixing model using $\delta^2\text{H}$ suggests that a majority of the discharge originated from the rock glacier and its neighboring scree slope, despite draining only 10% of the area of the catchment. The second-highest contribution emerged from the lake, the moraine complex, and the meadows around these landforms. This large contribution of the upper part of the catchment highlights the role of glacial and periglacial landforms as Alpine aquifers. The inflow from the rock glacier and the scree slope distinctly decreased the water temperature and increased the EC and deuterium excess of the main stream after their confluence. These changes remained detectable even at the outlet of the catchment. As permafrost degradation continues under a warming climate, it is assumed that these patterns of storage and discharge will change, potentially altering the timing and magnitude of discharge of the entire catchment.

While this thesis provided a first insight into the complex hydrological flow paths and their influence on the water quality of the Muragl and Champagna catchments, further research is needed to understand the mechanisms driving these distinct signatures. A primary limitation of this thesis was the restricted temporal scope, capturing only a short period of seasonal changes between July and October within a single year. To gain a deeper insight into the changing contributions of water sources, internal structure, and flow paths, longer-term measurements are essential. The Muragl catchment would be a suitable location to conduct further research, due to its large heterogeneity of streams, the distinct hydrological signature and response of the Muragl rock glacier, and its variety in glacial and periglacial landforms, without the presence of a glacier that might overshadow the hydrological response.

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Appendix

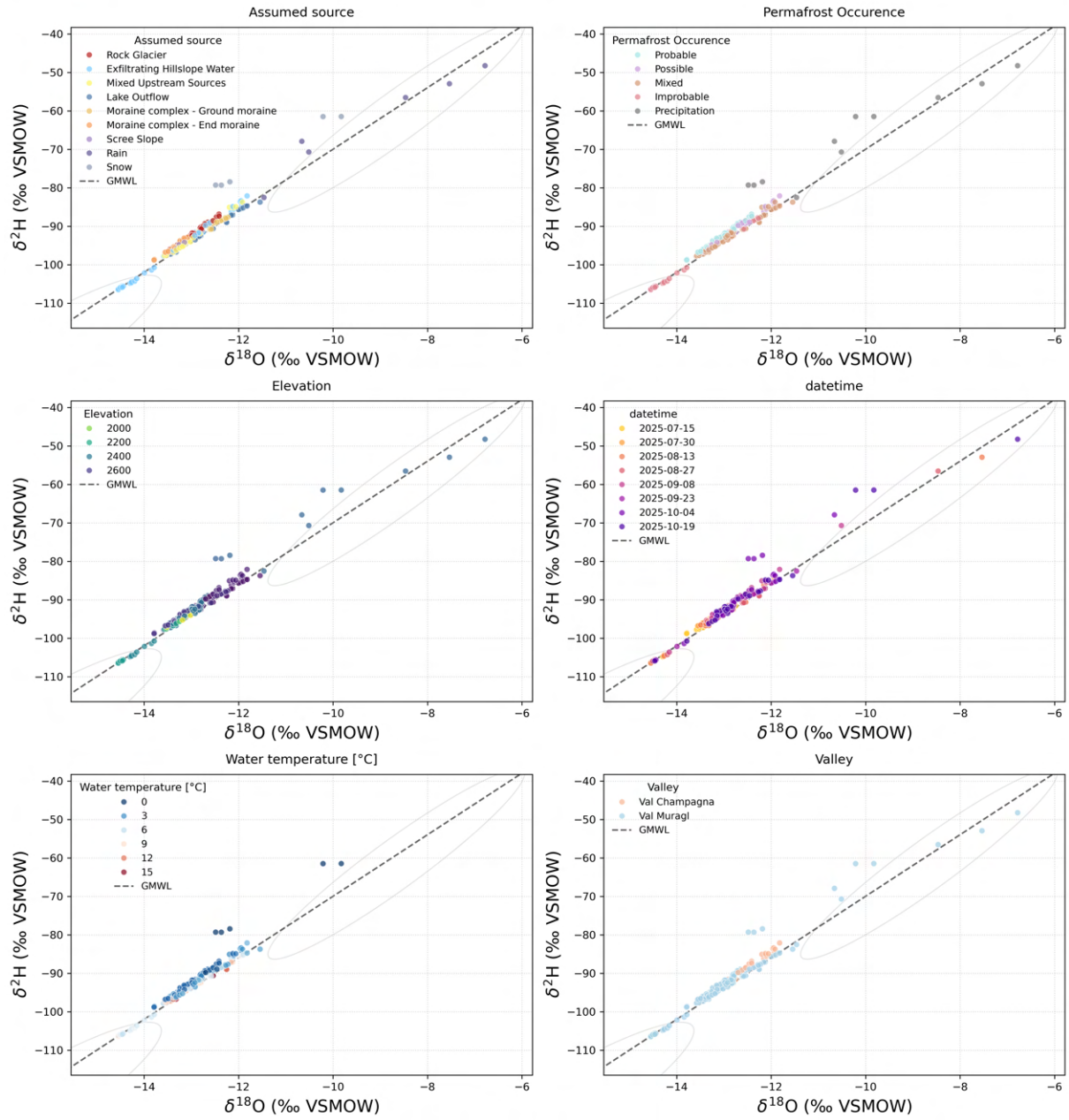


Figure 56: Dual isotope plot with the samples colored by their assumed source, permafrost occurrence, sampling date, and elevation of the sampling location.

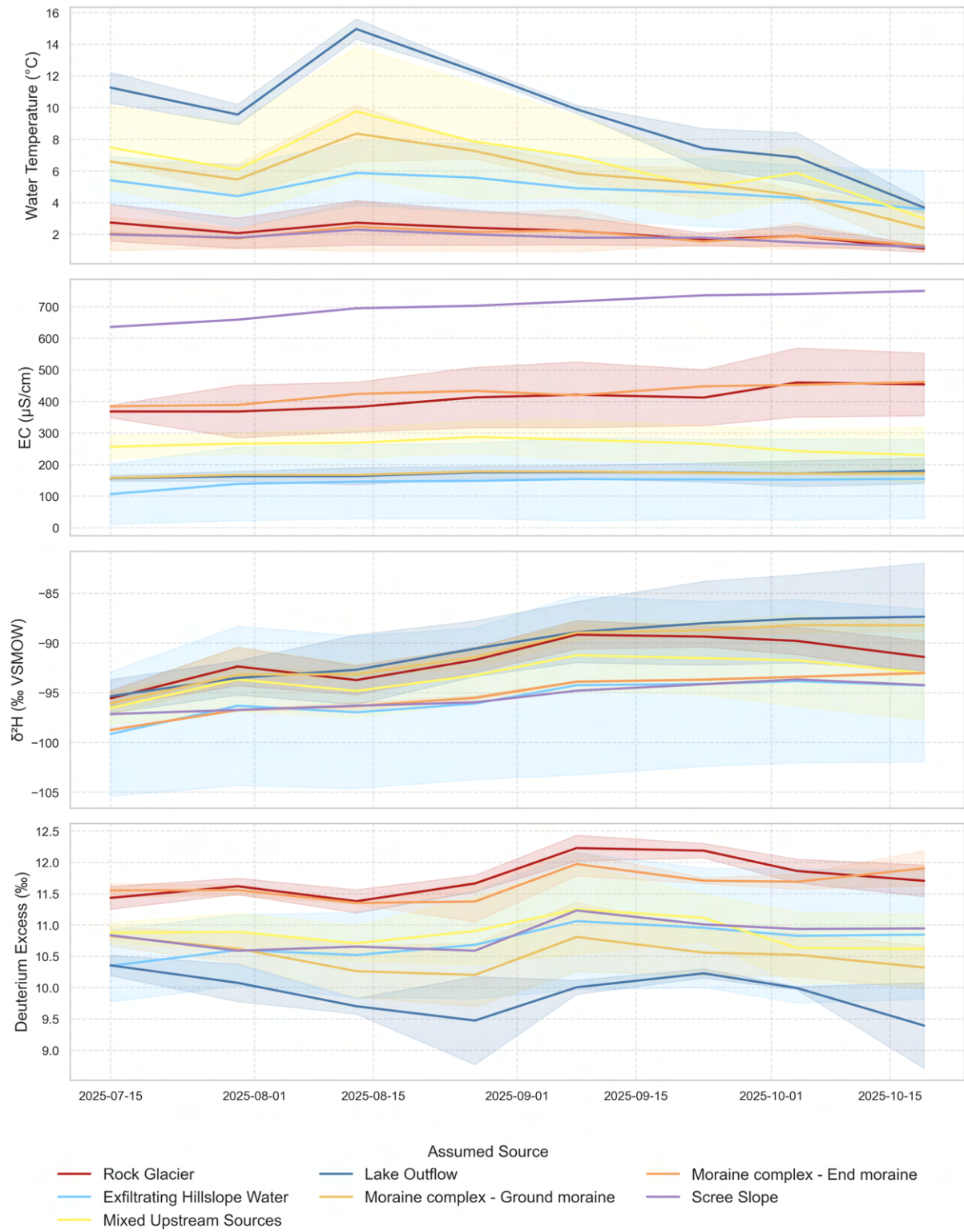


Figure 57: Evolution of mean water temperature, EC and stable water isotope composition between July and October 2025 and its standard deviation (shaded areas) for the different water sources.

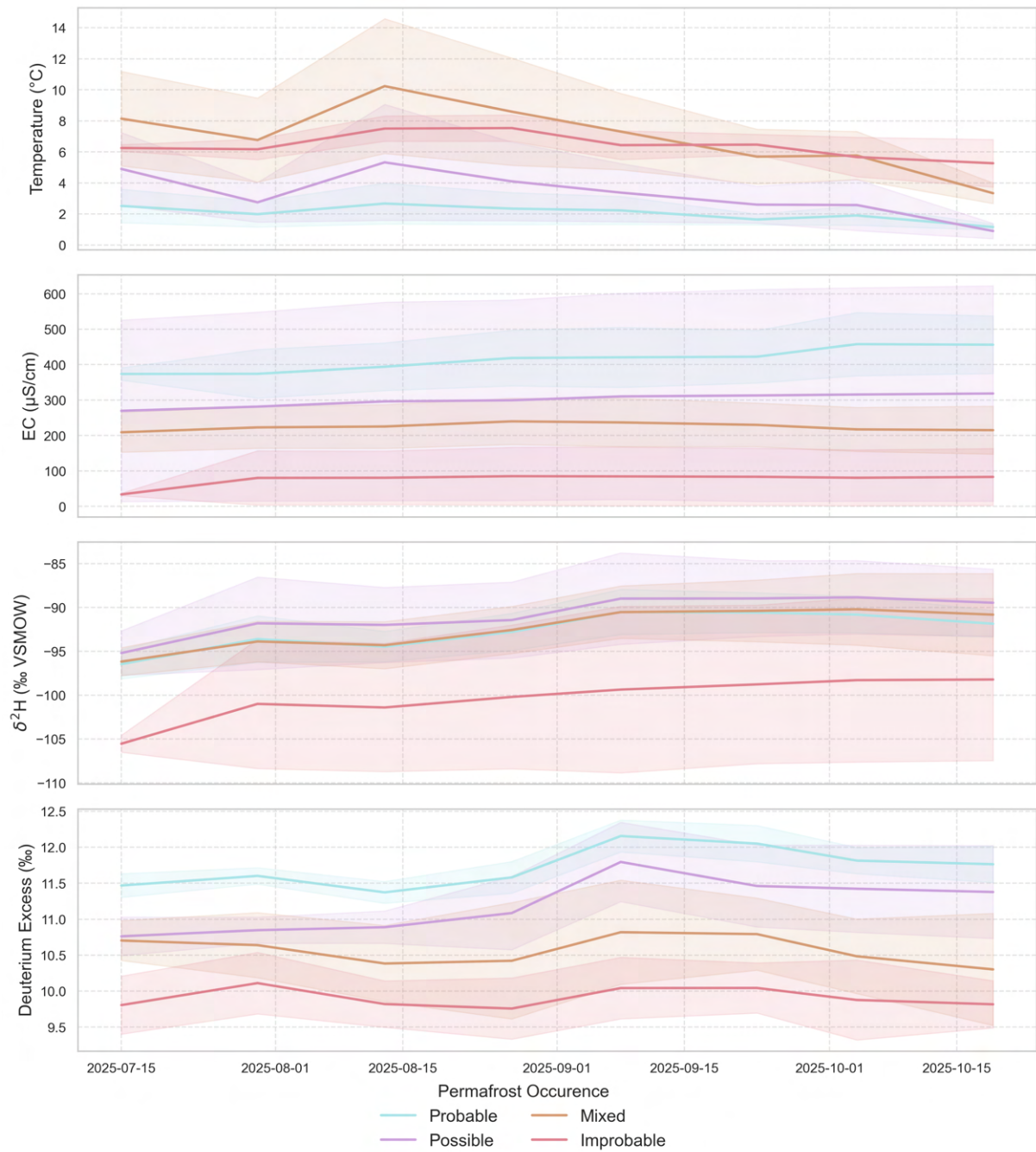


Figure 58: Evolution of the mean water temperature, EC and stable water isotope composition between July and October 2025 and its standard deviation (shaded areas) for streams with different permafrost occurrence in their catchment.

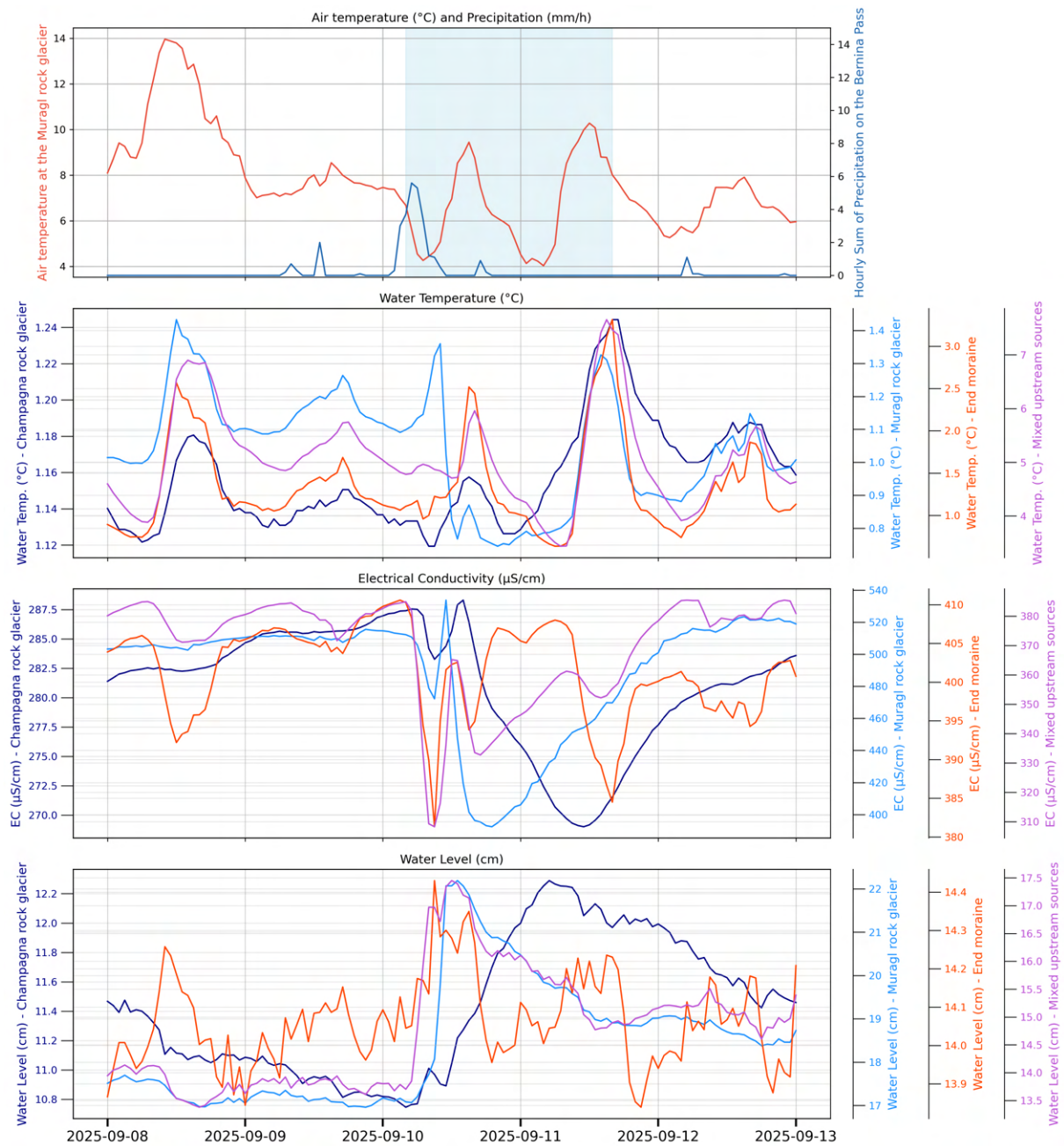


Figure 59: Time series of water temperature, EC, and water level during a warm and wet period in September 2025 at four different locations: the Champagna and Muragl rock glacier, the end moraine of the moraine complex, and a downstream mixing location.

Personal Declaration

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

AI has been used in this thesis as follows:

- Translation and stylistic improvements using DeepL translator.
- Correction of spelling using Grammarly.
- Formulation and structure suggestions of my own text using Gemini 3.
- Assistance in creating and debugging Python code for statistical analyses and plots using Gemini 3.

All text parts created by AI have been checked by me, the author of this text. I take full responsibility for the text.



Kathrin Habegger

24.04.2026, Zürich