

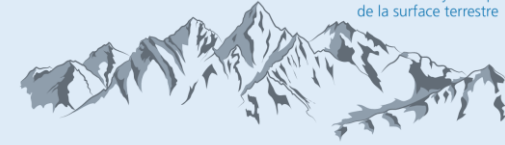
Assessing the effect of the geomorphological complexity of glacier forefields on the multi-temporal water dynamics will provide better future models

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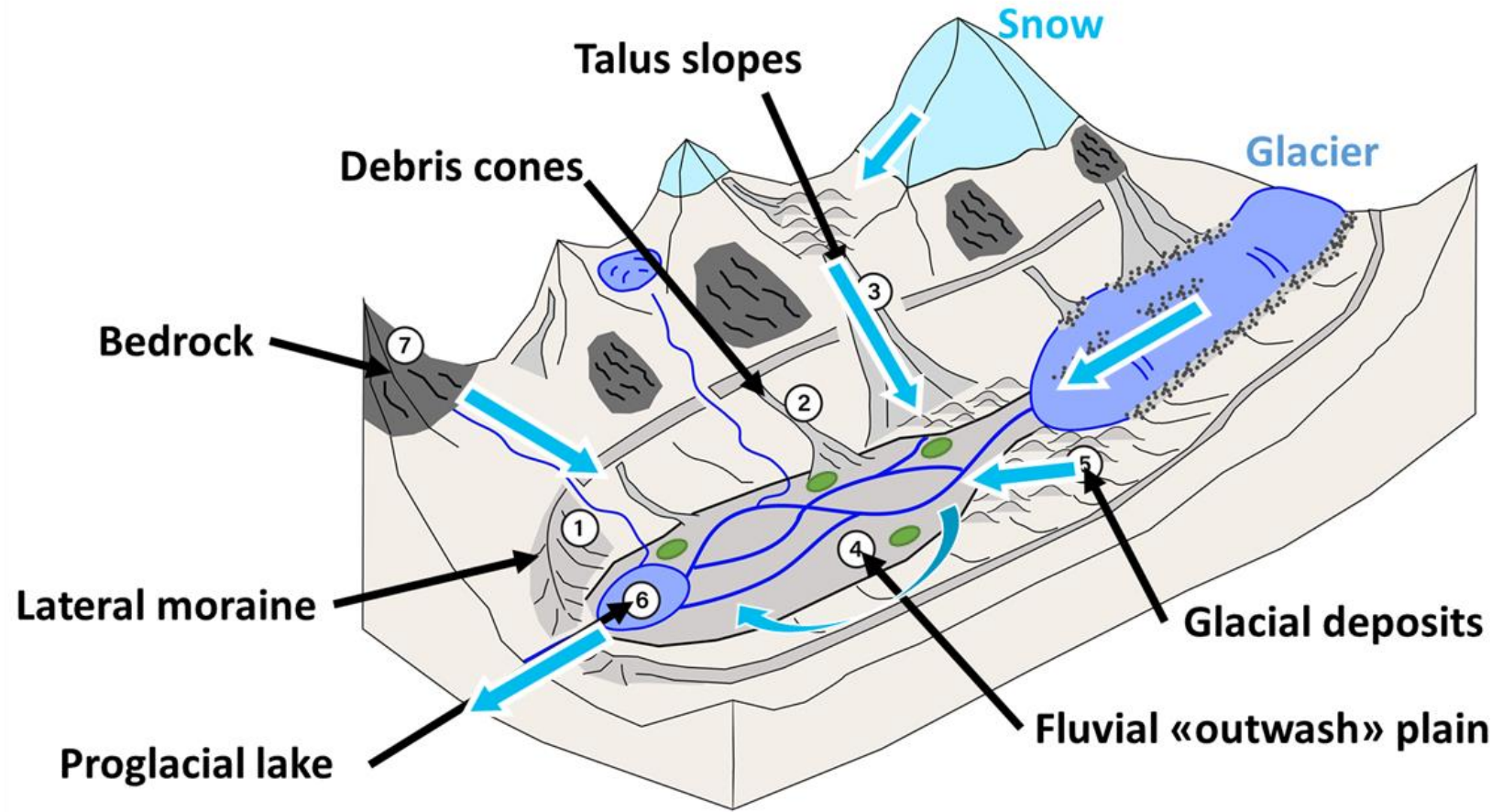
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Where is water stored ?

Geomorphological landforms in proglacial zones

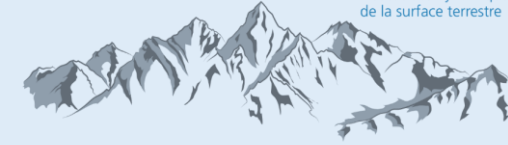


- Ice retreat uncovers and releases large amounts of unconsolidated sediments leading to a variety of landforms
- Water storage and release time depend on the type of landforms and their assemblage is key to understand the following processes in a context of rapid ice loss :
 1. Maintaining baseflow and ecosystem diversity
 2. Transmission/attenuation of future flood
 3. Providing water for downstream usage



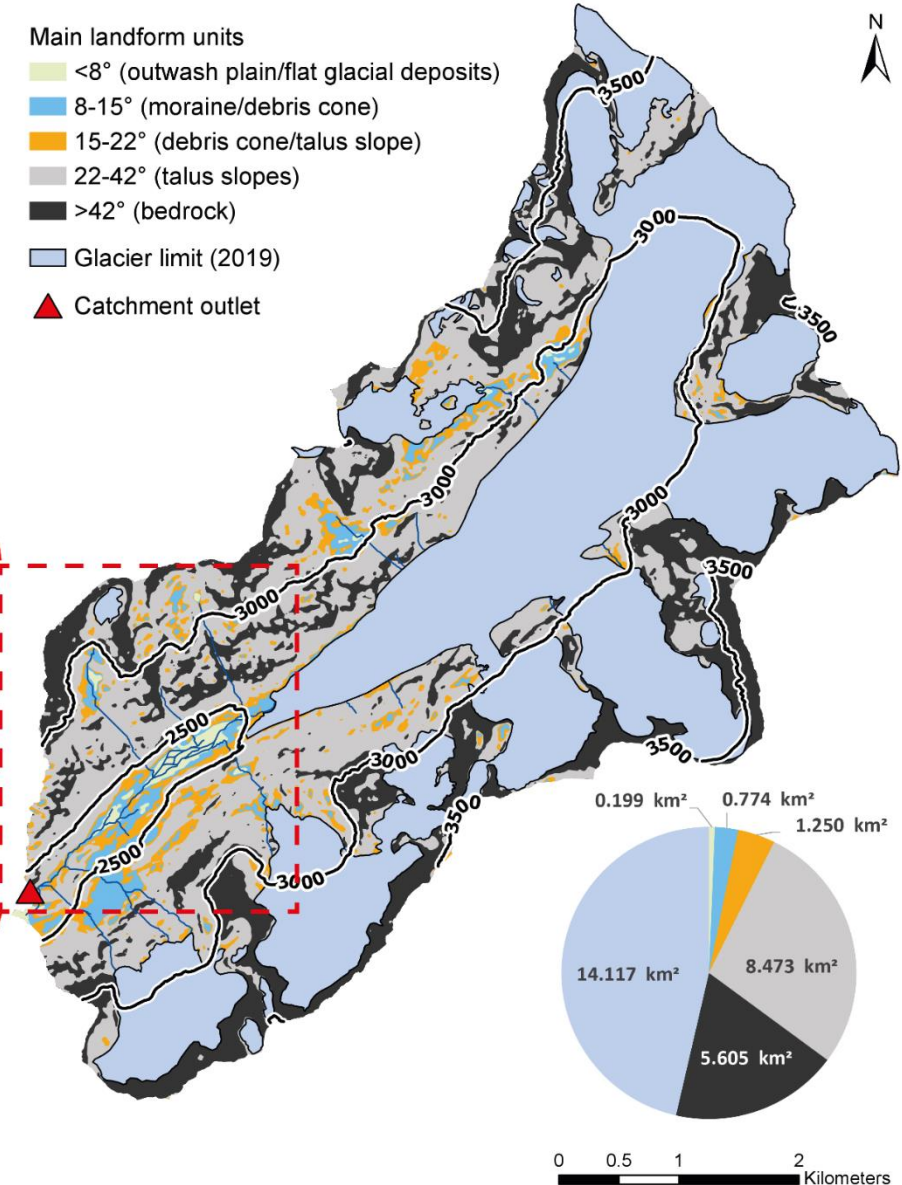
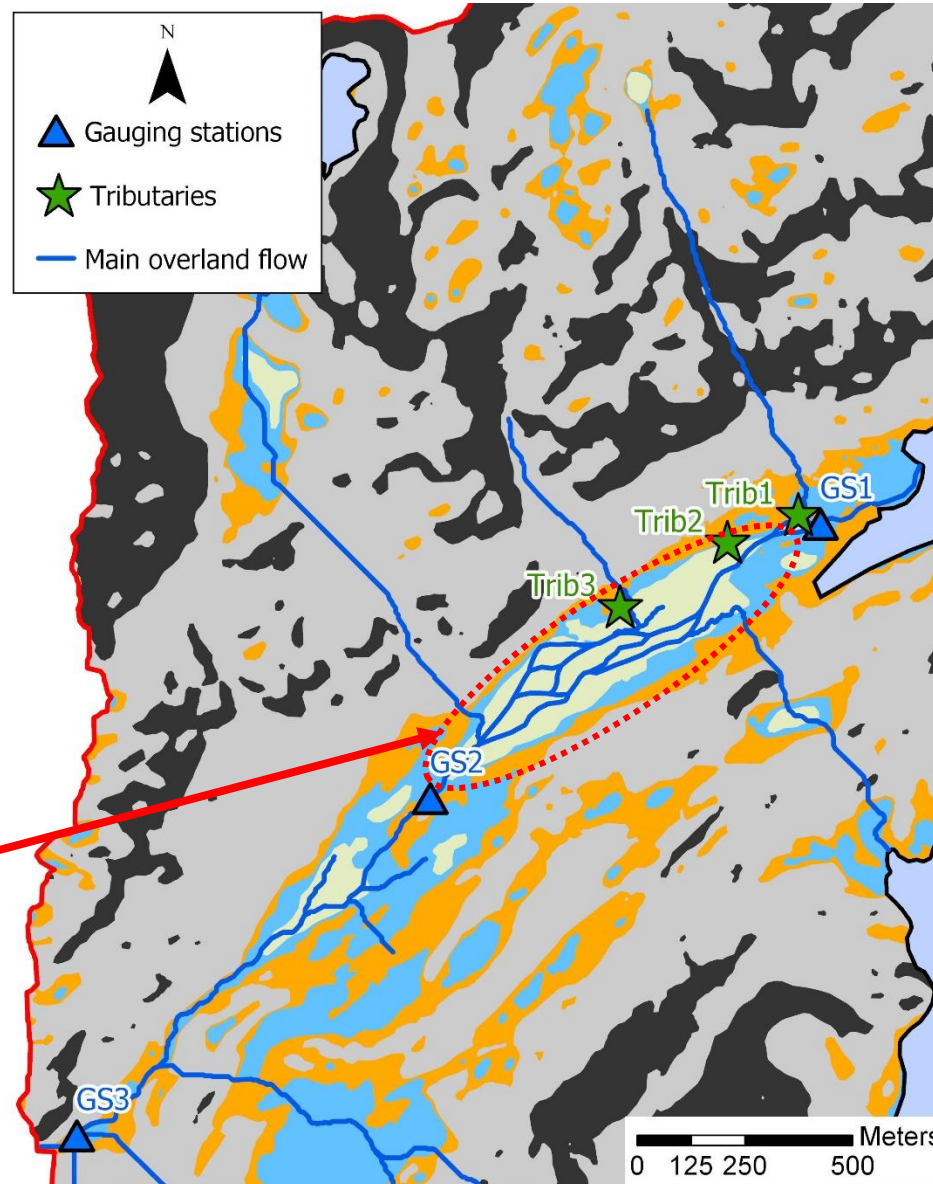
Field site – Glacier d'Otemma (CH)

Experimental setup in 2020



- 3 gauging stations (GS) are monitoring discharge, EC and isotopes
- Tributary and piezometer monitoring is also installed

Outwash
plain (gravely
sandy aquifer)

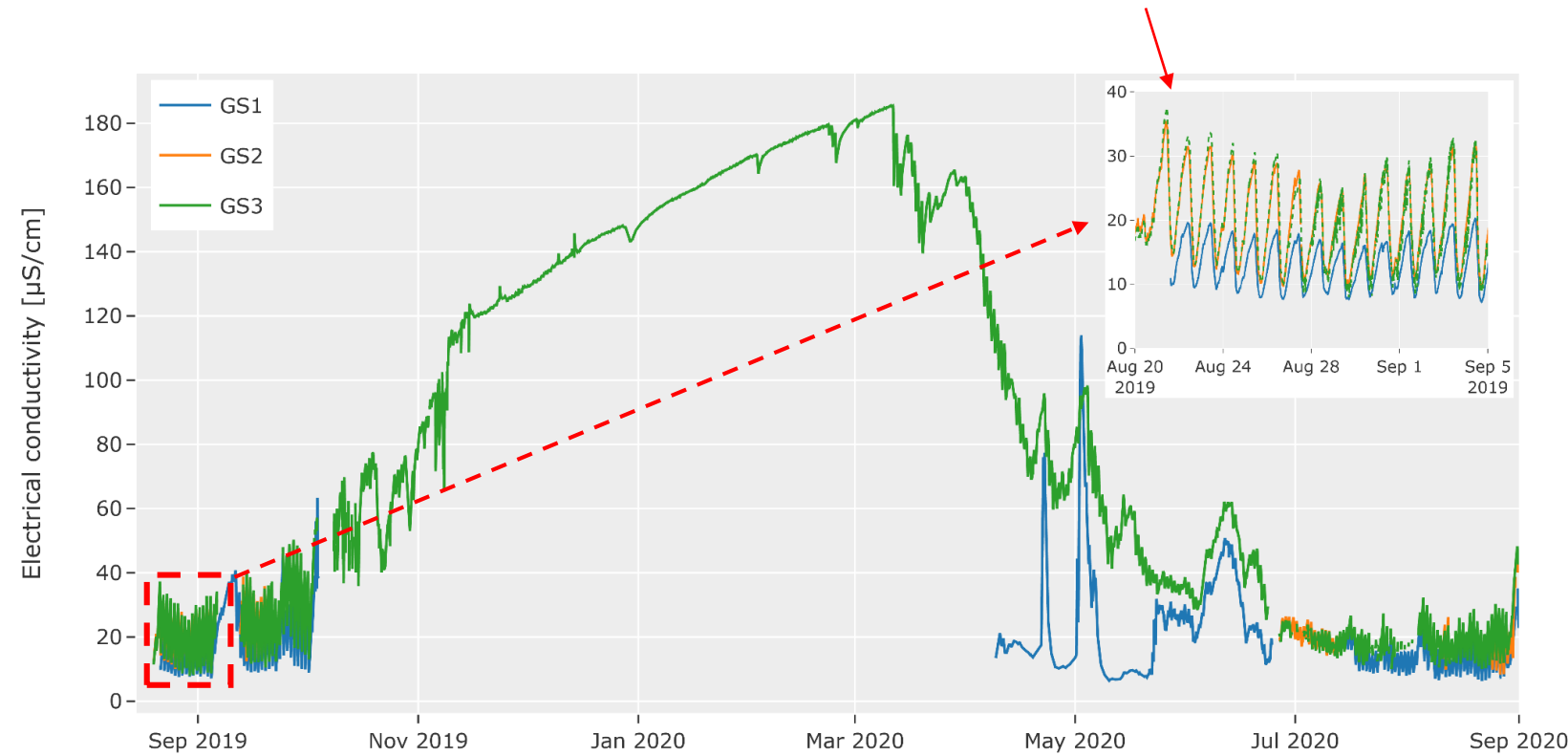


Groundwater evidence

River electrical conductivity

- Monitoring of electrical conductivity (EC) from the glacier snout (GS1) to catchment outlet (GS3)
- River discharge follows a relatively **linear recession** during the whole winter
- **River EC increases linearly during the winter**
- => This indicates a **clear contribution from groundwater sources**

During summer, EC only changes along the outwash plain section (GS1 to GS2)



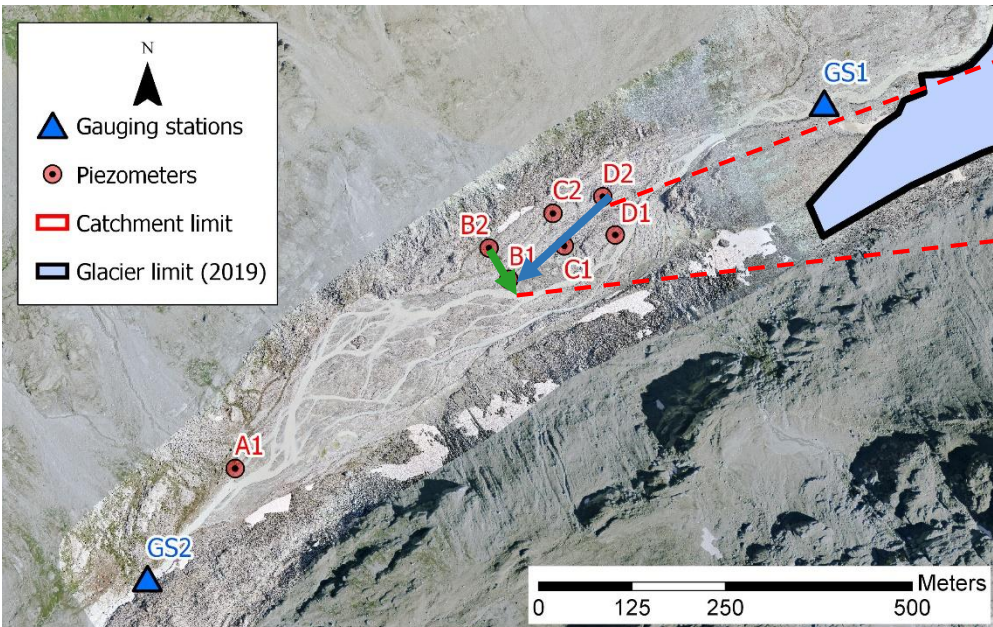
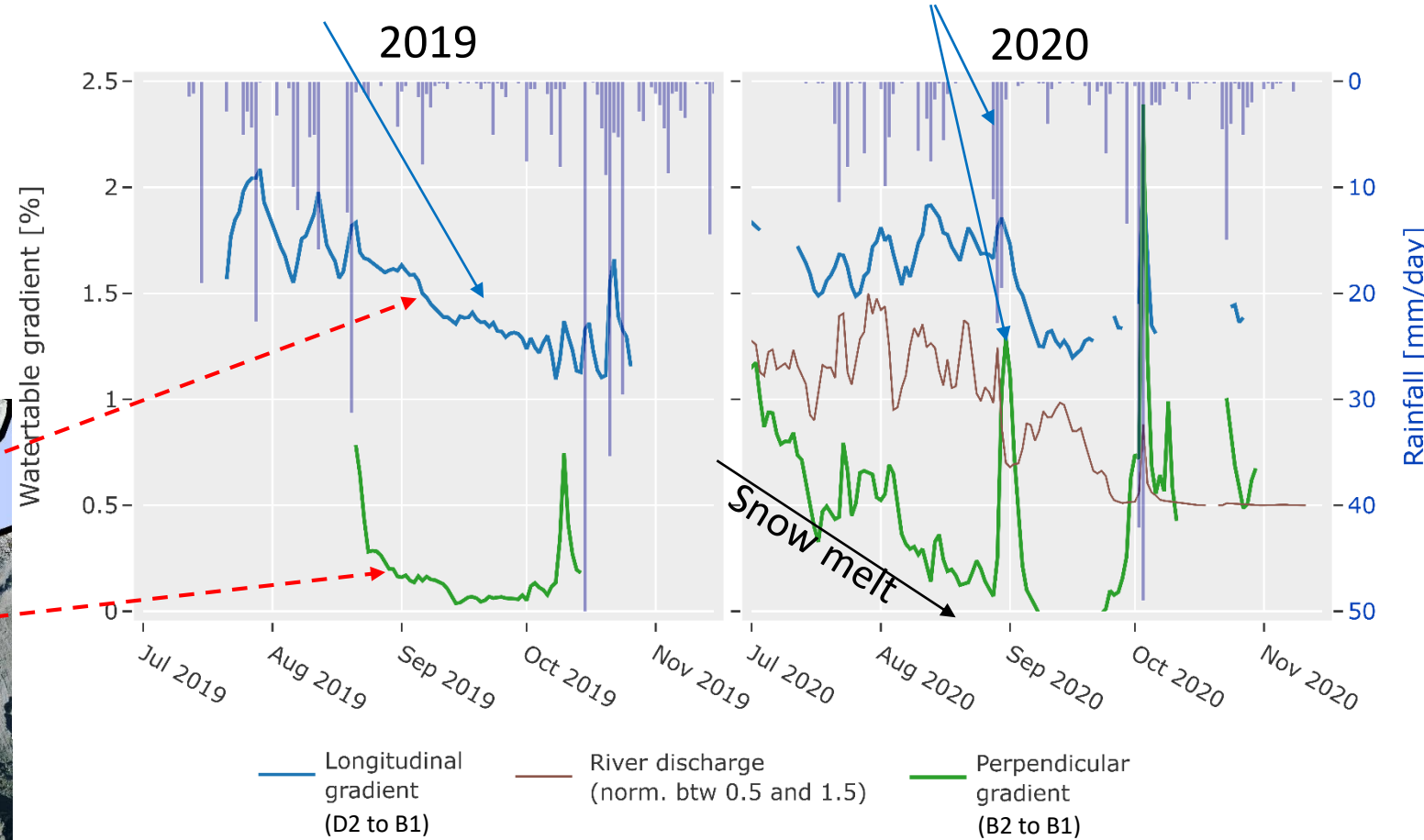
The outwash plain aquifer

Results from piezometer well monitoring

- The aquifer **main gradient follows the terrain** slope of (1-2%) (parallel to river)
- **River discharge** closely correlated to the longitudinal gradient indicates **strong river connectivity**
- **Lateral recharge** (snow melt) becomes marginal after August

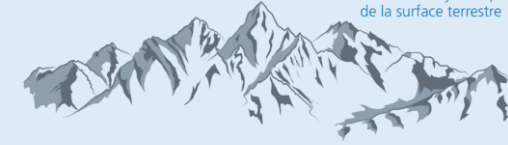
Aquifer stores water during Autumn and is slowly exfiltrating

Strong rain events provide lateral recharge during short timescales (5 days)

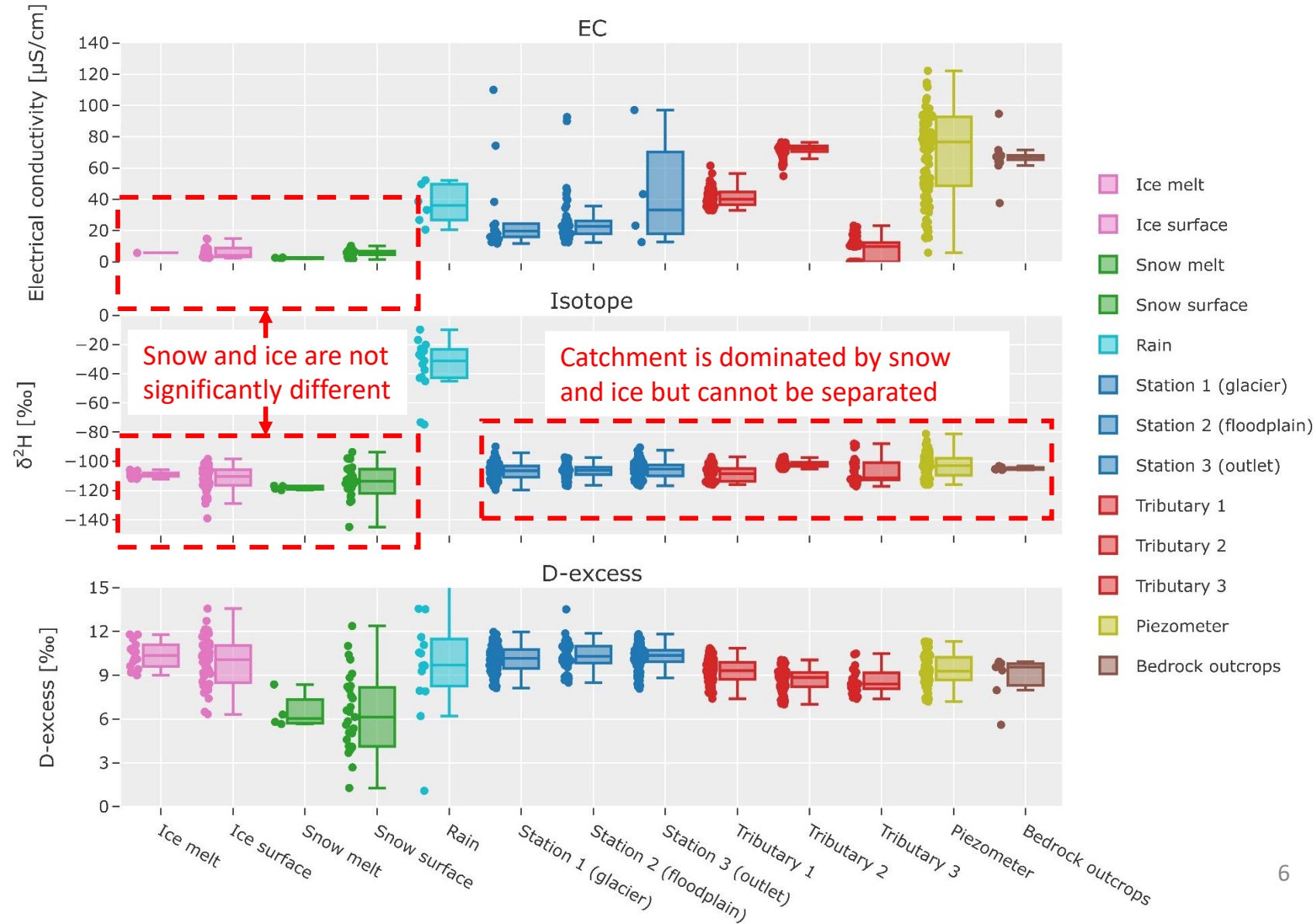


Sources of water

Water stable isotope ($\delta^2\text{H}$) & EC data, **overview**

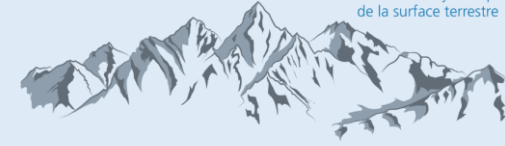


- Water isotopes of **snow** is spatially heterogenous and overlaps the **ice** signal
- Only **rain** can be detected clearly
- D-excess for snow is lower but has a large variability

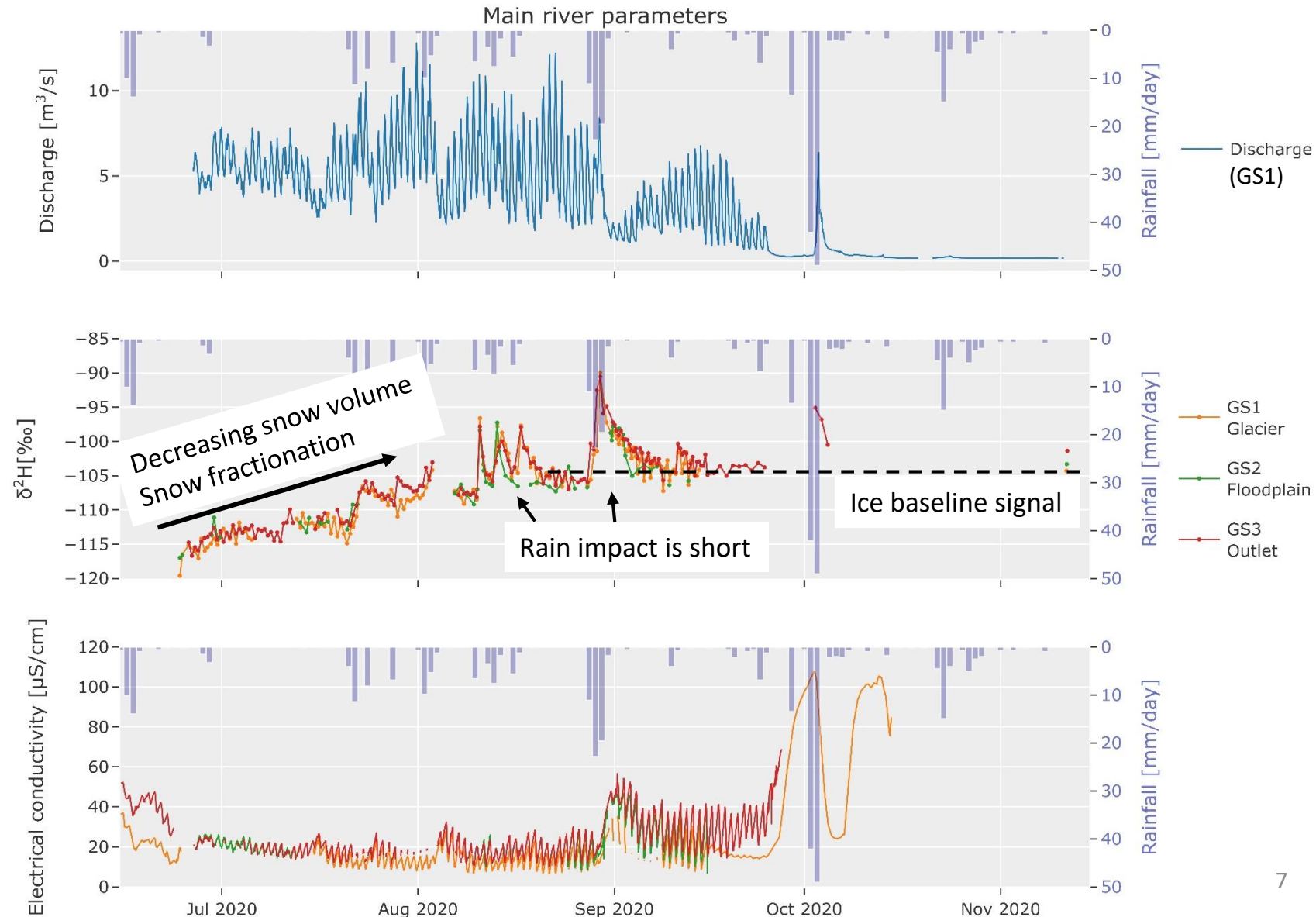


Sources of water

Water stable isotope ($\delta^2\text{H}$) & EC data in the **main river**



- No significant isotope ($\delta^2\text{H}$) or EC differences between the **glacier snout** and **catchment outlet** prevents quantification of lateral contributions
- End-member mixing analysis based on isotope is tricky because **snow fractionation** induces spatially heterogeneous values
- Snow/ice contribution could be assessed with a spatially-distributed snow fractionation model only
- Large **rain** events contribute only during short timescales



Sources of water

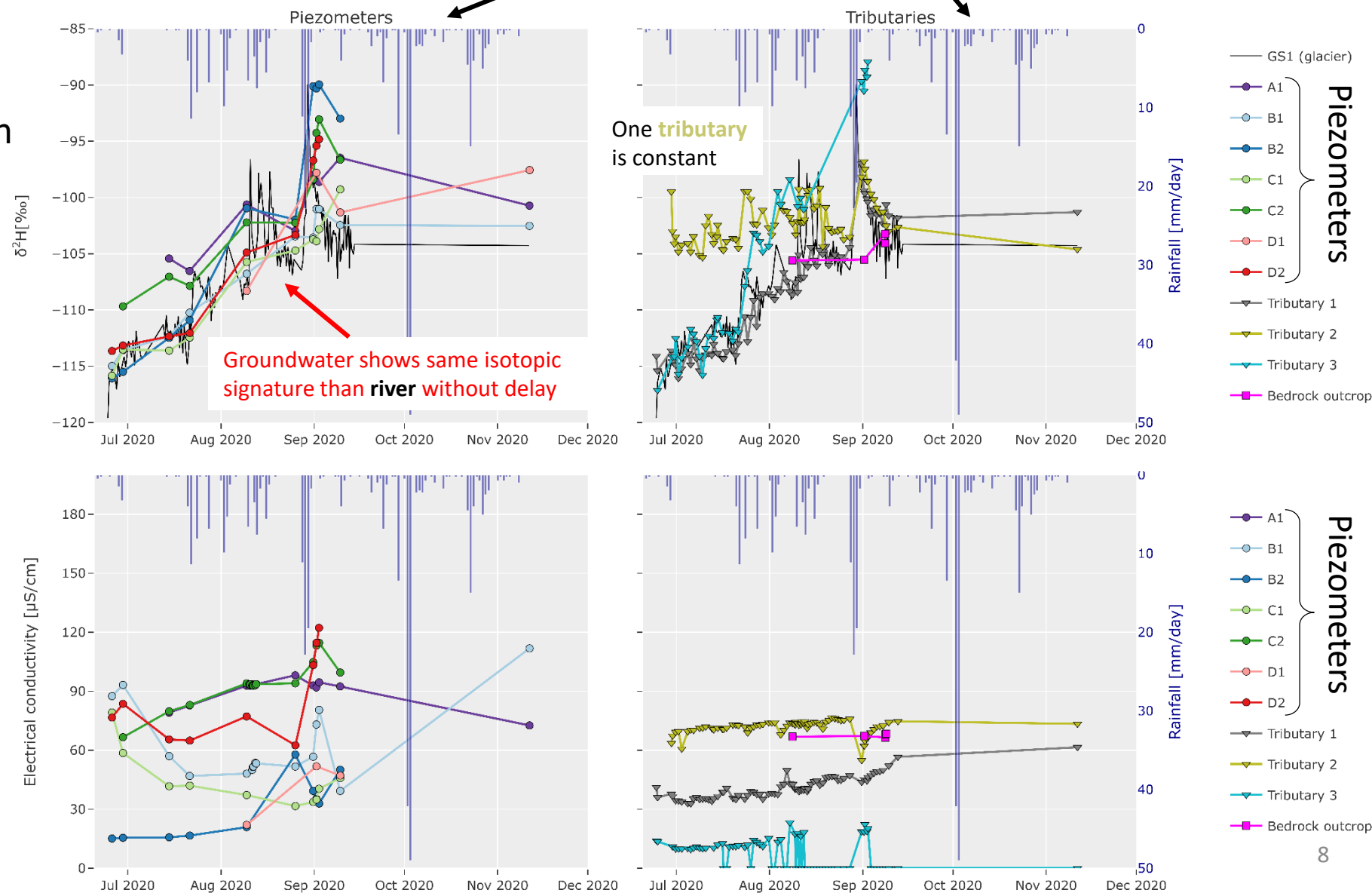
Water stable isotope ($\delta^2\text{H}$) & EC data in the **groundwater & tributaries**

- Piezometers in the outwash plain show same isotopic evolution than **river** even near the hillslope (**B2**, **C2**, **D2**)

=> very fast transit time from the river or strong hillslope influence ?
We need water age estimation !

- Tributary 2** is more constant and very similar to **bedrock** leakages

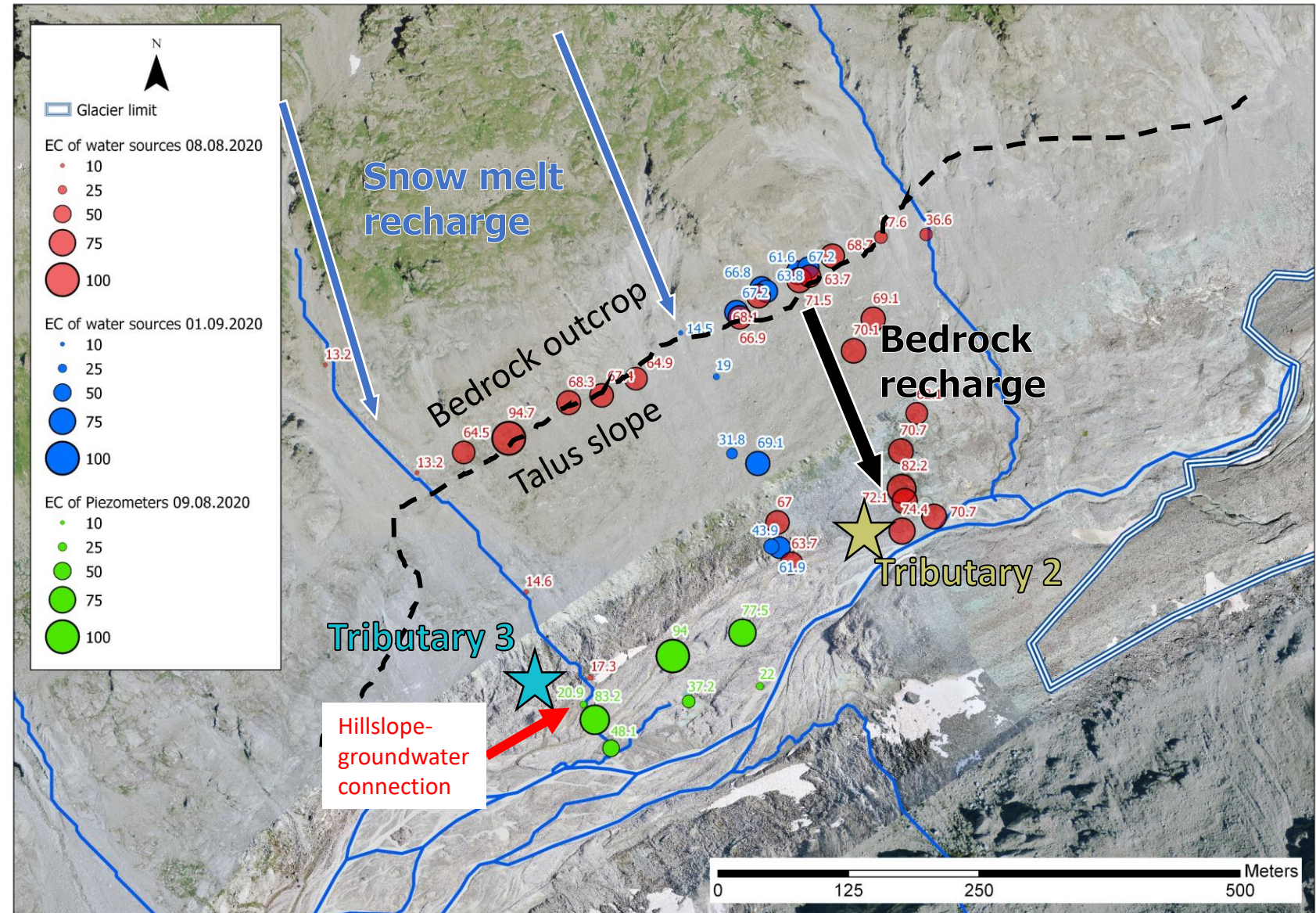
- Tributary 3** has low EC, is intermittent and most likely represents **snow** isotopic signature



Talus slopes & bedrock recharge

Looking at electrical conductivity of water sources

- **Bedrock leakages** at the outcrop constitute part of the talus slopes recharge (EC ~ 70 $\mu\text{S}/\text{cm}$) and provide constant water to **tributary 2**
- Intermittent **tributary 3** is sustained by **snow melt from hanging valleys** (lower EC) and percolates into the outwash plain
- EC in **piezometers** is highly **variable**
- Talus slopes itself does not seem to maintain water storage



A simple approach to identify relevant landforms for groundwater storage

Proposed idea (summary) :

Consider geomorphological landforms as simple hydrological units which release water following a recession constant α [time⁻¹] which inverse ($1/\alpha$) provides an idea of the timescale of water release.

For steeply sloping aquifers, the aquifer slope is mainly governed by the bedrock slope (θ) and a linear reservoir model has been shown to provide realistic estimates of its behavior (Rupp & Selker, 2006 or Harman & Sivapalan, 2009), thus we propose to use a first order estimation of α using simple catchment parameters :

$$Q_t = Q_o e^{-\alpha t}; \alpha \approx \frac{K_s \sin(\theta)}{\varphi \Delta L^2} \quad K_s \text{ the hydraulic conductivity; } \Delta L \text{ the aquifer flowpath length; } \varphi \text{ the porosity; } \theta \text{ the bedrock slope.}$$

A rapid literature review allows an estimate of **$1/\alpha$** , showing potential timescales at which landforms may play a role.

Author	Landform	Aquifer slope [%]	Porosity [-]	Aquifer length [m]	Slope parameter b [-]	Reported Ks [m/s]		Reported recession constant $1/\alpha$ in study [days]	Calculated recession constant $1/\alpha$ [days]	
						min.	max.		min.	max.
Muir et al. (2011)	Talus slopes	25	0.30	200	1.0	1.00E-02	3.00E-02	1	0.1	0.3
Caballero et al. (2002)	Lateral glacial deposits	25	0.25	200	1.0	2.90E-04		-	8	
Kobierska et al. (2015)	Glacial deposits	8	0.25	1000	1.0	5.15E-04	1.35E-03	0.27 (fast reservoir) 29 (slow reservoir)	27	71
Winkler et al. (2015)	Rock glacier	15	0.30	500	1.0	7.00E-05	4.60E-02	21 (early recession) 125 (20-80 days) 500 (late)	0.3	169
Käser et al. (2016)	Outwash plain	2	0.30	1000	0.5	6.00E-04	5.00E-03	-	35	289
This study	Outwash plain	2	0.30	1000	0.5	5.00E-04	4.00E-03	-	43	347

Key conclusions

- **Outwash plain** can **store a significant water** amount throughout the summer and autumn period (slide 5)
- **Strong river-outwash plain aquifer correlation** indicates strong river connectivity and thus a strong impact of river discharge or channel modifications on the available water storage (slide 5)
- But synchronous isotope evolution between river and the aquifer implies **very rapid flow paths** which would imply limited water storage/retention capacity which does not reflect the observed watertable evolution nor estimated hydraulic conductivity ? (slide 8)
- **Talus slopes only transmit water** from hanging valleys or from bedrock leakages (slide 8 & 9)
- The lack of EC increase in the river downstream of the outwash plain seems to indicate that **most groundwater contribution occurs from the outwash plain** and limited contribution from talus slopes or bedrock (slide 4)
- New outwash plain zone may emerge from future glacier retreat and may contribute to larger groundwater fractions but their water storage may be affected by less recharge due to less ice melt
- A careful consideration of water flow path lengths, terrain slope and sediment hydraulic conductivity should help in identifying the most relevant geomorphological landforms susceptible to sustain baseflow conditions (paper in preparation) (slide 10).
- **Vegetation onset** is mainly promoted by hillslope water sources (see also vPico [EGU21-4179](#)) but outwash plains will play a significant role in promoting larger vegetation that can reach water at depth of about 1 meter, but depends also on potential river channel deepening

Thank you for reading until here !

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