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Deciphering alpine stream responses to climate change: lessons from the METALP monitoring network

Nicola Deluigi and Andrew L. Robison
River Ecosystems Laboratory, Alpine and Polar Environmental Research Centre (ALPOLE), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Streams and rivers are increasingly recognized as vital components of the global carbon cycle, especially in the context of climate change. To comprehensively understand their impact, it is essential to move beyond the study of individual reaches and consider the entirety of fluvial networks, including their terrestrial interactions. This holistic perspective is crucial for integrating fluvial networks into Earth System models and accurately assessing their role in the global carbon cycle.

In this context, we describe the Metabolic Regimes in Alpine Stream Networks Program (METALP, https://metalp.epfl.ch), an ecohydrological and biogeochemical monitoring study of high-mountain streams in the Swiss Alps, running since 2016. Employing a network of high-frequency sensors (10-min) paired with monthly grab sampling, METALP examines the hydrological, thermal, light, and carbon regimes of high-mountain streams. Initially focused on the metabolism of alpine streams, the project has evolved to explore long-term trends in ecosystem characteristics and functions, with a particular emphasis on understanding climate change impacts. This unique observatory has so far collected over 20 million usable data points, describing annual regimes of streamwater flow, temperature, sediment load, carbon fluxes, and ecosystem metabolism.

We present insights into the hydrologic and biogeochemical consequences of glacier loss, along with findings on dissolved organic carbon, gas exchange and CO_2 emissions, oxygen concentrations, and gross primary production. Building on these insights, we then delve into the unique challenges associated with long-term monitoring in high-mountain catchments. These include marked hydrologic variability, with flows ranging over several orders of magnitude, and the need for monitoring equipment to withstand high flows, sediment loads, and avalanches, and remain functional during low flow periods. Seasonal snow cover and the remoteness complicate sampling campaigns and sensor maintenance. Additionally, the oligotrophic nature of high-mountain streams, with low analyte concentrations, necessitates sensitive monitoring programs capable of detecting subtle changes. These challenges inherently lead to gaps in data, necessitating not only technical adaptations for monitoring under difficult conditions but also innovative modeling strategies for compensating data loss.

Finally, the METALP network, along with river networks located in different climatic regions (i.e., the Krycklan catchment in Sweden, the StreamPULSE project, or the Arctic Great Rivers

Observatory), provides a broader perspective, enabling us to understand biogeochemical patterns and dynamics across multiple streams. This approach is crucial for constructing a comprehensive picture of stream biogeochemistry and its response to climate change.