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Rainfall as primary driver of discharge and solute export from rock glaciers: The Col d'Olen Rock Glacier in the NW Italian Alps

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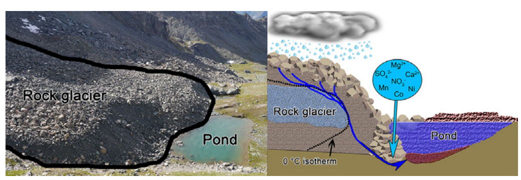
HIGHLIGHTS

- An intra-seasonal pattern of solute export from a rock glacier is described.
- Rain is the primary driver of rock-glacier discharge after snowmelt depletion.
- Increasing solute export is associated with higher rock-glacier discharge.

GRAPHICAL ABSTRACT



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ABSTRACT

Three hypotheses exist to explain how meteorological variables drive the amount and concentration of solute-enriched water from rock glaciers: (1) Warm periods cause increased subsurface ice melt, which releases solutes; (2) rain periods and the melt of long-lasting snow enhance dilution of rock-glacier outflows; and (3) percolation of rain through rock glaciers facilitates the export of solutes, causing an opposite effect as that described in hypothesis (2). This lack of detailed understanding likely exists because suitable studies of meteorological variables, hydrologic processes and chemical characteristics of water bodies downstream from rock glaciers are unavailable. In this study, a rock-glacier pond in the North-Western Italian Alps was studied on a weekly basis for the ice-free seasons 2014 and 2015 by observing the meteorological variables (air temperature, snowmelt, rainfall) assumed to drive the export of solute-enriched waters from the rock glacier and the hydrochemical response of the pond (water temperature as a proxy of rock-glacier discharge, stable water isotopes, major ions and selected trace elements). An intra-seasonal pattern of increasing solute export associated with higher rock-glacier discharge was found. Specifically, rainfall, after the winter snowpack depletion and prolonged periods of atmospheric temperature above 0 °C, was found to be the primary driver of solute export from the rock glacier during the ice-free season. This occurs likely through the flushing of isotopically- and geochemically-enriched icemelt, causing concomitant increases in the rock-glacier discharge and the solute export (SO_4^{2-}, Mg^{2+}, Ca^{2+}, Ni, Mn, Co). Moreover, flushing of microbially-active sediments can cause increases in NO_3^- export.

1. Introduction

Permafrost degradation has been reported to impact the chemical characteristics of surface fresh water across the globe (Frey and McClelland, 2009; Vonk et al., 2015; Colombo et al., 2018a). Active

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rock glaciers are considered indicators of ice-rich permafrost in mountainous environments (for a review: Haeberli et al., 2006). Tens of thousands of rock glaciers are estimated to exist worldwide (Barsch, 1996) and their water storage may be hydrologically significant in some areas and times (Jones et al., 2018). Recently, increases in electrical conductivity and solute concentrations have been found in some rock-glacier lakes in the European Alps (Thies et al., 2007; Ilyashuk et al., 2014, 2017) and in the outflow of a rock glacier in the Colorado Front Range (Williams et al., 2006). Similar evidence was reported from some Himalayan lakes over the past two decades, where significant enrichment in solutes has been attributed to the retreat of debris-covered glaciers (Salerno et al., 2016). In all these cases, the authors consider air temperature as the main climatic driver of change and hypothesise on underlying physical processes. Thies et al. (2013) also reported that rock-glacier outflows can be highly enriched in heavy metals. Seasonally, in the Northern Hemisphere, increased solute content has been reported in rock-glacier outflows from May to October (Krainer and Mostler, 2002; Krainer et al., 2007), with geochemically-enriched icemelt that progressively becomes predominant in rock-glacier outflows through the summer and fall seasons, after winter snowpack depletion (Williams et al., 2006).

The large area of mineral surfaces in contact with ice and undergoing chemical weathering in rock glaciers (Ilyashuk et al., 2014, 2017) is hypothesised to enhance the production of concentrated solutes in water (Williams et al., 2006; Fegel et al., 2016). Different hypotheses have been formulated to explain how weather and climate drive the export of solute-rich water from rock glaciers. Thies et al. (2007) proposed that atmospheric warming enhances solute export via ice melt at depth. Williams et al. (2006) suggested that a long-lasting snow cover reduces solute export by delaying subsurface ice melt, which is expected to release solutes, and that solute-rich water is diluted with snowmelt. Similarly, periods of summer rainfall were found to correspond with lower solute contents (Krainer et al., 2007), likely due to the low solute concentration in rain. By contrast, Thies et al. (2007) assumed rainfall to contribute to the export of solutes due to an intensification of water percolation through rock glaciers.

Generally, high-elevation impounded surface waters are considered key freshwater reference sites due to minimal direct human influence and because of their rapid hydrological, physical, chemical, and biological responses to climate-related changes (e.g., Catalan et al., 2006; Adrian et al., 2009; Tolotti et al., 2009; Salerno et al., 2014, 2016). A better understanding of the meteorological drivers responsible for solute export is therefore important for interpreting records of pond water quality and for anticipating and monitoring future changes. In this study, a pond adjacent to an active rock glacier located in the NW Italian Alps is used as a case study. At a weekly temporal resolution of observations, a pond has the advantage of integrating signals, which in a stream might otherwise vary too quickly to be sampled adequately (Guzzella et al., 2016; Salerno et al., 2016).

Some previous studies of the chemical characteristics of rock-glacier outflows (Williams et al., 2006; Thies et al., 2013) and lakes (Thies et al., 2007; Ilyashuk et al., 2014, 2017) exist. Their ability to reveal the response of these systems to meteorological drivers, however, is limited. This is because of low temporal resolution and only partial observation of the relevant meteorological, hydrologic, and chemical variables. Aiming to fill this gap, this study investigates how meteorological variables affect the export of solutes from a rock glacier into an adjacent pond.

In this study, a rock-glacier pond was monitored weekly, while the pond surface was without ice cover (ice-free season), during 2014 and 2015. The link between meteorological variables and hydrochemical characteristics was analysed by comparing air temperature, snowmelt and rainfall with the hydrochemical response of the pond as revealed by water temperature as a proxy of rock-glacier discharge, stable water isotopes, major ions and selected trace elements. Causal relationships between meteorological variables and pond response were investigated by analysing the differences in measured variables among three sampling points in the pond, considered representative of specific water sources.

2. Materials and methods

2.1. Study area

The Col d'Olen Rock Glacier Pond (45°52′8.22″N, 7°51′46.98″E) is located in the North-Western Italian Alps (Fig. 1a) along the Valle d'Aosta and Piemonte regions border, at an elevation of 2722 m a.s.l. The catchment area, determined by using a Digital Terrain Model (DTM, cell size: 2 m × 2 m, produced by Regione Autonoma Valle d'Aosta), is approximately 206,000 m^2 (Fig. 1b). The research site is a node of the Long-Term Ecological Research (LTER) network in Italy (http://www.lteritalia.it).

Geologically, from North to South, the Col d'Olen area is structurally composed by: i) the Monte Rosa nappe (micaschists and paragneisses with eclogite maphic rocks and aplitic tabular bodies); ii) the complex Ophiolitic Piedmont Zone, with the "Zermatt-Saas" unit (ophiolitic breccias, quartzite and manganese micaschists, phyllitic schists, and calcschists) and the "Combin Zone" unit (serpentinites and prasinites); and iii) the Sesia Lanzo Zone (gneisses of polimetamorphic origin) (Handy et al., 2010; Gasco et al., 2011; Steck et al., 2015).

A high-elevation automatic weather station (AWS) is operated at 800 m distance from the pond (Alpini Corps - Meteomont Service, Italian Army), the Col d'Olen station (2900 m a.s.l.). For the time span 2008–2015, the station recorded a mean liquid precipitation during the ice-free season of 400 mm and a mean annual air temperature of −2.6 °C. The snowpack generally developed by late October to early November. The snowpack usually becomes isothermal in late May to early June and melt out occurs in July.

The Col d'Olen Rock Glacier ("Corno Rosso 2 Rock Glacier" in the Aosta Valley rock glacier cadastre, http://geonavsct.partout.it/pub/GeoNavSCT/index.html?metadato=MTD010N0001) typology is a bouldery talus-tongue shaped (cf., Haeberli et al., 2006) (morphometric characteristics are listed in Table 1). The rock glacier is covered by boulders varying from tens of centimetres to several metres in size. Fine-grained sediments surface at the terminus and at the lateral scarps. Serpentinites constitute the main lithology of the fine-grained body, while calcschists and serpentinites are present as clasts and boulders on the surface. The rock glacier seems to be active based on limited lichen growth, sparse vegetation, microform evidence of recent movements in the steep frontal slopes, in addition to fresh and unstable boulders on the surface (Barsch, 1996; Millar and Westfall, 2008). The rock glacier is classified as intact according to the Aosta Valley rock-glacier cadastre. It has a main flow direction from NE to SW, towards a small valley depression where the pond is located (Fig. 1c) and no surficial springs or streams are visible. The contributing area of the rock glacier is 21,800 m^2, this is about 11% of the pond catchment. Given the possibility for sub-surface flow, the actual contribution area, however, could differ.

The pond has an elongated shape and is situated in front of the rock glacier, on the orographically right, marginal side of the tongue (Fig. 1c and d, Table 1). Its shoreline is surrounded by the rock glacier from NE to SE, with the front dipping into the pond, from N to SW by slopes with weathering deposits (scree accumulations and pedogenised fine-grained deposits often associated with alpine meadows) and a small rockfall deposit primarily composed of amphibolites, and it is partially bordered on the south by bare bedrock outcrop (calcschists). The pond has no persistent surficial inflows. Only a tiny ephemeral snowmelt stream that usually disappears during the ice-free season (July–August) is present; the stream had dried-out before the start of the investigated ice-free seasons 2014 (25 August to 9 October) and 2015 (9 July to 12 October). There are no surficial outflows from the pond and it is thermally mixed during the ice-free season (Colombo et al.,