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Hydrological significance of soil frost for pre-alpine areas

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ABSTRACT

Soil frost can have a substantial impact on water flows at the soil surface and—potentially—alter the dynamics of catchment runoff. While these findings are mainly based on studies from alpine and Northern-latitude areas (including permafrost areas), little is known about the significance of soil frost for hydrology in pre-alpine areas, i.e. the region at the transition from central European lowlands to high-alpine areas.

Here I synthesize soil temperature data and soil frost observations from ten sites in Switzerland to assess the occurrence of soil frost and to determine its impact on catchment runoff. In addition, a well-established numerical model was used to reconstruct the presence of soil frost in two first-order catchments for single runoff events and winters. The data clearly demonstrates that shallow soil frost has formed regularly in this altitudinal range over the past decade. The presence of a frozen soil surface was found to be highly variable among the sites under study and did not significantly correlate with altitude or forest density. For the first-order catchments, it was not possible to relate important flood peaks or increased runoff coefficients to winter situations with substantial soil frost. Thus, the present analysis suggests that although soil frost is widespread and regularly occurring at this altitudinal range, it has no significant impact on winter runoff in pre-alpine watersheds.

1. Introduction

In northern-latitude and high-altitude areas, soils are subjected to seasonal or permanent freezing. Zhang et al. (2003) estimates that 20–25% of the Northern Hemisphere is covered with permafrost, and approximately 50% of the exposed lands in the Northern Hemisphere encounters seasonal soil freezing. Soil frost can have manifold impacts on landscape, nature and infrastructure. It structures the soil surface (Kessler and Werner, 2003), deviates or inhibits water flow (Kane and Stein, 1983), reduces water uptake by plants in spring (Mellander et al., 2004) and may cause substantial damage to roads and buildings through heaving (Manz, 2011).

While most past research on soil frost and permafrost has focused on northern latitudes and high-alpine areas, little attention has been paid to lowlands, such as those of central Europe. Here, the occurrence of frozen soil surfaces is expected to be only temporal and of minor importance. For example, Kreyling and Henry (2011) explored trends in soil freeze-thaw cycles at 177 German weather stations from 1950 to 2000. In addition, Anis and Rode (2015) investigated the role of soil frost in overland flow generation in the lower Harz Mountains in central Germany.

Ascending from the lowlands to the mountains, air temperature decreases by 0.4–0.7 °C per 100 m (Rolland, 2003), which increases the potential for soil freezing at the same time as the buildup of an isolating snow cover. The combined effect of air cooling and snow-cover formation with regard to soil freezing is non-trivial. It is very much complicated by the large spatial heterogeneity of the microclimate and the surface vegetation, producing a highly variable snow-pack thickness across the landscape. As the heat conductance of snow increases exponentially with density (e.g. Sturm et al., 1997) not only the thickness but also the compaction of snow cover are first-order controls of soil freezing (Dutra et al., 2012).

Several studies of heat exchange at the soil-snow-atmosphere interface have demonstrated the considerable sensitivity of soil frost formation to the above-lying snow cover. For example, Goodrich (1982) concluded from his numerical model simulation that the depth of frost under snow cover is highly sensitive to details of the snow cover buildup. Further, Hirota et al. (2006) showed that the maximum annual frost depth correlates with the sum of negative air temperature only if the snow pack thickness is less than approximately 20 cm.

Systematic observations of the occurrence and spatial distribution of soil frost at the transition from lowland to high-alpine areas have been scarce. The most famous such long-term soil frost measurements have been carried out at the Hubbard Brook Experimental Forest, New Hampshire, USA, since 1965 (Campbell et al., 2010). In the Swiss pre-alps, no national monitoring systems are in place to record the occurrence of soil frost on a

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regular basis. The scarce soil frost observations that have been reported in the scientific literature originate from specific research projects investigating single sites and only for a few winters (e.g. Stadler et al., 1997; Bayard et al., 2005).

From numerous studies on soil columns, soil plot experiments and field observations, it is well known that a frozen soil surface can have substantial impacts on water infiltration and runoff. Depending on the ice content, the below-zero temperature and the type of the soil, its hydraulic permeability can be drastically reduced leading to an enhanced overland flow (Stähli et al., 1999). The soil pore system and, in particular, the presence of macropores play an important role in this context (Watanabe and Kugisaki, 2016). In addition, the feedback from small-scale topographic variability on soil frost formation is known to strongly control the flow paths of snowmelt infiltration (Hayashi et al., 2003).

While the local hydraulic effect of frozen soil is unambiguous, its significance for catchment runoff at larger scales is less distinct. Studies from Scandinavia (Lindström et al., 2002) and the United States (Cherkauer and Lettenmaier, 1999) have provided no significant evidence for an altered flood formation in winters with marked soil frost. This can be explained by the fact that soil frost often correlates with thin snow covers and, consequently, low amounts of snowmelt.

Here, the question of the occurrence and hydrological impact of soil frost on the pre-alpine elevation zone is addressed for the first time. Based on a comprehensive set of long-term soil temperature measurements and soil frost observations, together with a numerical heat and water transfer model at the soil-vegetationatmosphere boundary, I aim to answer the following questions: (a) How often and for how long is the soil surface typically frozen in this altitudinal range? (b) Is there a difference between forested and open locations in this respect? (c) What is the significance of soil frost for catchment runoff in these areas?

2. Materials and methods

2.1. Investigated area and locations

The present analysis focuses on the Swiss pre-alps, i.e., the montane, partly forested zone between the Swiss plateau and the non-vegetated Alps. The investigated sites (Fig. 1) span an altitudinal range from 880 m to 1790 m and include forested as well as non-forested locations. In this area, long-term mid-winter average temperatures are below the freezing point, and precipitation is abundant (Table 1). Thus, a significant snow cover of up to 2 m in depth builds up every year and covers the ground from November to April. The spatial and year-to-year variability in snow cover thickness is high and depends on altitude, exposure and forest coverage (Lopez-Moreno and Stähli, 2008). Specific soil, vegetation and topographic characteristics of the different investigated sites are summarized in Table 2. In-depth descriptions of the sites can be found in Graf-Pannatier et al. (2012) for Beatenberg and Schänis, in Zweifel et al. (2010) for Davos-Seehornwald, in Schleppi et al. (1998) for Erlenbach (Alptal), in Pellet and Hauck (2016) for La Frétaz, in Seneviratne et al. (2012) for Rietholzbach and in Stähli et al. (2011) for Sperbelgraben and Rappengraben. The latter two are first-order catchments with relatively small areas (<1 km^2), altitudinal ranges from 910 to 1250 m a.s.l and have mixed compositions of forest and open meadows.

2.2. Assessment of soil frost occurrence

The temporal occurrence of soil frost was assessed by means of long-term soil temperature measurements and manual observations. I used near-surface soil temperatures measured at ten locations (Table 2) between 1994 and 2015 overlapping with available measurements at all locations from 2000 to 2011 (see Fig. 2). The time resolution of these measurements was different, but not longer than 1 day.

At Beatenberg and Schänis, soil temperature was recorded along an altitudinal gradient, including four sub-sites at Beatenberg (at altitudes of 1790 m, 1640 m, 1430 m and 1290 m a.s.l.) and two sub-sites at Schänis (at altitudes of 1100 m and 970 m a.s.l). UTL-3 Scientific Dataloggers (Geotest, Switzerland), with an absolute accuracy of ±0.1 °C, were deployed at a depth of 5 cm. At Rietholzbach, soil temperature was measured every 30 min at 5-cm depth using Campbell T107 thermistors with a similar accuracy. At Davos-Seehornwald (5-cm depth) soil temperatures were recorded with MPS-1 sensors (Decagon Devices) with an absolute accuracy of ±1 °C. At the La Frétaz site (20-cm depth) PT100 resistance temperature sensors were installed with an accuracy of ±0.5 °C, and at Erlenbach (Alptal - 20-cm depth), soil temperature was measured using thermocouples with an absolute accuracy of ±0.1 °C. For the sake of comparability with the other sites, the corresponding soil temperature at 5-cm depth was extrapolated from the 20-cm-depth data at the latter two sites using the numerical model described in Section 2.4.

For all ten sites, the occurrence of soil frost was determined as follows. For days with soil temperatures close to and below the freezing point, the soil was classified as “possibly frozen” (+0.3 to −0.3 °C), “probably frozen” (−0.3 to −0.8 °C) or “definitely frozen” (< −0.8 °C) respectively. An unambiguous (sharp) derivation of soil frost occurrence from soil temperatures is not possible as the transition from frozen to unfrozen state is smooth and depends on soil water content and soil type (c.f. discussion in Section 4.2).

In addition, the presence or absence of a frozen soil surface was determined manually at 15 locations in the rear Alptal-catchment ($\sim$20 km^2) representing various altitudes, aspects and forest densities (or open meadows, respectively; see Table IV in Stähli and Gustafsson, 2006) on a weekly to monthly basis from 1998 to 2015. Since this assessment was made using a pointed rod pushed into the ground, it must therefore be denoted as *soft data* with a certain degree of subjectivity. Nevertheless, such an identification of a frozen soil surface is rather trustworthy and straightforward, and can be assumed to be fairly consistent as these observations were made by the same staff member for most of the time. Each time such soil frost observations were made, snow depth and snow density were determined simultaneously for the same location with a manual method described in Stähli and Gustafsson (2006). The same procedure to assess snow and soil frost was also performed once per week from 2000 to 2004 along four forested transects in the upper Sperbelgraben catchment (Badoux et al., 2006a).

2.3. Meteorological and hydrological data

For the data analysis, as well as for the application and verification of the numerical model (described in Section 2.4) the following hydro-meteorological data was available:

Alptal: A fully-instrumented weather station, located outside the forest near the soil frost measurements, provided values for air temperature, precipitation, relative humidity, global radiation and wind speed every 10 min. In addition, snow depth was measured continuously with a Judd Communications ultrasonic depth sensor. Runoff from the corresponding first-order catchment Erlenbach (0.7 km^2 area) has been recorded at 10-min to hourly time steps continuously since 1971 (Keller, 1990).

La Frétaz: Hourly records of air temperature, relative humidity, precipitation, wind speed and global radiation (since 1981) and snow depth (since 2009) were received from the local SwissMetNet surface weather station operated by MeteoSwiss.