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Research papers

Isotopic tracing of the outflow during artificial rain-on-snow event

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ABSTRACT

The frequency of rain-on-snow (ROS) occurrence is increasing and this natural phenomenon is beginning to play an important role in temperate climate regions. Present knowledge of outflow generation mechanisms and rainwater dynamics during ROS is still insufficient. The study introduces a combined method of artificial ROS, isotopic tracing and energy balance to partition the event rainwater and the pre-event non-rainwater in the outflow. A rainfall simulator and water enriched with deuterium were used for identifying event rainwater and pre-event non-rainwater during an ROS event.

The ROS experiment was conducted in the Krkonoše Mountains in the Czech Republic. An experimental snow block consisting of ripe and isothermal snow was sprayed with deuterium enriched water. The outflow from the snowpack was continuously monitored to gain quantitative and qualitative information about outflow water. The isotopic deuterium content was further analysed from the samples by means of laser spectroscopy in order to separate the hydrograph components. The deuterium content was also analysed from the snow samples gathered before and after the experiment to identify the retention of event rainwater in the snowpack.

Isotopic hydrograph separation revealed that although high rain intensity was applied, the event rainwater represented one half (52.7%) of the total outflow volume. The ripe snowpack retained about one third of the rainwater input (33.6%). Significant changes in the outflowing water quality can therefore be expected during ROS events. This experiment also shows that rainwater during ROS firstly pushes-out the non-rainwater and then contributes to the outflow. These results show that the presented technique allows us to gain sufficient information about rainwater dynamics during ROS.

1. Introduction

Rain-on-snow (ROS) events with associated snowmelt and snowpack transformation are important natural phenomena in temperate climate regions. Event rainwater can be either stored in the snowpack or flow through the snowpack toward the soil surface. Released water from the snowpack reaches the stream through the soil environment, by the surface runoff, or via the lateral flow in the snowpack (Eiriksson et al., 2013). ROS events can significantly increase the risk of floods, especially during snowmelt (Böhm et al., 2011; Čekal et al., 2011; Ferguson, 2000; HND Bayer, 2011; Singh et al., 1997; Sui and Koehler, 2001).

The pioneering study of Ambach and Howorka (1966) and numerous later studies have examined the ROS-induced wet avalanches (Carran et al., 2000; Conway and Raymond, 1993; Conway, 1994; Kattelmann, 1987a; Marshall et al., 1999) and slushflows (Gude and Scherer, 1999; Hestnes and Sandersen, 1987; Tomasson and Hestnes, 2000).

ROS events also affects the water quality in the adjacent streams, because rainwater mostly has a different chemical composition compared to stream water. Whereas Jones et al. (1989) found that up to 20% of the ionic mass in snow may be released by the ROS, significant oscillation of solutes concentration or pH values were observed in the stream water during natural ROS events (Casson et al., 2014; Dozier et al., 1989; Maclean et al., 1995).

Understanding of the processes in the snowpack during ROS is very important for hydrological modelling, natural hazards forecasting and prediction of water quality and chemical composition of the streams. The need to properly understand rainwater

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behaviour in the snowpack increases with higher ROS frequencies in higher altitudes which are expected in the temperate areas under changed climate conditions (Surfleet and Tullos, 2013).

During ROS events, the rain adds additional volume and energy to the snowpack, which subsequently affects the snowmelt, the snow metamorphism and the snow structure. Rainwater supports additional snowmelt during the warm-up of the snowpack (Kattelmann, 1987a). Liquid water also causes grain coarsening (Conway, 1994; Tusima, 1985), snow settlement and further densification (Marshall et al., 1999). These processes often lead to a weakening of the grain bonds, which can subsequently cause avalanche formation (Conway and Raymond, 1993). The water flow and storage in the snowpack are controlled by several factors, such as snow temperature, snow stratigraphy, grain size and snow ripeness (Colbeck and Davidson, 1973; Kattelmann, 1987b; Singh and Singh, 2001). Previous studies have also shown that new snow can hold much more water than ripe snow (Colbeck and Davidson, 1973; Martinec, 1987; Singh and Singh, 2001). Previous artificial ROS experiments revealed that ripe stratified snow can hold around 7% liquid water and this volume can double near the ice layer surface (Singh et al., 1997). Flowing velocity in the snowpack also affects the hydrological response of the snowpack under heavy rain. Kattelmann (1987a) mentions that this transmission rate is very variable and can reach up to 3 cm min^{-1} during natural ROS events. Several field sprinkling experiments have shown that, in extreme cases, the vertical water flow velocity reaches 10 cm min^{-1} (Kattelmann, 1987a; Singh et al., 1997).

Previous research of snowmelt-dominated ROS events has often been focused on partitioning the hydrograph into the meltwater component and the pre-event (subsurface water) component in the outflow within the catchment scale. This task has often been carried out by use of environmental tracers such as stable isotopes $\delta^{18}O$ and $\delta^{2}H$ (Buttle et al., 1995; Casson et al., 2014; Dinçer et al., 1970; Laudon et al., 2002; Maclean et al., 1995; Suecker et al., 2000). One of the first applications of isotopic tracers was conducted by Dinçer et al. (1970) in the Modrý Důl basin in the Krkonoše Mts, Czech Republic. This pioneering study revealed that two thirds of the total outflow from the catchment during the melting period originated from the subsurface storages. Another analysis of two natural ROS events in Canadian catchments established that rainwater contributed to the total outflow volume by 33% and 50% (Maclean et al., 1995). Nevertheless these studies (Dinçer et al., 1970; Maclean et al., 1995) were focused on the catchment scale, which usually leads to uncertainties in the runoff component separation caused by process heterogeneities at larger scales. However, the assessment of the rainwater ratio contributing to the outflow from the snowpack across scales is critical for understanding of runoff generation processes (Holko et al., 2015) and runoff modelling (Viviroli et al., 2009) up to catchment scale.

In the past decades, the impact of rain on the processes within the snowpack during ROS events has often been addressed using rainfall simulations or artificial snow wetting (Conway and Benedict, 1994; Eiriksson et al., 2013; Feng et al., 2001; Juras et al., 2013; Lee et al., 2010a; Marshall et al., 1999; Singh et al., 1997; Taylor et al., 2001). The most relevant studies are compiled in Table 1. The main focus of these studies addressed the investigation of ROS influence on solute transport through a snowpack (Feng et al., 2001; Lee et al., 2010a, 2008), runoff generation (Eiriksson et al., 2013; Singh et al., 1997), and particular mechanisms of water infiltration into the snowpack (Avanzi et al., 2015; Conway and Benedict, 1994; Kattelmann, 1987b). Some studies also focused on isotopic changes of water flowing through the snow, for instance pouring of isotopically enriched water to a snow-filled column in a cold laboratory environment (Herrmann et al., 1981). In this context, an increase in the $\delta^{18}O$ isotopic content of the outflow water was observed.

However, none of these experimental studies have partitioned the snowpack outflow hydrograph into event rainwater and pre-event non-rainwater in the natural snowpack during the rain event. Our study fills this gap and presents an innovative combination of a rainfall simulation technique with outflow partitioning. The expected main contribution of the experimental facility includes a better understanding of snowpack mass balance and rainwater propagation to the outflow during ROS events. It is assumed that the point scale approach brings more detailed insights into the process of runoff generation in contrast to catchment scale (Dinçer et al., 1970; Maclean et al., 1995) or the wetting of non-natural snow column approach (Herrmann et al., 1981). This paper addresses the main scientific question, whether the presented technique is suitable for investigation of rainwater interaction with snowpack and rainwater dynamics in the outflow.

2. Study site

The experiment was carried out on April 14th and 15th, 2012 near the Labská bouda chalet (50°46′13″N, 15°32′45″E), in the crystalline Krkonoše Mountains (Giant Mountains) in the Czech Republic at an elevation of approximately 1300 m (Fig. 1). The site of the experiment is located in the headwaters of the river Labe catchment, approximately 800 m southeast from the source of the Labe river. This part of the headwaters is oriented southwest-southeast, and the elevation ranges from 1270 m to 1465 m. The weather station, operated by the Czech Hydrometeorological Institute, is located 300 m southwest from the study site. This station monitors: air temperature, precipitation, snow depth, wind speed, wind direction, relative air humidity and global radiation. The mean April air temperature at Labská bouda is 0.6 °C and the mean precipitation sum from November until May is 795.7 mm (1962–2005). The mean duration of snow cover during the same period at the weather station is 161 days. During the 2011–2012 winter season (November–May), the weather station has recorded 944.5 mm of precipitation. The maximum snow depth at the weather station reached 260 cm in February 2012. The catchment is also significantly affected by the west and northwest winds that transport substantial portions of the snow on the leeward slopes and cause uneven snow depth distribution (Janásková, 2006). This fact was supported by the snow depth records from April 14th, 2012, when the snow depth was 144 cm near to the weather station and over 300 cm at the site of the experiment.

3. Material and methods

3.1. Experimental setup

A specially-tailored rainfall simulator (Fig. 2) was used for the experiment which was described by Juras et al. (2013). Water was sprayed on the snow block through a nozzle and the rain intensity was driven by water pressure in the system. The outflow was measured continuously by a tipping bucket flow meter (Fig. 3). The whole experiment lasted 734 min, from the beginning of the snow melt water recording (April 14th 2012 at 12:45) until the end of the discharge recording (April 15th 2012 at 0:59). Stable weather prevailed during the entire experiment. The air temperature varied between +0.8 °C at the beginning of the experiment and −0.3 °C at the end of the experiment. The temperature of the artificial rainwater varied between 7.2° and 10.7 °C during 61 min of the simulation. Natural snowmelt rate of approximately 0.05 L min^{-1} was observed prior to sprinkling.