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Hydrological response of an Alpine catchment to rainfall and snowmelt events

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SUMMARY

Alpine catchments are important sources of fresh water but compared to lower altitude catchments our understanding of the hydrological functioning of these catchments during rainfall and snowmelt events is still limited. The objectives of this study were i) to identify the dominant runoff generation mechanisms in the 0.14-km^2 Bridge Creek Catchment in the Italian Dolomites during nine rainfall–runoff events and six snowmelt–runoff events in spring, summer and autumn of 2010–2012; and ii) to assess the effect of the selection of the pre-event water sample on the isotope hydrograph separation results. The isotopic composition of the pre-event water was determined by either a stream water sample taken prior to the event or the average of 19 stream water samples taken during baseflow conditions. The hydrograph separation results for the two methods were very similar for the rainfall events but differed for the snowmelt events. Average event water contributions ranged between 4% and 19% or 2% and 20% of the total runoff during rainfall events, and between 7% and 25% or 9% and 38% during snowmelt events, depending on the method used to determine the isotopic composition of pre-event water. Event water contributions were important during large rainfall events, intense rainfall events and late in the snowmelt season, with maximum event water contributions up to 37% and 46%, depending on the method used for determining the pre-event water composition. The electrical conductivity of stream water tended to first decrease and reach a minimum before peak streamflow and then to increase above pre-event values. The results of this study suggest that during dry conditions, direct channel precipitation and overland flow from the permanently saturated part of the riparian zone dominated the runoff response, with limited contributions of riparian or hillslope groundwater. During wet or very wet conditions (large rainfall events or peak snowmelt), saturation overland flow increased due to the expansion of the saturated areas and riparian groundwater and hillslope subsurface flow to streamflow increased as well. On the one hand, this work contributes to a better understanding of runoff generation processes in mountain headwater catchments where rainfall and snowmelt events dominate the hydrological response. On the other hand, this study highlights the sensitivity of the two-component hydrograph separation technique to the selection of the pre-event water sample for snowmelt events. This calls for further studies in snow-dominated catchments to determine the consistency of the isotopic composition of stream water prior to individual snowmelt events and to assess whether the individual melt events during the melt season should be considered part of a single long snowmelt event.

1. Introduction

Mountain areas are important sources of streamflow. Understanding the hydrological functioning of headwater mountain catchments is, therefore, critical for scientific and management reasons, including flood forecasting, water supply and the protection of stream habitat. Mountain headwater catchments are commonly characterized by steep topography and shallow soils, which significantly affect runoff production and nutrient and solute transport (Tetzlaff et al., 2009; Payn et al., 2012). The two most obvious landscape units in these environments, hillslopes and the riparian zone, are characterized by a different hydrological behavior (McGlynn and McDonnell, 2003; Camporese et al., 2014).

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The water table tends to be high and close to the surface in the riparian zone, while it is deeper on the hillslopes. The riparian zone acts as a hydrological buffer because water from hillslopes must pass through the riparian corridor prior to contributing to streamflow (McGlynn and McDonnell, 2003). Marked increases in runoff are observed when the hillslopes and stream connect and a hill slope-riparian-hyporheic-stream continuum is established (Ward et al., 2013). The establishment of connectivity is influenced by catchment wetness conditions, event size, soil properties and surface and bedrock topography (Detty and McGuire, 2010; McGuire and McDonnell, 2010; Jencso and McGlynn, 2011).

Environmental tracers, particularly stable isotopes of water (^{2}H and ^{18}O) and electrical conductivity (EC), have been used in many catchment studies to infer the dominant hydrological pathways. The tracer-based hydrograph separation technique allows partitioning streamflow into pre-event water (water stored in the catchment prior to the rainfall or snowmelt event, assumed to be groundwater) and event water (input to the catchment, i.e., rainfall or snowmelt) (e.g., Pearce et al., 1986; Buttle, 1994) and has been used extensively to test the role of subsurface flow and preferential flow paths in transferring event water to the stream during rainfall (Peters et al., 1995; Buttle and Peters, 1997) and/or snowmelt events (Wels et al., 1991; Buttle and Sami, 1992) and to describe the rapid mobilization of pre-event water and its dominant contribution to stormflow (e.g., Muñoz-Villers and McDonnell, 2012; Penna et al., 2015b). Recent studies in high-elevation catchments have shown that isotopic and geochemical tracers can also help to assess the sources of streamflow at the annual and seasonal scale (Liu et al., 2012; Jeelani et al., 2013) and during spring snowmelt (Jin et al., 2012), to estimate glacier melt and snowmelt contributions to streamflow (Dahlke et al., 2014; Engel et al., 2016), and to determine the importance of snowmelt for groundwater recharge (Penna et al., 2014; Šanda et al., 2014). In mountainous catchments that are not dominated by snowmelt, stable isotopes and geochemical tracers allowed for the examination of the controls on hillslope-stream connectivity (McGuire and McDonnell, 2010), investigation of the vertical movement of soil water and mixing processes (Dusek et al., 2012), analysis of the onset of rapid flow pathways (Hrachowitz et al., 2011; Figueiredo et al., 2013) and estimation of water age and transit time distributions and the controls on their spatial variability (Asano and Uchida, 2012; Hrachowitz et al., 2013). Despite the wide use of isotope tracers in hydrological studies, most studies to date have focused on single rainfall events (e.g., Ladouche et al., 2001), a few rainfall events during the wet season (Muñoz-Villers and McDonnell, 2012) or a few events during the snowmelt period (Shanley et al., 2002). Relatively few studies have examined runoff generation processes during rainfall and snowmelt events and compared the hydrological responses during these events (e.g., Shanley and Chalmers, 1999; Šanda et al., 2014). Snowmelt is generally the most important contributor to runoff in mountain catchments in spring and early summer (Liu et al., 2012; Šanda et al., 2014) but large rainfall events affect streamflow as well and may result in the highest peak flows (Mirus and Loague, 2013). Thus, in order to gain more detailed knowledge on runoff generation for catchments where snowmelt and rainfall are important, a comparative analysis during rainfall and snowmelt events is necessary, particularly to study the effects of antecedent wetness conditions, event size and rainfall intensity on the fraction of event water (e.g., Brown et al., 1999; Shanley et al., 2002; Muñoz-Villers and McDonnell, 2012).

Previous hydrograph separation studies have either used a sample of stream water collected prior to the onset of the rainfall or snowmelt event (e.g., Sklash and Farvolden, 1979; Hoeg et al., 2000; Blume et al., 2008) or the average isotopic composition of stream water during baseflow conditions (e.g., Shanley et al., 2002; Maurya et al., 2011) to represent the isotopic composition of pre-event water. The choice of the method may affect the results of the hydrograph separation analyses, and thus the interpretation of the dominant hydrological flow pathways, but detailed studies on the effects of the choice of the pre-event water sample are rare.

In this study, we used three years of hydrometric, isotopic and EC data to gain a better understanding of the dominant runoff mechanisms and the hydrological functioning of a small Alpine catchment during rainfall and snowmelt events. Specifically, we addressed the following research questions:

(i) What is the relative contribution of event water to streamflow and what factors affect the event water fractions in streamflow during rainfall and snowmelt events?
(ii) What are the dominant flow pathways for the transport of event and pre-event water to the stream?
(iii) Does the selection of the pre-event water sample significantly affect the results of the hydrograph separation analyses?

2. Study area

The research took place in the 0.14-km^2 Bridge Creek Catchment (BCC, Fig. 1), located in the Italian Dolomites, Central-Eastern Italian Alps. Average monthly temperatures (period 1985–2006) vary between −5.7 °C in January and 14.1 °C in July; mean annual precipitation is 1220 mm/year, of which 49% falls as snow. The elevation in BCC ranges from 1932 m to 2515 m above sea level (a.s.l.). The highest part of the catchment is characterized by sub-vertical dolomitic walls, whereas the central and lower parts are covered by Quaternary deposits, where vegetation is dominated by Alpine grassland and sparse small trees (*Picea abies* and *Larix decidua*). The hillslopes are short and steep (40–45°) and end quite abruptly in a narrow riparian zone. The riparian zone is 1.2 ha in size and occupies 8.6% of the catchment area (as estimated by Penna et al., 2011). The stream is 374 m long and, on average, 0.5 m wide. The permanently saturated area, estimated on several occasions in late spring, summer and early fall of 2010–2012 using the approach of Rinderer et al. (2012) (wetness classes 6 and 7) combined with mapping of hydrophilic vegetation, is 1145 m^2 or 0.8% of the catchment area (stream included). Soil depth in the lower part of the catchment, estimated by the depth to refusal method, varies between 0.10 m on the upper hillslopes to 1.43 m at the bottom of the hillslopes (Penna et al., 2015a) and is greater than 1.5 m in the riparian zone. The soil is classified as a Cambisol with mull, containing a thick surficial layer of organic matter. Porosity ranges between 71% in the first 10 cm of soil and 45% in the deeper layers (mean value for the 0.70 m profile: 58%). Macropores, mesopores and micropores represent 59%, 7% and 34% of the total porosity, respectively. Clay content ranges between 45% and 73%. The average saturated hydraulic conductivity, measured at 0.20 m depth at seven locations on the hillslopes with a Guelph permeameter, is 3.0×10^{-6} m/s. Further information on the study site is given in Penna et al. (2011, 2013).

3. Materials and methods

3.1. Meteorological and hydrological measurements

Precipitation, air temperature, and streamflow were measured continuously from mid-March to the end of October 2010–2013. Rainfall was measured by a 0.2 mm tipping bucket raingauge (Onset Computer Corporation, United States of America) in the lower part of the catchment, at 1940 m a.s.l. and aggregated to a 15-min interval. Air temperature was recorded every 15-min using