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Implications of hydrologic connectivity between hillslopes and riparian zones on streamflow composition

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ABSTRACT

Hydrological responses in mountainous headwater catchments are often highly non-linear with a distinct threshold-related behavior, which is associated to steep hillslopes, shallow soils and strong climatic variability. A holistic understanding of the dominant physical processes that control streamflow generation and non-linearity is required in order to assess potential negative effects of agricultural land use and water management in those areas. Therefore, streamflow generation in a small pre-Alpine headwater catchment (Upper Rietholzbach (URHB), ~1 km^2) was analyzed over a 2-year period by means of rainfall-response analysis and water quality data under explicit consideration of the joint behaviors of climate forcing and shallow groundwater dynamics. The runoff coefficients indicate that only a small fraction of the total catchment area (1–26%) generates streamflow during rainfall events. Hereby, the valley bottom areas (riparian zones) were the most important event-water source whereas only the lower parts of the hillslopes became hydrologically connected to the river network with higher antecedent moisture conditions. However, a distinct threshold-like behavior could not be observed, suggesting a more continuous shift from a riparian-zone to a more hillslope-dominated streamflow hydrograph. Regular manure application on the hillslopes in combinations with lateral hillslope groundwater flux and long groundwater residence times in the riparian zones resulted in a higher mineralization (e.g., total phosphorous) and significant denitrification in the valley bottom area. Despite the important role of the riparian zones for event-flow generation in the URHB, their nutrient buffer capacity is expected to be small due to the low permeability of the local subsurface material. The findings of this integrated analysis are summarized in a conceptual framework describing the hydrological functioning of hillslopes and riparian zones in the URHB.

1. Introduction

Understanding the hydrologic connectivity between hillslopes and the river system as well as the dominant groundwater-flow pathways can help to assess implications of land use on river water quality (e.g., Burt and Pinay, 2005; Pringle, 2003; Tetzlaff et al., 2007). Thus, long-term, seasonal or event-based monitoring of river water quality (i.e., solutes used as environmental tracers) provides valuable information about the source zones of catchment streamflow (e.g., quickflow, baseflow) and groundwater–surface water interaction processes (e.g., Cook and Herczeg, 2000; Leibundgut and Seibert, 2011). In association with agricultural land use, various studies found a rapid and significant increase of nutrient export rates when potential source areas become hydrologically connected to the river system during rainfall events (e.g., Doppler et al., 2012; Ocampo et al., 2006; Stieglitz et al., 2003).

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In mountainous catchments the hillslopes are often agriculturally used (e.g., pastureland, cattle grazing), which is generally accompanied with the application of fertilizers. Thus their hydraulic and hydrological connectivity with the rivers and riverine areas is inextricably linked to the mobilization and transport of solutes, such as nutrients and pollutants, to the surface waters fed by mountainous catchments (e.g., Jencso et al., 2010; Thompson et al., 2012; van Verseveld et al., 2009). The flushing out and drainage of such substances from agriculturally used hillslope areas can have a negative effect on the riverine ecosystem and may harm aquatic organisms in these particularly vulnerable high-elevation environments.

Landscape properties (e.g., topography, vegetation patterns, soil type distributions) have been identified as important drivers for catchment hydrology, which makes them an appropriate tool for investigating runoff generation mechanisms at various spatial scales (McGlynn et al., 2004). In mountainous regions large portions of the landscape are hillslopes, which makes them the dominant landscape unit that essentially act as filter for climatic and biogeochemical responses (Bachmair and Weiler, 2011). Numerous hillslope and catchment-scale studies focused on the investigation of subsurface flow mechanisms and characteristic threshold responses that drive non-linear hydrological processes. Hereby, valuable information can be obtained by investigating the response dynamics of river flow, hydrochemistry and shallow groundwater tables to rainfall events. For instance, Haga et al. (2005) found a clear shift in lag time (time between peak rainfall and peak discharge) a suitable proxy for the activation of hillslope groundwater flux towards the river system. Many of these studies proved a strong dependency of the rainfall-responses on antecedent moisture conditions (e.g., James and Roulet, 2009; Penna et al., 2011; Sidle et al., 1995; Tromp-van Meerveld and McDonnell, 2006b), which is a proxy for the overall degree of hydrologic connectivity among the active landscape units (e.g., hillslopes) with the river system. Generally, during “wet” conditions a larger portion of the catchment contributes to streamflow (i.e., high degree of connectivity) compared to “dry” conditions in which the hydrologically active zones are small (i.e., low degree of connectivity) (James and Roulet, 2009).

Further, total rainfall and rainfall intensity (e.g., Anderson et al., 2009; Tromp-van Meerveld and McDonnell, 2006b), shallow groundwater flow pathways (e.g., Detty and McGuire, 2010; Haught and Meerveld, 2011; Rodhe and Seibert, 2011; Wienhöfer et al., 2009), and subsurface properties (e.g., Graham et al., 2010) were found as important first-order controls on streamflow response and solute export (Burt and Pinay, 2005). In complex landscapes such as mountainous catchments, a mechanistic understanding of the hillslope groundwater re- and discharge dynamics and the interrelations between the other landscape units builds the foundation for the conceptualization of the catchment's hydrological behavior, which is relevant in the context of water quality management or flood prediction.

Thus, the rationale for the present work is to improve the mechanistic understanding of stream-landscape connectivity and to highlight possible implications on nutrient transport from agriculturally used hillslopes. For this, a small pre-Alpine headwater catchment (~1 km^2) in Switzerland was chosen as a case study since its hydro-climatology was shown to be representative for the wider region of the eastern Swiss Plateau (Seneviratne et al., 2012). The present study investigates the hydrological functioning of this catchment with focus on shallow groundwater variations at the hillslope-scale and its implications on nutrient export from agricultural areas. The integrated analysis is carried out by means of spatially dense and high-frequency hydrometric observations and a detailed investigation of rainfall-response dynamics.

The paper is organized as follows: Section 2 provides information about the small pre-Alpine headwater catchment and experimental set-up. In Section 3.1 a conceptual model of the dominant groundwater flow processes at the hillslope scale is derived based on hydrometric observations and rainfall-response analysis. In Section 3.2, the analysis of streamflow-rainfall response facilitates the transfer of the conceptual model from the hillslope- to the catchment scale. Section 3.3 compares seasonal effects of hydro-climatic variables on river- and groundwater quality under consideration of the conceptual model. In Section 3.4, the respective portions of streamflow-generating areas are estimated and possible implications for solute export from those landscape units are derived. The present work is critically evaluated and put into the broader context of hydrological behavior of mountainous catchments in the conclusions-section.

2. Materials and methods

2.1. Site description and Instrumentation

The Rietholzbach Research Catchment (RHB, ~3 km^2) is a first-order watershed of the Thur river that is located in the pre-Alps in north-east Switzerland (Fig. 1a). The present study focuses on the Upper Rietholzbach sub-catchment (URHB, ~0.94 km^2) that comprises the western part of the RHB. The local climate is characterized by temperate humid conditions with an elevated thunderstorm frequency in summer (MeteoSchweiz, 2013). The landscape is dominantly used for cattle grazing and hay production, which is associated with regular manure application. Around 19% is forested and settlements and streets cover approximately 4% of the catchment area.

The geology of the URHB is characterized primarily by the Tertiary Upper Freshwater Molasse (UFM, consolidated clastic sediments and layers of marls, sandstones and freshwater limestone) and quaternary moraine deposits from the Würm glacial period (QMD, unconsolidated gravel pockets). The latter is accumulated primary in the valley bottoms and the lower hillslopes, whereas the UFM-unit generates steep slopes and hilltops in the URHB (Fig. 2a). Generally, shallow Regosols developed on the UFM-unit. On the hillslopes of the QMD locally several meter thick Cambisols can be found, which become Gleysols and peaty soils in the more shallow areas and in the valley bottoms (Fig. 1a). Here, hydraulic conductivities are very low resulting in a limited infiltration capacity of the Gleysols and peaty soils (Germann, 1981).

An extensive groundwater-monitoring network (Büel site) is located on the south-facing slope in close vicinity to the outlet of the URHB (Fig. 1b). Here, a dense cluster of standard 2″-groundwater observation pipes (i.e., piezometers with pipe diameter of 5.08 cm) was installed in the shallow QMD-aquifer along the hillslope and the bottom area using Direct Push Technology (Geoprobe®, USA). Along with piezometer installation soil cores