Journal of Hydrology 367 (2009) 177–187

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

The role of hillslope hydrology in controlling nutrient loss

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ARTICLE INFO

Article history:
Received 29 September 2007
Received in revised form 10 August 2008
Accepted 4 November 2008

This manuscript was handled by G. Vachaud, Editor-in-Chief

Keywords:
Hillslope hydrology
Small watershed
Dissolved organic carbon
Dissolved organic nitrogen
Specific UV-absorbance

SUMMARY

Hydrological controls on DOC and N transport at the catchment scale were studied for five storm events from the fall of 2004 through the spring of 2005 in WS10, H.J. Andrews Experimental Forest in the western Cascade Mountains of Oregon. This catchment is devoid of any riparian zone and characterized by hillslopes that issue directly into the stream. This enabled us to compare a trenched hillslope response to the stream response without the influence of riparian zone mixing. DOC and N concentrations and dissolved organic matter (DOM) quality (specific UV-absorbance (SUVA) and C:N of DOM) were investigated at the plot scale, in lateral subsurface flow from the trenched hillslope and stream water at the catchment outlet at the annual and seasonal scale (transition vs. wet period) during baseflow and stormflow conditions. DON was the dominant form of total dissolved nitrogen (TDN) in all sampled solutions, except in transient groundwater, where DIN was the dominant form. Organic horizon leachate and transient groundwater were characterized by high SUVA, and high DOC and total N concentrations, while SUVA and DOC and DON concentrations in lysimeters decreased with depth in the soil profile. This suggests vertical preferential flow without much soil matrix interaction occurred at the site. Deep groundwater (from a spring at the base of the hillslope) was characterized by low SUVA and low DOC and N concentrations. SUVA was always lower in lateral subsurface flow than in stream water at the seasonal scale, even during the wet period when other solutes were similar between lateral subsurface flow and stream water. This suggested mixing of deep groundwater and shallow transient groundwater was different at the hillslope scale compared to the catchment scale. DOC and DON sources were finite (production of DOC and DON from the hillslope soils appeared to be limited) at the seasonal scale since DOC and DON concentrations were significantly lower during the wet period compared to the transition period during stormflow conditions. This was also reflected in the DOC and DON peak and flow weighted storm event concentrations and antecedent soil moisture relationship where drier conditions (less prior flushing) resulted in the highest DOC and DON peak and flow weighted storm event concentrations. Results from this study showed the importance of the hillslope component in DOC and N transport at the catchment scale and underscore the importance of sampling solutes below the root zone (transient groundwater) and the value of using SUVA to fingerprint DOC sources.

Introduction

Controls on dissolved organic matter (DOM) losses at the catchment scale are poorly understood, and yet DOM fluxes may have important consequences for both terrestrial and aquatic ecosystem function. DOM has the ability to form complexes with metals, and thus plays an important role in metal toxicity and transport (Leenheer et al., 1998). Dissolved organic nitrogen (DON) can represent a significant loss of nitrogen (N) (Sollins et al., 1980; Hedin et al., 1995; Perakis and Hedin, 2002; Vanderbilt et al., 2003) in unpolluted forested ecosystems, and may be a critical factor in maintaining N-limitation in these systems (Vitousek et al., 1998). In addition, dissolved organic carbon (DOC) is an important energy source to bacteria and some algae in streams (Kaplan and Newbold, 1993) and absorbs UV-radiation (Morris et al., 1995) that can damage aquatic organisms.

Recent research has focused on the hydrological controls on stream concentrations and quality of dissolved organic carbon (DOC) (McKnight et al., 2002; McGlynn and McDonnell, 2003; Inamdar and Mitchell, 2006; Park et al., 2007), dissolved organic nitrogen (DON) (Hill et al., 1999; Hagedorn et al., 2000; Buffam et al., 2001; Bernal et al., 2005), and nitrate (NO_3–N) (McHale et al., 2002; Ocampo et al., 2006). While these studies have improved our understanding of flushing and draining processes of nutrients at the catchment scale (as described by Hornberger et al., 1994; Boyer et al., 1997; Creed et al., 1996), quantifying spatial sources of these nutrients during storm events and across seasons remain

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0022-1694/$ - see front matter © 2008 Published by Elsevier B.V.
doi:10.1016/j.jhydrol.2008.11.002

poorly understood. The main reason is that it is difficult to separate different geomorphic units of the catchment. While hillslopes make up the largest part of catchments, research has been mostly focused on the riparian zone (Cirmo and McDonnell, 1997), such that sources of nutrients from the hillslope component are more poorly understood compared than those from the riparian zone.

One approach to increase our understanding of spatial sources of DOM and N at the catchment scale, is to isolate discrete landscape units and to understand their individual hydro-biogeochemical dynamics. While some studies have done this for the riparian zone (e.g., Hill, 1993; McDowell et al., 1992; Vidon and Hill, 2004) few studies have been able to isolate the hillslope hydro-biogeochemical response (McGlynn and McDonnell, 2003). It is difficult to observe hydro-biogeochemical expressions of hillslopes in the stream (Hooper, 2001), due to chemical transformations in the riparian zone (Hedin et al., 1998) or infrequent episodic flow into the riparian zone (McGlynn and McDonnell, 2003). An approach to quantify the hillslope response directly, without any riparian zone modulation, is to trench experimental hillslopes. A few trenched experimental hillslopes exist around the world (Woods and Rowe, 1996 (Maimai, New Zealand); Tromp-van Meerveld and McDonnell, 2006 (Panola, USA);Uchida et al., 2003 (Fudoji, Japan)) but these experiments have typically monitored only a handful of storms to work with (Tromp-van Meerveld and McDonnell, 2006), and often lack detailed biogeochemical data.

While isolating the hillslope or riparian zone has led to new insights into spatial sources of nutrients, questions remain about the hydrological controls on DOM and N export from the hillslope component at seasonal and storm event scales. It is especially important to understand the role of hillslopes in DOM and N export across different antecedent wetness conditions because several studies have suggested that seasonal variation in stream DOC, DON and NO_3–N is related to antecedent wetness conditions (Triska et al., 1984; Vanderbilt et al., 2003; Bernal et al., 2005) and many studies have reported significant increases in DON, DOC and NO_3–N during individual storm events (Creed et al., 1996; McHale et al., 2002; Boyer et al., 1997).

We report on work from a small well-studied hillslope trench within a headwater catchment at the H. J. Andrews Experimental Forest (HJA), Oregon. The catchment is well-suited for exploring questions of how hillslope hydrological processes control stream DOC and N concentrations. This study site has a unique feature: hillslopes that issue directly into the headwater stream without any riparian zone modulation. Riparian zone water storage was effectively removed from the site due to 1986 and 1996 debris flows that evacuated the valley bottom. This setup made it possible to isolate lateral subsurface flow from the hillslope trench and compare the hydro-biogeochemical response from this hillslope to the response of the whole array of hillslopes that make up this watershed. Furthermore, we explored the use of different indices of DOM quality (specific UV-absorbance (SUVA) and DOC:DON) to fingerprint terrestrial sources of DOM. Recent studies have demonstrated that SUVA can be used as a surrogate for the aromatic carbon content and molecular weight of DOC (Chin et al., 1994; McKnight et al., 1997; Weishaar et al., 2003; Hood et al., 2005). The chemical character of DOM (DOC:DON, (SUVA)) has been used to identify terrestrial sources of DOM at seasonal scales (Hood et al., 2003, 2005; McKnight et al., 1997, 2001) and during storms at the catchment (Hagedorn et al., 2000; Hood et al., 2006; Katsuyama and Ohte, 2002) and plot scale (Kaiser and Guggenberger, 2005).

Our study builds upon a wealth of previous hydrological (Harr, 1977; McGuire, 2004) and biogeochemical (Sollins et al., 1980; Sollins et al., 1981; Triska et al., 1984) research at the site. The H.J. Andrews Experimental Forest is characterized by dry summers, a gradual wet up between October and December (transition period), and from December through late spring the watershed is persistently wet. This steady and progressive shift from dry to very wet conditions allowed us to explore the role of antecedent wetness and flow conditions on DOC and nitrogen (N) patterns at seasonal and storm event scales. Monitoring and sampling of lateral subsurface flow from the hillslope trench, and stream water at the catchment outlet between August 2004 and June 2005 during and between storm events allowed us to compare DOC and N concentrations and SUVA values between the transition period and the wet period at the hillslope and catchment scale, and between these two scales, during baseflow and stormflow conditions. In addition, sampling storm events at the hillslope and catchments scale during the transition and wet period enabled us to examine the role of antecedent wetness conditions on DOC and N concentrations and compare export rates between these two scales.

We address the following questions to improve our understanding of the hydrological controls on DOM and N fluxes from hillslopes in a small watershed: (1) What is the variation in DIN, DON and DOC concentrations and DOM quality (SUVA and DOC:DON) among sources from the plot scale, lateral subsurface flow and stream water on an annual scale? (2) What is the influence of flow conditions at the seasonal scale (transition vs. wet period) on the variation of solutes and DOM quality in lateral subsurface flow and stream water during baseflow and stormflow conditions? (3) What is the role of timing (transition vs. wet period) and under what flow conditions are the single gauged hillslope and catchment response similar with respect to the solutes and DOM quality? (4) Do peak and flow averaged DOC and N concentrations during storms at the catchment and hillslope scale increase with a decrease in antecedent soil moisture and antecedent precipitation conditions? (5) Is the total carbon and nitrogen export at the hillslope and catchment scale during storm events the same?

Site description

The study was conducted in Watershed 10 (WS10), a 10.2 ha headwater catchment located in the H.J. Andrews Experimental Forest (HJA), in the western-central Cascade Mountains of Oregon, USA (44.2°N, 122.25°W) (Fig. 1). Elevations range from 470 m at the watershed flume to a maximum watershed elevation of 680 m. HJA has a Mediterranean climate, with dry summers and wet winters characterized by long, low intensity storms. Average annual rainfall is 2220 mm and about 80% falls between October and April. Snow accumulation in WS10 seldom exceeds 30 cm, and seldom persists for more than 2 weeks (Sollins et al., 1981). Atmospheric total bulk N deposition is low compared to other sites in USA and averages 1.6–2 kg N ha^{-1} yr^{-1} (Vanderbilt et al., 2003). The watershed was harvested in 1975 and is now dominated by a naturally regenerated second growth Douglas-fir (*Pseudotsuga menziesii*) stand. Seep areas along the stream have been observed (Harr, 1977; Triska et al., 1984), which are related to the local topography of bedrock and/or saprolite, or to the presence of vertical, andesitic dikes approximately 5 m wide, located within the south-facing hillslope (Swanson and James, 1975; Harr, 1977).

The hillslope study area is located on the south aspect of WS10, 91 m upstream from the stream gauging station (Fig. 1). The 125 m long stream-to-ridge slope has an average gradient of 37°, ranging from 27° near the ridge to 48° adjacent to the stream (McGuire, 2004). Elevation at the hillslope ranges from 480 to 565 m. The bedrock is of volcanic origin, including andesitic and dacitic tuff and coarse breccia (Swanson and James, 1975). The depth to unweathered bedrock ranges from 0.3 to 0.6 m at the stream–hillslope interface and increases gradually toward the ridge to approximately 3–8 m. Soils are about 1 m deep, and formed either in residual parent material or in colluvium originating from these