Journal of Hydrology 388 (2010) 52–64

Contents lists available at ScienceDirect

Journal of Hydrology

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

Groundwater-fed surface flow path hydrodynamics and nitrate removal in three riparian zones in southern Ontario, Canada

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ARTICLE INFO

Article history:
Received 27 May 2009
Received in revised form 27 January 2010
Accepted 16 April 2010

This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Bernhard Wehrli, Associate Editor

Keywords:
Denitrification
Overland flow
Nitrate
Riparian zone

ABSTRACT

Although the ability of stream riparian buffers to reduce nitrate in groundwater has been promoted, the effectiveness of nitrate removal in riparian zones with upwelling springs and overland flows is not well understood. The relationship between groundwater-fed surface flow path hydrodynamics and nitrate removal was investigated in three riparian zones in southern Ontario, Canada. Spring-fed surface flow in white cedar forests at the upland perimeter of the riparian zones occurred as rivulets linked to shallow horizontal pipe systems in peat deposits. These rivulet–pipe systems transported water at rates that were up to 13× faster than in downslope portions of the riparian zones where diffuse flow paths occurred in marshes and areas of mixed cedar–grass vegetation. Bromide tracers indicated the exchange of water along surface flow paths between areas of faster flow and storage zones in soil pore-water or in slow moving and stagnant pools of surface water. High nitrate concentrations in upwelling groundwater showed little decline for distances of up to 100 m along rivulet–pipe networks suggesting that these flow paths were ineffective in nitrate removal. Nitrate concentrations declined by 50–95% during the summer in areas of diffuse surface flow in the three riparian zones. Analysis of the distribution of $\delta^{15}N–NO_3$ values suggests that denitrification is an important mechanism of nitrate removal. Nitrate concentrations also declined by 25–80% along diffuse surface flow paths in the spring season when the riparian water table was at or above the ground surface. Cold water temperatures (1–6 °C) limited biological removal and most of this nitrate decline resulted from dilution by exfiltration of groundwater that had a low nitrate concentration as a result of denitrification during subsurface transport. Measurements in one of the riparian zones showed that, despite this nitrate dilution, the increase in runoff volume resulted in an 8× larger nitrate–N flux entering the stream from riparian surface flow paths in the spring vs. summer. This study indicates that riparian zones with groundwater-fed surface flow paths vary in their ability to deplete nitrate. A conceptual model linking different surface flow patterns to solute exchanges with riparian soils and water residence time is developed to understand and predict nitrate removal effectiveness.

1. Introduction

The ability of stream riparian zones to remove nitrates from groundwater has been a major focus of research in recent decades (Hill, 1996; Mayer et al., 2007). This capacity is dependent on the interaction of nitrate transported by various hydrologic flow paths with sites of biotic retention within the riparian zone. Many studies have indicated that riparian areas are highly effective in removing nitrate from shallow groundwater flow paths that increase interaction with organic-rich surface soils favouring denitrification and plant uptake (Peterjohn and Correll, 1984; Cooper, 1990; Haycock and Burt, 1993). In contrast, in landscapes where a shallow confining layer is absent, groundwater can be transported along deeper longer flow paths through the riparian zone. Nitrate removal in these riparian zones is often less effective and is dependent on interactions with sufficient supplies of electron donors such as organic C and reduced forms of S or Fe (Bohlke and Denver, 1995; Devito et al., 2000; Puckett et al., 2002; Puckett and Hughes, 2005).

Overland flow produced by groundwater discharging as springs and seeps represents a third major riparian flow path that occurs in some landscapes. This pathway is often present in riparian zones where large groundwater fluxes from thick upland aquifers are forced to the surface as a result of the low conductivity or restricted depth of riparian sediments (Vidon and Hill, 2004a). An extensive survey of riparian zones in Rhode Island, USA reported the frequent occurrence of surface seeps where groundwater emerges onto the riparian surface in hydric riparian zones located in till landscapes (Gold et al., 2001; Rosenblatt et al., 2001).

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doi:10.1016/j.jhydrol.2010.04.028

Currently, it is difficult to develop generalizations about the extent of nitrate removal in groundwater-fed overland flow paths. Relatively few studies have focussed on these surface flow paths in riparian zones and their conclusions are not consistent (Rosenblatt et al., 2001). Some studies of overland flow paths have reported substantial removal of nitrate (Howard-Williams et al., 1986; Brüsch and Nilsson, 1993; Blackwell et al., 1999; Rutherford and Nguyen, 2004), whereas other studies have found ineffective removal (Warwick and Hill, 1988; Hill, 1990; Angier et al., 2002, 2005). Most studies have not examined the hydrological characteristics of surface flow paths and how these affect water residence times and the degree of interactions with surface soils. The assessment of nitrate removal has often focused on the analysis of declines in nitrate concentration along flow paths and less attention has been directed to the mechanisms responsible for nitrate attenuation, or how these may change seasonally. Data on spatial patterns of water temperature and dissolved oxygen in surface flows are also lacking. Consequently, knowledge of the key factors that influence the nitrate removal capacity of riparian overland flow paths and the processes responsible for this depletion are limited.

The goal of the present paper was to examine the relationship between groundwater-fed surface flow path hydrodynamics and nitrate transport and depletion in order to develop a better understanding of differences in nitrate removal effectiveness. A secondary objective was to examine the role of dilution and denitrification which are major processes that can produce a decline in nitrate concentration along surface flow paths. Dye and bromide tracers were used to delineate flow paths and interactions with surface soils in three riparian zones in southern Ontario, Canada, that display differences in flow path characteristics. We also analysed nitrate, chloride and dissolved oxygen concentrations in surface water together with temperature and $\delta^{15}N$–NO_3 values to examine nitrate depletion in riparian surface flow paths. These results are used in the concluding section of the paper to develop a conceptual framework that links surface flow path hydrodynamics to nitrate removal effectiveness. This study focuses on spring-fed overland flow in the time intervals between storm events. During storms, saturation-excess overland flow produces rapid increases in flow on saturated riparian areas (Hill and Waddington, 1993; Waddington et al., 1993). However, these discharge peaks are of short duration and do not contribute a large fraction of the seasonal or annual nitrate flux at riparian sites where surface flows occur for long time periods during the year.

2. Study sites

The study sites are located in agricultural catchments in southern Ontario with an annual precipitation of 800–900 mm, of which 120–240 mm falls as snow between December and April (Singer et al., 1997). The mean annual temperature is 7.2 °C, with a mean January temperature of −6.7 °C and a mean July temperature of 20.5 °C. Spring snow-melt usually occurs in March–April, when surface run-off and stream water levels are generally highest. Lowest stream discharge occurs in July–August when evapotranspiration is highest.

The Boyne Upstream and Downstream riparian sites are located approximately 400 m apart along the Boyne River, a 5th order stream that is incised in a forested valley 10–12 m below the Alliston sand plain that forms an unconfined thick aquifer about 70 km north of Toronto, Ontario. The riparian floodplain at both Boyne sites is underlain by a regional silt and clay aquitard ranging from 5 to 6 m below the riparian surface at the upstream site to 4 m at the downstream site (Devito et al., 2000). Low conductivity peat deposits that range up to 3 m in depth are present at both sites and are underlain by coarse sand and gravel deposits with Ks value of 10^{-3} cm/s. (Fig. 1a and b).

Groundwater flow patterns are similar throughout the year at the two Boyne River sites (Devito et al., 2000). Groundwater flow at the Boyne Upstream site is generally horizontal, with some recharge of near-surface groundwater from the peat into areas of sand in the mid-section of the riparian zone (Fig. 1a). An upward groundwater flow occurs at the upslope perimeter of the Boyne Downstream site (Fig. 1b). Groundwater flow is horizontal through the peat and the sand aquifer in the mid-section of the riparian zone, whereas flow is downwards to deeper sediments near the river (Devito et al., 2000).

The Eramosa river is a 4th order stream flowing through a former glacial meltwater channel west of the Niagara Escarpment about 80 km northwest of Toronto. The river valley is bordered by a 9–10 m thick gravel and cobble terrace in the upland terrain. A 2.5 m thick wedge of coarse gravel and loamy-sand ($Ks = 10^{-4}$ cm/s) at the upslope perimeter of the riparian zone thins rapidly downslope where poorly conductive peat deposits ($Ks = 10^{-5}$ cm/s) are underlain by sandy loam with clay layers (Vidon and Hill, 2004a). Groundwater flow is upwards to the surface at the upland perimeter, whereas near surface water recharges to deeper sediments further downslope (Fig. 1c).

The Boyne and Eramosa riparian zones are primarily forest sites dominated mainly by northern white cedar (*Thuja occidentalis*) near the upland perimeter (Fig. 1). Further downslope vegetation changes to a mixed deciduous-cedar forest and patches of cedar interspersed with grasses at Boyne Upstream, whereas cedar-grass patches and areas of marsh occur in the other two riparian zones. The marshes are dominated by dense grass and sedge tussocks and patches of cattails (*Typha latifolia*). The adjacent uplands are mainly under potato crops at the Boyne sites and corn at Eramosa. High NO_3^-–N (10–30 mg/l) and chloride concentrations (10–80 mg/l) occurr in groundwater discharging from the upland aquifers to the riparian zones. The $\delta^{15}N$ (+5‰ to +6‰) and $\delta^{18}O$ (+1.2‰ to +1.9‰) values at the Boyne sites and $\delta^{15}N$ (+5‰) values at Eramosa in this groundwater nitrate suggest that the high nitrate concentrations originate from fertilizer application on the cropland (Devito et al., 2000; Vidon and Hill, 2004c). Previous research at the three riparian sites has focused on subsurface groundwater nitrate transport and removal (Devito et al., 2000; Hill et al., 2000; Vidon and Hill, 2004b). However, springs and seeps at the upslope boundary of the three riparian zones also produce extensive areas of overland flow that are the focus of this study.

3. Methods

3.1. Surface hydrology

A network of wells and piezometer nests was installed along transects at the Boyne and Eramosa sites during previous research (Devito et al., 2000; Vidon and Hill, 2004a). Water table elevations in the wells along these transects were measured approximately twice per month between April and October 2004. The topography of the riparian zones, the location of the surface water sampling sites and length of flow paths were determined using a total surveying station. A dye tracer (Rhodamine WT) injected at various sites in the riparian zones was used for visual observation of surface flow paths directions. Flow rates, calculated by dividing the length of flow path by the time of arrival of the dye, were used to identify variations in rates of water movement, but do not indicate average flow velocities. Small V notch weirs were constructed on the marsh rivulet outlets at the Boyne Downstream site and discharge was measured biweekly by timing the filling of a graduated beaker at each weir.