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Nutrient dynamics in relation to surface–subsurface hydrological exchange in a groundwater fed chalk stream

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Summary Mini-piezometers were used to assess surface–subsurface hydrological exchange and biogeochemical processing in different patches on the river bed (coarse gravel, fine gravel/sand, silt/sand) at two sites on the River Lambourn (Berkshire, UK). Positive vertical hydraulic gradients (VHG) dominated the riverbed, indicating potentially upwelling subsurface water. Hydraulic conductivity was highly variable in the shallow sediments, but was generally low at greater depths, suggesting that positive VHG may not translate to the rapid movement of subsurface water. Well defined areas of downwelling were not identified, although negative VHG did occur at the low/intermediate depths (~10–20 cm). Furthermore, steep temperature gradients within the top 30 cm suggested that connectivity with the surface water was restricted to a shallow layer within the sediments.

The three patch types differed in biogeochemical activity, largely as a function of their sediment size distribution, organic content and surface–subsurface exchange dynamics. Nitrate reduction was associated with hypoxic (<90 μM oxygen), organically rich silt/sand deposits and, at one site, with fine gravel/sand. Nitrate reduction was related to the depth of the silt/sand, and did not occur in the deep samples (>30 cm) that contained oxygen >90 μM. A high background concentration of nitrous oxide (~180 nM) occurred within the river bed, regardless of patch type and depth into the bed. In the nitrate reduction zone, N_2O concentration was highly variable, with production and reduction of N_2O. Ammonium concentration was higher within the river bed than in surface water and decreased with depth, particularly in the organically rich silt/sand and coarse gravels, where organic matter may get trapped.

From a hydrological/biogeochemical perspective, the Lambourn differs from many other rivers. Despite being hypernutrified (surface and subsurface nitrate >400 μM), the bed of the

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Lambourn is predominantly aerobic and does not serve as a significant nitrate sink. In addition, despite the permeable geology of the catchment, biogeochemical processing of nutrients may be restricted to the thin, but biologically productive, layer in the shallow river bed sediments.

Introduction

Recognition of the importance of the exchange between groundwater, hyporheic water and surface water in river channels began more than 40 years ago (Schwoerbel, 1961; Hynes, 1983). Surface—subsurface hydrological interactions have now been shown to influence many facets of river ecology (see reviews by Brunke and Gonser, 1997; Dahm et al., 1998; Malard et al., 2002). The extent and direction of surface—subsurface exchange may regulate the supply of oxygen and organic material to the hyporheic zone, thus influencing hyporheic metabolism (Findlay et al., 1993; Jones et al., 1995) and the processing of key nutrients (Duff and Triska, 2000; Hendricks and White, 2000). In addition, physicochemical gradients associated with surface—subsurface exchange can affect algal production and recovery from disturbance (Valett et al., 1994), invertebrate community composition (Plénet et al., 1995; Franken et al., 2001; Olsen and Townsend, 2003), plant distribution (White and Hendricks, 2000) and the quality of salmonid spawning habitat (Baxter and Hauer, 2000). In permeable catchments such exchange is of particular importance, due to the potentially high connectivity between surface and subsurface water bodies, yet it remains poorly defined from a spatial and temporal aspect.

Surface—subsurface hydrological exchange may occur at different spatial and temporal scales (Dahm et al., 1998; Dent et al., 2001; Malard et al., 2002). Large-scale determinants of surface—subsurface connectivity are related to catchment geology, hydrology and landuse, while at a smaller 'reach-scale' surface—subsurface exchange is governed by channel morphology and flow dynamics (Brunke and Gonser, 1997; Malard et al., 2002). Patches of up- and downwelling are commonly determined by river bed topography and associated changes in hydraulic pressure, with downwelling surface water at the upstream end of shallow riffles and upwelling at the tail of riffles where depth increases (Harvey and Bencala, 1993; Hill et al., 1998; Franken et al., 2001). In addition, in-stream features such as boulders, woody debris dams and macrophyte stands can modify flow patterns and streambed topography, and create local areas of up- and downwelling (Baxter and Hauer, 2000; White and Hendricks, 2000).

Similarly, substratum characteristics such as particle size, degree of sorting and organic matter content are determined by channel morphology and flow dynamics, resulting in a mosaic of different substratum patches within the river channel. Substratum type may play a crucial role in surface—subsurface exchange because different patches differ in their hydraulic conductivity, thus influencing hyporheic residence time (Malard et al., 2002). For example, coarse gravels may have high hydraulic conductivity and short hyporheic residence times relative to finer sediments (Munn and Meyer, 1988; Packman and Salehin, 2003). In finer sediments with low hydraulic conductivity and long hyporheic residence times, oxygen may become depleted through aerobic respiration, leading to the use of alternative terminal electron acceptors like nitrate and sulphate (Baker et al., 2000). Consequently, the hyporheic zone in catchments with high hydraulic conductivity may be dominated by aerobic processes, while those with low hydraulic conductivity (i.e. long residence times) may be dominated by anaerobic processes (Valett et al., 1996; Grimaldi and Chaplot, 2000). Therefore, hyporheic residence time is an important factor in determining the dominant biogeochemical processes that occur within the sediment and, therefore, the availability of key nutrients (N and P) to river biota.

Numerous studies in low nutrient (N limited) streams have shown that the hyporheic zone is enriched in inorganic N and P relative to surface water (Valett, 1993; Valett et al., 1994). Downwelling surface water carries dissolved and particulate organic material into the hyporheic zone, providing a carbon source that promotes high microbial metabolism (Jones et al., 1995). The mineralisation of organic material releases ammonium that may subsequently be oxidised to nitrite and nitrate by nitrifying bacteria in oxygenated sediments (Jones, 2002). Consequently, hyporheic water can provide a source of nutrients to surface biota via upwelling patches, creating areas of high algal production relative to other parts of the stream bed (Valett et al., 1994).

In contrast, in high-N rivers there is evidence that the hyporheic zone may act as a sink for N rather than a source, because dissolved oxygen can be rapidly depleted in organically rich sediments, leading to denitrification (Cooke and White, 1987; Hill et al., 1998). Compared to low-N streams, rivers with high-N may not exhibit such strong spatial relationships between surface—subsurface exchange and surface biota, because surface communities may not be nutrient limited. However, while low nutrient systems have been relatively well studied, comparable studies in high nutrient rivers are scarce, making generalisations difficult (Hill et al., 1998).

For over a decade a considerable research effort into the effect of surface—subsurface exchange on nutrient dynamics has taken place in North America, largely from headwater streams in relatively pristine catchments (e.g. Triska et al., 1989; Valett et al., 1994, 1996). In Europe, a majority of work has centred on large (7th order) rivers such as the Garonne and Rhône in France (Claret et al., 1997; Baker and Vervier, 2004). In Britain, despite extensive knowledge on the hydrogeology of many chalk and limestone catchments (the most important UK aquifers, in terms of public water supply) and studies modelling their surface water quality (Neal et al., 2004; Wade et al., 2004), no studies have looked directly at nutrient dynamics in relation to surface—subsurface exchange at a reach scale. This study aimed to identify different areas of surface—subsurface