Advances in Water Resources 73 (2014) 185–197

Contents lists available at ScienceDirect

Advances in Water Resources

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

Impact of microforms on nitrate transport at the groundwater–surface water interface in gaining streams

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ARTICLE INFO

Article history:
Received 21 October 2013
Received in revised form 23 July 2014
Accepted 28 July 2014
Available online 8 August 2014

Keywords:
Hyporheic flow
Nitrate transfer
Riffle-pool sequence
Microform
Nitrification
Denitrification

ABSTRACT

Small streambed structures (or microforms, 0.01–1 m in length) exist ubiquitously in riverbed systems. Small-scale topography is potentially important in controlling hyporheic exchange flow and transport of conservative and reactive solutes at the groundwater–surface water interface. The role of microforms on NO_3^- transfer in a riffle-scale (macroforms of >1 m length) hyporheic zone within a gaining river setting is investigated using a 2-D flow and transport model which accounts for both nitrification and denitrification. Results show that the short pathlines caused by microforms lead to more NO_3^- discharge to the river compared with a macroform-only condition due to shortened residence times of both surface water and groundwater in mixing zones. Short hyporheic exchange flow pathways caused by microforms could remain oxic along their entire length or switch from nitrate producing to nitrate consuming as oxygen concentrations decline. Microforms affect net NO_3^- flux by the combined effect of introducing more stream mass flux and reducing their residence time in mixing zones under different hydrological and biogeochemical conditions. Our findings underscore that ignoring microforms in river beds may underestimate NO_3^- load to the river and have practical implications for pore water sampling strategies in groundwater–surface water studies.

1. Introduction

The hydrologic exchange of stream water and groundwater (GW) underlying a stream channel plays an important role in biogeochemical cycles in streambed sediments, where reactive solutes undergo physio-chemical transformations and thus influence nutrient supply and benthic habitat quality in riverine ecosystem [1–5]. Hyporheic exchange flow (HEF) is the process by which stream water invades the subsurface and rejoins the downstream channel [6,7]. HEF is driven essentially by variations of the hydraulic gradient along the stream-subsurface interface, which can occur due to topographic features ranging from individual particles, ripples, dunes, bars up to riffle-pool sequences and meanders [8]. The streambed morphology can be a key factor in controlling upwelling and downwelling fluxes, increasing hyporheic residence time (RT), expanding the extent of the hyporheic zone (HZ), and has important biogeochemical implications on stream water chemistry [3,4,9]. Here we apply the same classification of HEF processes as Käser et al. [10], i.e. microform HEF (0.01–1 m), which tends to be induced by hydrodynamic pressure variations, and macroform HEF (>1 m), which is more likely generated by hydrostatic pressure.

As a means of evaluating hyporheic exchange, a number of GW models have been used to simulate the spatial variability of movement of surface water (SW) into the subsurface and examine the effect of morphologic features on HEF from a process-based perspective, rather than a lumped model based on the stream behaviour [11–13]. Flow-simulation results from MODFLOW [14] and MODPATH [15], for example, suggest that channel unit, size, and sequence are all important in determining hyporheic exchange patterns [16]. By using the same models combined with MT3DMS [17], Saenger et al. [18] showed that hyporheic exchange in a riffle-pool sequence increased with increasing SW flow, and that mass transfer is more influenced by the hydraulic conductivity of riverbed sediments than SW flow. Lautz and Siegel [19] simulated the hyporheic exchange around debris dams and meanders along a semi-arid stream using MODFLOW and MT3D [20]; their results indicate a predominant role of advective processes.

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http://dx.doi.org/10.1016/j.advwatres.2014.07.013
0309-1708/

Conservative tracer experiments conducted in a river with pool-riffle morphology indicate that a major mechanism for hyporheic exchange is bed form-induced advection [3]. Tonina and Buffington [13] arrived at a similar conclusion based on observations in their laboratory experiment simulating a gravel pool-riffle channel. Advection was also found to be a major control in micro-scale induced HEF by Jin et al. [21] and Vollmer et al. [22]. Mass transfer and spatial evolution of reactive solutes in the HZ have received less attention, although several studies deserve note and are discussed below.

For reactive species, the fate, transport and concentration distribution in the HZ is not only regulated by various bed topographies of a river but also biogeochemical reactions [5,23–25]. The transport of nitrogen, being a nutrient essential to sustain life, has important implications for quality of both SW and GW. In most freshwaters, nitrate (NO_3^-), is the dominant form of nitrogen present and, as such, the removal of NO_3^- by denitrification, the microbially mediated reduction of NO_3^- to nitrogen gas (N_2), is of interest [26]. HZs have been recognised as hotspots of denitrification in the landscape because of the potential for anoxic conditions in the HZ and the availability of labile carbon [27,28]. For example, Hill et al. [3] reported that the hyporheic zone of a small N-rich stream in Ontario served as a NO_3^- sink. Pinay et al. [29] noted that the streambed can serve as NO_3^- sink, and residence time plays an important role in allowing denitrification to decrease NO_3^- concentration. Zarnetske et al. [30] revealed changes in redox conditions from oxic to anoxic with nitrate produced at the start of the flow path and consumed at the end of the flow path across a gravel bar in western Oregon. Given the constraints of field measurements, concentration distributions in HZ have been well investigated via the simulation of coupling between hyporheic flow and biogeochemical activity. For example, significant spatial variations in concentration of reactive solutes have been observed below a riffled sediment bed by Shum [25]; Bardini et al. [31] reported on chemical zonation of nutrients in a duned streambed.

Recently, hyporheic nitrogen cycling in gravel bed rivers with riffle-pool morphologies has been investigated by process-based models in Lagrangian coordinates [4,32], and a one-dimensional (1D) model with coupled nitrification–denitrification dynamics has been applied to simulate the fate of NO_3^- in HZ by Sheibley et al. [33]. In addition to these approaches, Monte Carlo sensitivity analyses with a non-dimensional form of a 1D reactive transport model has been used to identify whether the HZ is a net source or sink of NO_3^- across different temporal and spatial scales [34].

Among the various types of topography triggering HEF, riffle-scale HEF is well documented because of its common occurrence in natural streams. Recently, HEF induced by the roughness of the stream bed or in-stream obstacle-induced oscillation has received attention. Although the role of small-scale HEF, in comparison to large-scale HEF, has been less reported in field studies, the influence of microforms on interfacial exchange system is recognised [10,22]. Microforms embedded in a riffle-pool sequence can potentially affect HZ development and biogeochemical process at larger scales and have important implications for the hyporheos [6,35]. However, the evidence of scale of microforms and macroforms and their coupling impact on NO_3^- transfer between surface and subsurface water has received little attention to date.

Fig. 1 illustrates physical evidence of microforms along a short (40 m) sub-reach of the River Leith in Cumbria, UK. A 250 m reach (also shown in Fig. 1) has been the focus of a number of recent studies on spatial patterns of groundwater–surface water exchange and nutrient transport (e.g. [36,37]). Distinct macroforms are evident in the stream bed topography along the reach, however, from high resolution topographic surveying (i.e. greater sampling density) over a 40 m sub-reach, considerable microform structure can also be seen. Our study here is not specifically targeted at the River Leith site; we use this example as an illustration of the presence of microforms and, through a generic model, explore the implications of neglecting such features in the study of reactive transport between groundwater and surface water.

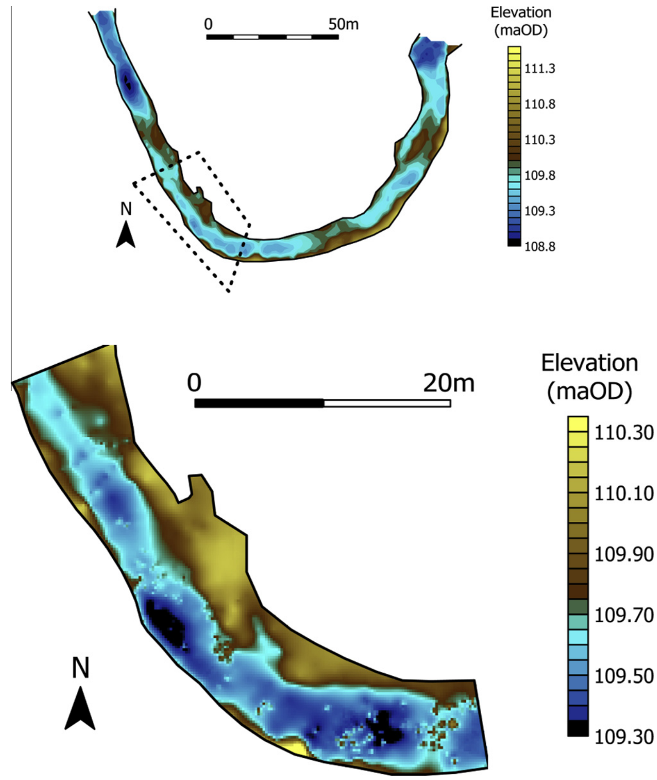

Fig. 1. Evidence of microforms in a sub-reach of the River Leith. The upper image shows bed topography along the 250 m study reach; the lower image shows bed topography along a sub-reach (location is marked by the dashed lines in the upper image) derived from higher resolution spatial sampling. Flow is from left to right. Microforms, embedded in macroforms, are clearly seen in the downstream section of the sub-reach. maOD stands for metres above ordnance datum (UK sea level measurement).

In their modelling study, Käser et al. [10] verified that microforms can generate a higher total water flux through the subsurface, and reduce the mean residence time of HEF. Furthermore, distinct flow patterns are induced by the interaction between microforms and macroforms. Käser et al. [10] focused their work on conservative transport; here we build on their work and examine: (1) whether microforms can significantly affect the exchange and spatial distribution of NO_3^- across the streambed within a riffle-pool sequence; (2) which hydrological and biogeochemical factors influence NO_3^- delivery to a gaining stream in a streambed topography with microforms embedded in a macroform. In order to address these questions, a vertical 2D flow and transport model coupled with Monod kinetics is developed. Both advective and dispersive transport, along with nitrification and denitrification, are considered in the model. A base (reference) case is first established to evaluate the net mass exchange and spatial distribution of solute in the streambed. The impacts of microforms are investigated for this base case by comparing responses with and without microforms. Four vertical sampling profiles of streambed chemistry (Cl^- and NO_3^-) within 1 m depth are taken to illustrate NO_3^- transformation in this base case. Sensitivity analyses are then performed to evaluate the effect of hydrological and chemical properties on the net nitrate transfer with and without the presence of microforms. The properties of the base case and the configurations of the models used for the subsequent sensitive analysis are shown in Table 1.