Hyporheic Exchange Flow (HEF) Under a Unit, Medial Gravel Bar: A High-resolution Field Study

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Introduction

Stream water may infiltrate into shallow near-channel sediments such as stream beds, banks, and bars, mix with groundwater, and return to surface water bodies over relatively short times and distances, as compared to other surface water-groundwater interactions. This movement of stream water, called hyporheic exchange flow (HEF, Gordon et al. 2013), can be originated due to different effects, such as topographical, hydrological, anthropogenic, ecological, and hydrogeological (Magliozzi et al. 2018). Each of these drivers can lead to hyporheic exchange over a wide range of spatial scales, from the entire catchment to exchange induced by small ripples on the riverbed fluctuations or in-channel vegetation patches, and over varied time scales from minutes to months.

The literature widely recognizes HEF's contributions to the physical and biochemical properties of a stream's water. By increasing water transient storage and contact time with microorganisms, HEF plays a significant role in solute and nutrient transport, altering stream water quality properties (e.g., dissolved oxygen (DO), dissolved and particulate organic matter, inorganic nutrients). Furthermore, HEF provides a suitable habitat for a broad range of aquatic organisms, moderates water temperature fluctuations, and controls the rooting depth of riparian vegetation (Alexander et al. 2009; Cardenas 2010; Wondzell 2011; Bardini et al. 2012a; Cardenas 2015; Stonedahl et al. 2015; Schaper et al. 2019; Krause et al. 2022).

Despite the significant role that emergent fluvial features such as gravel bars play in hyporheic exchange contribution to stream's self-depuration capacity (Kasahara and Wondzell 2003; Fischer et al. 2005; Cranswick and Cook 2015), most previous research has scrutinized biogeochemical and physical processes at the smaller-scale or for submerged bed features (e.g., bedofrms, Cardenas et al. 2004; Boano et al. 2007; Cardenas et al. 2008; Bardini et al. 2012b; Harvey and Gooseff 2015; Fox et al. 2016; Tonina et al. 2016; Krause et al. 2017). On top of that, most of the few existing studies on emergent, channel-scale size features were conducted on rather large bars or fluvial islands, but only with a limited number of observation wells. Shope et al. (2012) stated that spatial flux patterns and nutrient transport processes within in-stream fluvial features such as islands and gravel bars are still elusive. Considering the size and heterogeneity of their bar though, field hydraulic conductivity was measured at a very low resolution (only 6 mini-piezometers, Shope et al. 2012). Arrigoni et al. (2008) found that temperature variations up- and downstream of large gravel bars in the Umatilla River give clear evidence for the occurrence of HEF; however, this research does not describe any of the biogeochemical processes that occur within the bars. Zarnetske et al. (2011) measured solute tracers in a small lateral gravel bar, revealing that denitrification occurs even within such a restricted (6.1 m x 4m) bar. Still, they only measured at one depth and did not attempt to couple the biogeochemical and physical aspects of HEF. Trauth et al. (2015) coupled a 3-D computational fluid dynamics model to a groundwater reactive transport model, to study the impacts that discharge fluctuations have on HEF processing. Their results highlight the role of emergent river bars in solute transformation and biogeochemical processes due to HEF; however, hydraulic conductivity and electrical conductivity (EC) values were measured only at a very limited number of locations. McGarr et al. (2021) studied a gravel bar using geophysical methods and physical/chemical sediment analyses, underlining the importance of sediment heterogeneity on HEF and nutrient cycling. Their results revealed that the complexity of sediment structure led to formation of zones with higher rate of biochemical reactions such as denitrification and higher organic matter content. Yet, no further description of the underlying biogeochemical processes was provided. The results revealed that electrical resistivity (ER) is a competent proxy for chemical hotspots within emergent gravel bars (McGarr et al. 2021).

The enormous spatial variability in hyporheic processes within gravel bars, due to the interactions between a highly complex sediment structure, flow heterogeneities, and the variability in biogeochemical processing, hampers our capacity for appropriately describing and elucidating HEF. This heterogeneity of the medium, alongside the high temporal and spatial variability of hyporheic processes in themselves, underscores the necessity of using approaches with a higher spatio-temporal resolution. These should also be focused first on simpler systems, such as unit, medial gravel bars (MGBs), which are smaller, display a more continuous variability, and have simpler boundary conditions for the flow than river islands or large compound bars.

Methodology

We aim to provide a clear picture of the physical and biogeochemical processes induced by HEF under a unit MGB. A unit bar is deposited in a single flood event, so that its sedimentary architecture varies gradually in space. Hence, we will instrument a small, emergent MGB in a natural stream with a 3-D high-resolution grid of mini-piezometer nests. Each nest will be located at less than 1 m lateral grid spacing (X-Y) and less than 0.2 m spacing in depth (Z). This high-resolution system of mini-piezometers allows us to describe the spatial fluctuations in physical and biochemical processes due to the heterogeneity of the sedimentary structure and the flow, with an observation scale that is much closer to the actual process scale.

Each nest will contain three to four PVC wells, screened at different depths to measure piezometer levels. A continuous-screen well will give the position of the alluvial water table. Performing a constant injection test at each mini piezometer location, we will measure hydraulic conductivity with high resolution as a proxy that depicts sediment heterogeneity. We will perform an extensive tracer injection experiment using both a conservative saline tracer (measured as electrical conductivity at a 10 Hz frequency – following the work of Alqusaireen (2021) and a non-conservative thermal tracer (measured with iButtons at a frequency of 1 Hz). Moreover, biochemical variables such as DO, and different nitrogen (NO_3, NH_4) and carbon (DOC, POC) forms will be measured with low sampling intervals for at least two steady flow rates.

Expected Results

The described framework will give us a clear 3-D picture of hydraulic conductivity within the MGB. With a clear grasp of the spatial variability in the sediments, we will describe the physical processes taking place under the bar due to hyporheic exchange, such as flow velocities, residence times, and flow rates, with their actual temporal and spatial resolution. On top of that, the tracer injection tests and chemical sampling will produce the corresponding picture of the biogeochemistry of HEF under the bar, for instance, aerobic and anaerobic zones, nutrient transformations, and chemical hot zones.

The datasets will be later utilized for developing a numerical model representing the coupled physical and biogeochemical processes due to Hyporheic Exchange under a unit MGB. We expect that our results will set the first step stone in providing a model elucidating HEF contributions to stream water quality at broader scales (e.g., reach, catchment).

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