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A laboratory method for the visualization and quantification of hyporheic flow paths and velocities

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Abstract

Hyporheic flow, the flow of water through the permeable material immediately surrounding a river, is important for nutrient cycling, dissolved oxygen transport and contaminant transport. In addition, there is recent concern regarding the role of hyporheic flow on the contamination of rivers following oil spills. To better understand hyporheic flow paths and velocities, it is important to measure hyporheic flow at high spatial and temporal resolution. A practical method to measure hyporheic flow in a laboratory flume based on dye injection, digital images and moment analysis was developed. An experiment conducted using a single gravel bar demonstrated good agreement between observations and estimates based on image processing. The measured hyporheic flow field showed upstream and downstream flow that discharged downstream of the bar top, the presence of a flow divide and flow stagnation, and hyporheic flow velocities indicative of turbulent flow for which Darcy's law is not applicable.

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Introduction

The hyporheic zone is a region of permeable sediments surrounding a river in which the mixing of surface water and groundwater (hyporheic exchange) occurs, creating a transition zone characterized by steep gradients in velocity and chemical composition (Brunke and Gonser 1997; Tonina and Buffington 2007). The upward and downward (upwelling and downwelling) exchange of water is influenced by bed forms (e.g., bars and dunes), debris (e.g., fallen trees), hydraulic structures (e.g., weirs), underlying geology, and changes in river flow and direction (Tonina and Buffington 2007; Brunke and Gonser 1997; Ward et al. 2013). One example is hyporheic flow through a single bar, and a conceptual representation is shown in Figure 1. Flow over the bar produces a local minimum in the height of the free surface. Changes in flow depth over the bar, both due to free surface elevation changes as well as bar topography, produce a pressure gradient within the gravel bed, with lower pressure on the downstream side, which results in flow of water through the bed. This flow of water, and the resulting exchange of surface water and groundwater through the hyporheic zone, has a significant impact on nutrient cycling (Bjornn and Reiser 1991; Geist and Dauble 1998; Packman et al. 2004; Salehin et al. 2004) and the health of aquatic organisms that reside within the hyporheic zone. For example, hyporheic exchange can provide added warmth during winter, as well as dissolved oxygen, and remove metabolic waste from bed sediments to sustain embryo development for fish species that incubate and develop in the hyporheic zone (Bjornn and Reiser 1991; Geist and Dauble 1998).

In addition to providing a mechanism for the exchange of nutrients and dissolved gases, hyporheic flow also has the potential to transport dissolved or suspended contaminants from the surface water to the bed sediments, particularly in coarse-grained sediments where higher permeability is expected to create higher hyporheic velocities and greater hyporheic exchange. Of recent concern is the potential for oil spilled to gravel-bedded rivers to become suspended as droplets in turbulent river water, be transported to the river bed through vertical mixing or settling as oil-particle aggregates (Lee et al. 2015; Fitzpatrick et al. 2015), and be transported into the gravel sediment by hyporheic flow. This potential scenario was outlined in a recent Royal Society of Canada report (Lee et al. 2015) in which it was identified as a research gap related to assessing the risk of oil spills in Canada. This scenario is a particular concern for new, planned and proposed oil pipelines that cross or have routes near fast-flowing, steep-gradient, gravel-bedded rivers, and includes

pipelines that transport diluted bitumen, which has the potential to sink due to a density close to water (Government of Canada 2013).

Owing to their practical and scientific significance, hyporheic flows have been the object of experimental and numerical research for decades (e.g., Boano et al. 2014; Jin et al. 2010). As highlighted by Palmer (1993), Ward et al. (2013), Wondzzell (2015) and da Silva et al. (2016), experimental studies including laboratory research are important for understanding and characterizing the steep vertical gradients in these systems, and for establishing comprehensive data sets for the evaluation of high-resolution numerical models. However, there have been few experimental studies aimed at resolving hyporheic flow processes at high spatial and temporal resolutions (Jin et al. 2010). This is true also for the case of the visualization and quantification of the hyporheic flow itself, as past laboratory studies have been limited in their ability to measure hyporheic flow paths and velocities in realistic physical models.

Indeed, most previous laboratory studies of hyporheic flow have focused on measurements of net exchange between the free surface flow and the underlying sediment bed, and not on the flow within the bed itself. Commonly, these measurements are based on decreases in the dissolved concentration of a conservative tracer in the free surface flow and/or increases in the tracer concentrations with the sediment (Elliott et al. 1997; Nagaoka and Ohgaki 1990; Packman et al. 2004; Salehin et al. 2004; Zhou and Endreny 2013; Tonina and Buffington 2007). Changes in tracer concentration are used to calculate exchange volumes, which can be related to physical features of the bed, but are not used to measure local flow velocities. A few studies focused also on solute transport within the bed (Elliott and Brooks 1997; Cardenas and Wilson 1997; Jin et al. 2010). Some of the studies that measured hyporheic flow depths (Elliott et al. 1997; Salehin et al. 2004) collected samples at intervals ranging from minutes to days between samples. For flow velocities expected to be on the order of cm/s (Thibodeaux and Boyle 1987) these sampling intervals are likely inappropriate for measuring hyporheic flow velocities.

Other previous studies have used highly-instrumented experiments, including Particle Imaging Velocimetry to measure interstitial velocities (Blois et al. 2012; Detert et al. 2007), hotfilm sensors to measure turbulence intensity (Nagaoka and Ohgaki 1990), or micro piezometers to determine

the pressure distributions along the surface of the bed (Tonina and Buffington 2007). In studies that measured velocities, these measurements were made at the pore scale and were in only a small fraction of the bed (in 1-6 pores). In addition, some of the techniques employed have been limited to surrogate porous media, including ceramic spheres (Nagaoka and Ohgaki 1990; Blois et al. 2012). Equally important, they did not map the flow pathways through the bed.

Specific studies that traced hyporheic flow paths include Packman et al. (2004), Endreny et al. (2011), Salehin et al. (2004), Savant et al. (1987), Thibodeaux and Boyle (1987), and Zhou and Endreny (2013). Invariably dyes were used to visualize flow through the bed over time. Many of these studies relied on tracing the outline of dye plumes on the walls of the flume, making measurements of fast flows difficult. Others used photos to map the macroscopic features of the dye plumes, but did not use them to calculate velocities. Reports of flow velocities resulting from these studies are rare and limited to a small part of the hyporheic flow domain (e.g., Savant et al. 1987).

This paper focuses on the visualization and quantification of the hyporheic flow field. The objective of the study was to develop a practical, easy-to-implement, and yet precise method to measure hyporheic flow in a laboratory flume. The technique was based on the visualization of dye injected into the sediment, which was photographed with a digital camera. Dyes have been used successfully in conjunction with digital imaging techniques to quantify water flow through porous media based on the measurement of pixel colour intensities in a variety of applications (Forrer et al. 2000; Huang et al. 2002; Rahman et al. 2005; Werth et al. 2010). In this study, the technique was applied to an experiment of hyporheic flow through a single gravel bar, and used moment analysis to define the hyporheic flow paths. Gravel was chosen for this experiment for two reasons: 1) because of its relevance to pipeline routes through the Rocky Mountains from Alberta to British Columbia, Canada, and 2) because the faster flow through gravel, compared to finer material, represents a challenging environment in which to test this new method.

Description of laboratory experiment

The experiment was carried out in a recirculating tilting flume at the Queen's University Coastal Engineering Laboratory in Kingston, Ontario, Canada. The flume was 11 m long, 0.382 m wide,

and 0.41 m deep. The flume side walls were made of glass. A tailgate was installed at the downstream end of the flume to enable control of the free surface slope. Water was supplied from a constant head tank to the flume through a pipe equipped with a valve for control of the flow rate, and discharged from the flume to a sump from where it was recirculated by pumping it back to the constant head tank.

To simulate the substrate underneath a bar, a 0.20 m deep layer of gravel was placed in the flume between 5.07 m and 7.27 m from the flume entrance (Figure 2). A single, two-dimensional, axisymmetric gravel bar was then placed on top of this gravel layer. The bar was 1.4 m long and 0.076 m high, with the bar top located 6.2 m from the flume entrance (Figure 2). The remainder of the flume was filled with elevated wooden platforms that supported a layer of gravel approximately two grains thick. The top of this gravel layer, which was used to provide consistent roughness along the length of the flume upstream and downstream of the bar, was at the same elevation as the top of the base gravel in the midst of the flume. All granular material emplaced in the flume was a peastone gravel with grain sizes between 1.7 mm and 12.5 mm. The gravel had a median grain size (d_{50}) of 7.7 mm and a uniformity coefficient (d_{60}/d_{10}) of 1.5.

The flume was inclined to a slope of 1/750. The hydraulic conditions of the free surface flow were as shown in Table 1. Here B is flow width, S is bed slope, Q is flow rate, h is flow depth, u_{av} is average flow velocity, Re is flow Reynolds number ($= u_{av} R_h / \nu$, in which R_h is hydraulic radius and ν is fluid kinematic viscosity), Fr is Froude number ($= u_{av} / (gh)^{1/2}$, in which g is acceleration due to gravity), θ is Shields parameter ($= (\rho v_*^2) / (\gamma_s d)$, in which ρ is fluid density, v_* is shear velocity ($= (gSR_h)^{1/2}$), γ_s is submerged specific weight of granular material and d is a representative grain size, in this work identified with d_{50}), and θ_{cr} is the value of θ at the critical stage of initiation of sediment transport. For the present purposes, ρ , ν and γ_s were identified with 1000 kg/m³, 10⁻⁶ m²/s and 16186.5 N/m³; following da Silva and Bolisetti (2000) and da Silva and Yalin (2017), $\theta_{cr} = 0.045$. As implied by the value of θ / θ_{cr} in Table 1, the bed shear stress was substantially smaller than that associated with the initiation of sediment transport, and no sediment motion was observed during the test.

149

150 Flow depth was measured with the aid of a point gauge (resolution ± 0.1 mm). As follows from
151 subsequent figures in this paper, the flow was sufficiently deep so that the free surface was only
152 minimally disturbed over the bar. Note that the value of h in Table 1 is that measured at 9 m from
153 the flume entrance, and represents the flow depth sufficiently upstream and downstream of the bar.
154 The flow rate was estimated using the velocity-area method. For this purpose, flow velocity was
155 measured at a total of 45 different points on the cross-section located 4 m from the flume entrance,
156 using a 16 MHz 2D Sontek Micro Acoustic Doppler Velocimeter.

157

158 Injections of blue food colour dye (mixture of water, citric acid, sodium benzoate and FD&C Blue
159 #1; Castella distributors) were used to visualize hyporheic flow in the gravel bar. During
160 emplacement of the base gravel and gravel bar, 11 individual tubes (polyvinyl chloride, 4 mm
161 inner diameter) were installed within the gravel and adjacent to the front glass wall of the flume.
162 Placing all 11 injection tubes prior to beginning the experiment allowed multiple, sequential
163 injections to be performed at the different locations without disturbing individual gravel grains,
164 which would increase the noise in processed images. The tube outlets were located at various
165 depths upstream (locations U1-U7) and downstream (locations D1-D4) of the bar (Figure 3). The
166 tube inlets were connected to a 20 l constant head reservoir located beside the flume. The reservoir
167 was filled with a solution of dye and water at a concentration of 2.2% by volume. This
168 concentration was chosen to be high enough to allow clear visualization but low enough to avoid
169 density-driven flow.

170

171 For injections at each location U1-U7 and D1-D4, the reservoir was filled with dye and maintained
172 at a level 0.01 m above the free surface directly above the injection location being tested. Dye was
173 released by rapidly opening a valve in the injection tube. This valve was closed again once the
174 dye passed down through the gravel and reached up to the surface water, creating an extended slug
175 release. Dye injections at each location were conducted independently rather than simultaneously
176 to clearly identify the flow path and measure the velocity associated with each injection point.
177 Dye from previous injections (less than 0.01 m^3 over all 11 injections) was returned to the
178 recirculation system between injections. This dyed water was diluted in approximately 10 m^3 of
179 water and was, therefore, not expected to affect subsequent injections.

Quantitative visualization technique

Image acquisition and processing

Images of the dye in the gravel were captured using a remote-controlled digital camera (Canon Rebel EOS T5i) located 2 m from the front wall of the flume. Images were captured at a rate of 24 frames per second and at a resolution of 1080×1920 pixels ($0.6 \text{ mm} \times 0.6 \text{ mm}$ per pixel). The glass wall of the flume was lit with fluorescent lights mounted immediately above and below the front wall of the flume.

Images were initially extracted from video files as red-green-blue (RGB) images and converted to greyscale images using MATLAB (R2015a), in which each pixel was assigned an intensity value between 0 (black) and 255 (white). These intensity values varied in both space and time, based on the lighting, colour of the gravel grains, and dye concentration in the pore water. Each greyscale (intensity) image was aligned with a single reference image captured prior to any of the dye injections. This alignment reduced noise during further processing associated with small movements of the camera, and oriented each image in a common coordinate system for comparison between injections. This alignment (referred to as registration) was conducted using MATLAB, and was based on four control points marked on the front glass wall of the flume. The code used for all processing and calculation of flow paths and velocities is available upon request from the corresponding author. Further processing was used to highlight the plume of injected dye by subtracting the reference image from each of the aligned intensity images to create an array of intensity differences, which also varied in both space and time, and had values of 0-255:

$$D'(x, z, t) = I(x, z, t) - I(x, z, 0) \quad (1)$$

where D' is the intensity difference image and I is the aligned intensity image. By subtracting the reference image from each aligned intensity image, and assuming negligible rearrangement of gravel grains during dye injection, differences in intensity caused by the colour of individual grains were eliminated and any remaining differences were due to either changes in dye concentration or lighting variability. Lighting effects were accounted for by adjusting local intensity differences

relative to intensity differences in a noise reference region that did not contain dye, as described below, during the determination of hyporheic flow paths and velocities:

$$D(x, z, t) = D'(x, z, t) - N(t) \quad (2)$$

where D is the noise-corrected intensity difference image and N is the mean intensity of a region within the gravel, taken to be 0.1 m long $\times$ 0.03 m high and located approximately 5.8 m from the flume entrance and 0.1 m from the flume base. This region was selected such that it did not contain any dye throughout each injection, and any changes in image intensity there were due to lighting variations caused by the frequency and position of the fluorescent lights.

Determination of hyporheic flow paths

Hyporheic flow paths were determined by moment analysis conducted on the noise-corrected intensity difference images captured immediately before the dye front entered the surface water (i.e., using images of dye plumes that extended from the injection point and through the gravel). A series of radial transects were defined, starting at a point 0.01-0.09 m directly below the bar top (depending on the depth of the flow path) and extending into the gravel (Figure 4). These transects extended toward the bottom and ends of the flume, and across the dye plume. Each transect was spaced such that they were separated by 6.7 mm along the approximate middle of the dye plume. Therefore, between 16 and 108 transects were used for the dye injections, depending on the length of the plume. The centre of mass in the direction of the transect was based on the ratio of the first and zeroth moments of the noise-corrected intensity difference. Assuming that intensity difference was a proxy for dye concentration, the centre of mass was calculated as:

$$M_j = \frac{\sum_{i=1}^{500} L_i D_i}{\sum_{i=1}^{500} D_i} \quad (3)$$

where M_j is the centre of mass of transect j , L_i is the distance along the transect to location i , D_i is noise-corrected intensity difference at location i , and each transect is discretized into 500 locations. Because of the large grain size relative to the discretization of the transects ($d_{50} = 7.7$ mm compared to 0.6 mm $\times$ 0.6 mm per pixel), the intensity difference profile along each transect varied between

transects. This included regions where the intensity difference decreased to zero because changes in dye concentration were obscured by individual grains. To account for this variation, an average centre of mass was also calculated using the mean noise-corrected intensity difference profiles for each group of four adjacent transects as:

$$M_k = \frac{\sum_{i=1}^{500} L_i \bar{D}_i}{\sum_{i=1}^{500} \bar{D}_i} \quad (4)$$

where M_k is average centre of mass of transect group k , and $\bar{D}_i$ is the average, noise-corrected intensity difference at location i . These represent the average centre of mass over a 20 mm, rather than a 6.7 mm, distance along the flow path. The total flow path was then determined by linear interpolation between adjacent average centres of mass locations (Eq. (4)), and the variation between the individual centres of mass for each transect (Eq. (3)) was used to assess the uncertainty of those locations.

Measurement of hyporheic flow velocities

The intensity difference images were also used to measure the hyporheic flow velocities for flow paths beginning at each of the injection points. Breakthrough curves (i.e., the noise-corrected intensity differences over time) were generated for two locations, corresponding to the first and last average centre of mass locations used to determine each flow path. These were located 10 mm from each end of the flow path. Similar to the method employed for the determination of the flow paths, the mean noise-corrected intensity difference over an area greater than the size of a single grain was used to reduce the effect of single grains that obscured changes in intensity. For the breakthrough curve analysis, the mean noise-corrected intensity difference over a circular area with a diameter of 14.2 mm (approximately two grain diameters) was used to prevent artificially high or low values at locations completely within or outside of one grain.

The average velocity for each flow path was calculated based on the length of the flow path and the difference in the arrival times between these two locations. It is important to note that these velocities are those that occurred near the glass wall, where injected dye could be visualized. The arrival time was estimated as the time corresponding to 50% of the peak intensity difference.

Uncertainty in these measurements was based on the coefficient of variation of the noise-corrected intensity difference measured over time at the first centre of mass location during the D4 injection, during which the dye concentration remained high for an extended period (137 s). This variation was used along with the slope of the noise-corrected intensity difference breakthrough curve near the arrival time to determine the uncertainty in the arrival time. To assess the accuracy of the calculated arrival times, they were compared to approximate arrival times based on the beginning of each injection and the first observation of dye in the surface water.

Results and discussion

Dye injection

Example RGB and noise-corrected intensity difference images during dye injection are shown for locations U1 (Figure 5) and D4 (Figure 6), and are representative of the results from other upstream and downstream injection locations, respectively (Fruetel, 2016). As observed during injections at all of the upstream locations, Figure 5 shows a relatively narrow (30-80 mm wide) dye plume that travels in the downstream direction and penetrates deeper into the gravel before turning upwards towards the surface water flow near the downgradient edge of the bar top. While this can be seen in the RGB images (Figure 5a-d), which also show the bed surface and the gravel grains, the dye plume is more clearly visible in the noise-corrected intensity difference images (Figure 5e-h). The opposite flow occurs during injections at the downstream locations, with flow opposite to the surface water flow (Figure 6), which agrees with previously reported results (Elliott and Brooks 1997; Bjornn and Reiser 1991; Zhou and Endreny 2013; Savant et al. 1987) and is consistent with negligible momentum effects and the local minimum in the free surface downstream of the bar top. In all cases, the dye plume increased in width due to transverse vertical dispersion as it progressed along the flow path. The intensity difference of the dye plume decreased along the flow path, due to a combination of transverse vertical and transverse horizontal (perpendicular to the glass wall and into the gravel) dispersion.

Increases in the width of the dye plume were particularly apparent for the downstream injections, as the dye plume became asymmetric about the flow path close to the bar (e.g., Figure 6h). This is indicative of a flow divide between the upstream and downstream flow paths, and appears as a sharp line of dye downstream of the bar top and nearly perpendicular to the flume bottom. In

larger scale systems, the base of this flow divide is expected to be a flow stagnation zone that divides the shallower upstream and downstream hyporheic flow from the deeper flow in the direction of the surface water flow. Such a stagnation zone could affect the transport of dissolved compounds, with exchange to the surrounding hyporheic flow dominated by diffusion.

Hyporheic flow paths and velocities

Example flow paths determined using Eq. (1)-(4) are shown along with the noise-corrected intensity difference images in Figure 7. A comparison of the centres of mass from individual transects compared to those averaged over four adjacent transects gives an uncertainty envelope (based on a 95% confidence interval) of approximately two grain diameters (14 mm in this gravel). This uncertainty envelope is expected to be larger in these gravel experiments than in other experiments with finer material and slower velocities. This uncertainty envelope lies within the 30-80 mm width of the dye plumes, and demonstrates that the combination of image processing and moment analysis used in this study is capable of accurately determining the hyporheic flow path. Similar agreement was observed for all injections conducted at all upstream and downstream locations (see Supplementary Material).

Example breakthrough curves are shown in Figure 8, and are representative of those from injections at other locations (Fruetel 2016). For each pair of curves (one at each end of the flow path) for injection at locations U1, U3 and D1 breakthrough at the end of the flow path is characterized by a delayed increase in intensity difference due to increased travel time along the flow path, and lower peak intensity difference due to transverse dispersion. Breakthrough following injection at location D4 was also delayed at the end of the flow path, but the intensity difference was higher due to lower lighting levels at the far downstream side of the gravel bar (Figure 6a-d). In addition, each breakthrough curve is asymmetric, with a faster return to low intensity difference values than the initial increase to the peak intensity difference.

Despite corrections made for variations in lighting intensity using a region outside of the dye plume, variations in the noise-corrected intensity difference were still observed at all breakthrough locations (Figure 8). The periodic nature of the signal noise is particularly apparent in the breakthrough curves at the end of the flow path for injections U1 (Figure 8a) and U3 (Figure 8b),

and is attributed to lighting variations that were not corrected using the reference region. Improvements in lighting are required to reduce this signal noise.

Arrival times based on the breakthrough curves are compared to those observed directly in the surface water during the dye injections in Table 2. For dye injection at all locations, the observed arrival time in the surface water was greater than the calculated arrival time based on the noise-corrected intensity difference breakthrough (Figure 8) due to dilution of the dye in the water above the gravel that made visual detection difficult. Because of this delayed detection, the breakthrough-based estimates were used to estimate velocity. The magnitude of these hyporheic velocities was controlled predominantly by whether the injections were made upstream or downstream of the bar top. Within the upstream or downstream locations, velocities were similar ($1.0\text{--}2.2 \times 10^{-2}$ m/s for upstream injections and $5.6\text{--}6.3 \times 10^{-3}$ m/s for downstream injections) and were higher for the upstream injections than for the downstream injections (Table 2). In addition, velocities generally increased with depth, for example, velocities along the U2, U3 and U4 flow paths were greater than those along the U1, U5, U6 and U7 flow paths. All of these hyporheic velocities were near the upper limit of the $10^{-5}\text{--}10^{-2}$ m/s that have been reported previously (Boulton et al. 1998) and represent fast velocities for flow in porous media. For example, the Reynolds number in the porous medium (Re_{pm}) in this study was 43–170, well above the typically-considered value of $Re_{pm}=1\text{--}10$ for the onset of turbulent flow in porous media. This is due to both the magnitude of the velocities as well as the size of the gravel grains. As also noted by Packman et al. (2004), Darcy's law no longer applies at these higher velocities and alternate governing equations would be required for the simulation of hyporheic flow under these conditions. These high hyporheic velocities represent a measurement challenge in laboratory experiments, with short plume arrival times of 4–124 s (Table 2). The ability of the visualization technique presented here to measure those velocities highlights its usefulness, and it is expected that performance of the technique will improve when applied to systems with finer material and slower flow.

Hyporheic flow field

By registering all of the captured images to the same initial reference image, and because no changes were made to the gravel bar or the flow conditions in the flume between dye injections, the flow path results for each of the injection locations can be combined to show the complete hyporheic flow field in the gravel within and below the bar (Figure 9). As expected, hyporheic

flow that originates upstream of the bar travels below the bar and discharges downstream of the bar top, while flow that originates downstream of the bar travels down through the gravel but does not cross under the bar. All flow paths discharge within an approximately 0.3 m-wide region immediately downstream of the bar top. It is this region that would likely be most at risk from aqueous phase contaminants, such as dissolved hydrocarbons from oil trapped in the gravel, exiting the gravel.

It is important to note that the upstream flow lines are neither symmetric about the bar top, nor is their exit location coincident with the location of the minimum free surface elevation (as expected if only a hydrostatic pressure distribution at the bed surface was considered). The location of the flow divide, based on the sharp edge of the dye plume in the later images from the D4 injection, was approximately 0.2 m downstream of the local minimum of the free surface. Despite the injection locations being closely spaced, the flow lines did not cross, which further demonstrates the precision of this technique. While the flow lines do not cross, they do converge towards the discharge region (Thibodeaux and Boyle, 1987); for example, as demonstrated by comparing the distance between the upstream and downstream ends of the U2 and U3 flow paths (Figure 9).

The geometry of this flow system is controlled by the flow conditions in the flume, the hydraulic conductivity of the gravel and the morphology of the bar, but it is also controlled by the depth of the flume, the bottom of which provides a no-flow boundary that was less than 0.3 m below the top of the bar. In larger-scale systems, hyporheic flow paths are expected to travel deeper below the bar but still discharge downstream of the bar top. The flow field is also controlled by the homogeneity of the gravel. In a more heterogeneous system (e.g., a layered system with coarser material near the bed surface and finer material beneath it), flow lines would focus in the more permeable material.

Conclusions

This study developed a practical method to measure hyporheic flow (pathways and velocities) in a laboratory flume based on dye injection, digital images and moment analysis. The positions of flow paths were determined to within ± 14 mm, and agreed with visual observations of dye plumes. Individual flow paths determined using separate dye injections were combined to provide a

detailed depiction of the hyporheic flow field, both upstream and downstream of a single gravel bar. This flow field showed asymmetry about the bar top, discharge downstream of the minimum free surface elevation, and a distinct flow divide between the upstream and downstream hyporheic flow. Hyporheic velocities determined using breakthrough curve analysis agreed with observations of dye transport through the gravel, and were $1.0\text{--}2.2 \times 10^{-2}$ m/s for injections upstream of the bar top and $5.6\text{--}6.3 \times 10^{-3}$ m/s for injections downstream of the bar top. These velocities correspond to Reynolds numbers in the gravel of 43–170, which represent conditions under which Darcy's law does not apply and alternate approaches are required for the simulation of these faster hyporheic flows.

The emphasis of this study was on the development of a visual method, and its demonstration applied to hyporheic flow beneath a single gravel bar. Further improvements to the method would be valuable, including improved lighting control to reduce imaging noise and the establishment of guidance regarding the area over which image intensities are measured compared to the grain size of the porous medium. Additional hyporheic flow conditions also require investigation, including the influence of multiple bars, deeper beds, heterogeneity in hydraulic conductivity (e.g., armouring), and three dimensional effects. Despite the need for further investigation, the results presented here demonstrate key considerations for contaminant transport by hyporheic flow: i) dissolved contaminants are likely to be discharged close to but downstream of the top of bars, ii) upstream and downstream hyporheic flows will create stagnation zones that will be dominated by diffusive, rather than advective, transport, and iii) hyporheic velocities in gravel will be faster than those typically considered for flow in porous media (i.e., cm/s), with implications for risk assessment and the numerical simulation of hyporheic flow in gravel-bedded rivers.

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544 List of Symbols

545		
546	B	flow width [m]
547	d	representative grain size (identified with d_{50}) [m]
548	D	noise-corrected image intensity difference [-]
549	D'	image intensity difference [-]
550	Fr	Froude number ($= u_{av} / (gh)^{1/2}$) [-]
551	g	acceleration due to gravity [m^2/s]
552	h	flow depth (of free surface flow) [m]
553	I	aligned image intensity [-]
554	L	distance along transect [m]
555	M	centre of mass location [m]
556	N	mean image intensity of noise reference region [-]
557	Q	flow rate (of free surface flow) [m^3/s]
558	Re	flow Reynolds number ($u_{av} R_h / \nu$) [-]
559	Re_{pm}	Reynolds number in the porous medium ($= u_{pm} d_{50} / \nu$) [-]
560	R_h	hydraulic radius [m]
561	S	flume slope [-]
562	u_{av}	average flow velocity (of free surface flow) [m/s]
563	u_{pm}	average flow velocity in the porous medium [m/s]
564	ν_*	shear velocity [m/s]
565	γ_s	specific weight of grains in fluid [N/m^3]
566	θ	Shields parameter ($= (\rho \nu_*^2) / (\gamma_s d)$) [-]
567	θ_{cr}	value of θ at the critical stage of initiation of sediment transport [-]
568	ν	fluid kinematic viscosity [m^2/s]
569	ρ	fluid density [kg/m^3]

1 Table 1: Hydraulic conditions of the free surface flow ($B = 0.382$ m; $d_{50} = 7.7$ mm, $S = 1/750$).

Q (m ³ /s)	h (m)	u_{av} (m/s)	v_* (m/s)	R_h (m)	Re	Fr	θ/θ_{cr}
0.021	0.180	0.305	0.035	0.093	28365	0.23	0.22

2

Draft

Table 2: Flow velocities based on observations and dye breakthrough at each injection point.

Injection point	Flow path length (mm)	Arrival time (s)		Velocity (m/s)	Re _{pm}
		In surface water ¹	From dye images ²		
U1	506	53	49	1.0×10^{-2}	79
U2	354	21	16	2.2×10^{-2}	170
U3	211	24	11	1.9×10^{-2}	147
U4	80	5	4	1.9×10^{-2}	145
U5	423	39	34	1.2×10^{-2}	95
U6	206	18	18	1.2×10^{-2}	91
U7	120	14	8	1.4×10^{-2}	110
D1	187	31	30	6.2×10^{-3}	48
D2	580	113	104	5.6×10^{-3}	43
D3	540	86	86	6.3×10^{-3}	49
D4	715	133	124	5.8×10^{-3}	44

¹Observations of dye entering the surface water after travelling through the gravel.
²Average difference between breakthrough times for 50% of the peak noise-corrected intensity difference at either end of the flow path for the leading edge of the dye plume.

List of Figure Captions

Figure 1: Conceptual representation of hyporheic flow through a single bar (from da Silva et al., 2016, reprinted with permission from CRC Press).

Figure 2: Schematic of experimental set-up.

Figure 3: Dye injection locations.

Figure 4: Schematic of a dye plume generated from an upstream injection location showing one set of four radial transects used to determine the centre of mass of the dye plume in the direction of the transects.

Figure 5: Results of dye injection at location U1 showing (a-d) original RGB images and (e-h) noise-corrected intensity difference images at times (a, e) immediately prior to injection and (b, f) 20 s, (c, g) 60 s and (d, h) 100 s after the start of injection. Free surface flow and hyporheic flow are from left to right.

Figure 6: Results of dye injection at location D4 showing (a-d) original RGB images and (e-h) noise-corrected intensity difference images at times (a, e) immediately prior to injection and (b, f) 60 s, (c, g) 120 s and (d, h) 180 s after the start of injection. Free surface flow is from left to right and hyporheic flow is from right to left.

Figure 7: Flow paths (blue lines) for injections (a) U1, (b) U3, (c) D1 and (d) D4 shown along with the corresponding noise-corrected intensity difference images, the free water surface (upper white line) and the gravel-water interface (lower white line).

Figure 8: Breakthrough of the noise-corrected intensity difference at the first and last centre of mass locations along the flow paths (start and end of the flow path) for dye injections at locations (a) U1, (b) U3, (c) D1 and (d) D4.

Figure 9: Hyporheic flow field based on flow paths from all injection points.

High-pressure
zone

Low-pressure
zone

Streamflow

Flume entrance

Elevated flume floor

Near-static water

Near-static water

Gravel

Flume floor

0.20 m

5.07 m

0.4 m

Bar length = 1.4 m

0.4 m

Figure 5: Results of dye injection at location U1 showing (a-d) original RGB images and (e-h) noise-corrected intensity difference images at times (a, e) immediately prior to injection and (b, f) 20 s, (c, g) 60 s and (d, h) 100 s after the start of injection. Free surface flow and hyporheic flow are from left to right.

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11 Figure 6: Results of dye injection at location D4 showing (a-d) original RGB images and (e-h)
 12 noise-corrected intensity difference images at times (a, e) immediately prior to injection and (b,
 13 f) 60 s, (c, g) 120 s and (d, h) 180 s after the start of injection. Free surface flow is from left to
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