Impacts of Emergent Vegetation on Hyporheic Exchange

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Key Points:

- Emergent vegetation increases the exchange of solutes between surface and subsurface water in the hyporheic zone.
- Vegetation-induced hyporheic exchange can be characterized by the first-order equations with an effective hyporheic exchange velocity.
- The effective velocity of the vegetation-induced hyporheic exchange scale as the total near-bed turbulent kinetic energy k_t.

Abstract

Hyporheic exchange, or the exchange of water and solutes between surface and subsurface water at the sediment-water interface, regulates water quality and biogeochemical cycles in aquatic ecosystems. Vegetation, which is ubiquitous in nature, is known to impact hyporheic exchange, yet how vegetation impacts hyporheic exchange remains to be characterized. Here, we show that at the same spatially and temporally averaged flow velocity U, vegetation increases the rate of hyporheic exchange by a factor of four. By tracking the movement of fluorescent dye in a flume with index-matched sediment and translucent vegetation dowels, we demonstrate that vegetation-induced hyporheic exchange at the sediment-water interface can be characterized by an effective hyporheic exchange velocity, V_H. We further demonstrate that V_H could correlate with the total near-bed turbulent kinetic energy k_t rather than mean flow velocity U when $k_t < 6 \times 10^{-4}$ $\mathrm{m^2/s^2}$. A k_t-based model was developed to characterize the impacts of vegetation on hyporheic exchange.

Plain Language Summary

The exchange of contaminants and nutrients between surface- and subsurface-water in the hyporheic zone of rivers and wetlands controls water quality as well as the metabolism of benthic microbes and the associated biogeochemical cycles. Vegetation, which is ubiquitous in aquatic ecosystems, has been found to affect the surface- and subsurface-exchange and as such impact water quality and stream biogeochemical cycles. However, how vegetation impacts this exchange remains unclear, making it difficult to predict the contaminant transport and biogeochemical cycles in streams, lakes, and coastal areas with vegetation. In this study, we directly visualized the release of fluorescent dye from the transparent sediment into the surface water in a water-recirculating tank filled with translucent vegetation. We discovered that vegetation can significantly increase the exchange in the hyporheic zone. Furthermore, we proposed a model to predict the impacts of the vegetation on hyporheic exchange. We believe this finding will help improve predictions of contaminant transport and biogeochemical cycles in streams and other aquatic ecosystems. The results of this study will also help ecologists design stream restoration projects that use vegetation to increase the retention and degradation of contaminants in sediment.

1 Introduction

Hyporheic zone is often referred to the region of saturated sediments underneath the surface water of a stream, where water, gases, nutrients, and contaminants are consistently being exchanged (Boano et al., 2014; Boulton et al., 1998; Gooseff, 2010). The exchange between surface and subsurface water supplies nutrients and oxygen to underground microbes and as such controls the biogeochemical cycles and biodiversity of stream bed (Battin et al., 2008; Jones Jr & Holmes, 1996; Tonina & Buffington, 2009; Wohl, 2016). The exchange in hyporheic zone also determines the retention and degradation of contaminants in stream (Grant et al., 2014; Lewandowski et al., 2011; McCallum et al., 2020). Fundamental understanding of the exchange in hyporheic zone is critical for predicting the biogeochemical cycles, biodiversity, and fate of contaminants in streams.

Over the past decades, extensive studies have been conducted to characterize the impacts of channel morphology such as bedforms (Buffington & Tonina, 2009; Dudunake et al., 2020; Marion et al., 2002; Packman et al., 2004; Tonina & Buffington, 2007) and sinuosity of river (Boano et al., 2006; Cardenas, 2009) on hyporheic exchange. Recent field studies show that the

presence of vegetation in stream increases the in-stream transient storage controlled by hyporheic exchange (Ensign & Doyle, 2005; Salehin et al., 2003). However, the impact of in-channel aquatic vegetation on the hyporheic exchange has not been systematically quantified (Ding et al., 2020).

In-channel aquatic vegetation exerts drag on the surface flow (Cheng & Nguyen, 2011; D'Ippolito et al., 2019), which creates spatial heterogeneities in near-bed mean flow velocity (Zhao & Fan, 2019), shear stress (Salvador et al., 2007; Yang et al., 2015), turbulent kinetic energy (Xu & Nepf, 2020), and pressure (Nepf & Koch, 1999; Yuan et al., 2021). In addition, vegetation drag also extracts energy from the mean flow and converts it to turbulent kinetic energy k_t (Nepf, 1999, 2012; Tanino & Nepf, 2008). Both spatial heterogeneity in hydraulic head (Boano et al., 2014; Lee et al., 2022; Shen et al., 2020; Tonina & Buffington, 2007; Yuan et al., 2021) and turbulence (Roche et al., 2018; Roche et al., 2019; Rousseau & Ancey, 2020; Voermans et al., 2017; Voermans et al., 2018b) are known to induce hyporheic exchange. Therefore, we anticipate that the drag exerted by vegetation, which induces spatial hydraulic gradient and turbulence, can induce hyporheic exchange.

The goal of this study is to quantify the impact of emergent vegetation, i.e., plants that extend out of the water surface, on hyporheic exchange across the sediment-water interface in streams with a flat gravel bed through systematically controlled laboratory experiments. We conducted a series of dye-visualization experiments in a water-recirculating flume filled with transparent hydrogel beads that simulate a gravel bed and acrylic cylinders that simulate emergent vegetation stems. We used an effective hyporheic exchange velocity, V_H, to characterize the exchange rate of fluorescent dye between surface and subsurface water in the hyporheic zone. In addition, the mean flow velocities were measured and the near-bed turbulent kinetic energy k_t was calculated. Our experiments show that V_H in channels with emergent vegetation scales with k_t when $k_t < 6 \times 10^{-4}$ $\mathrm{m^2/s^2}$, because k_t reflects the vegetation-drag-induced near-bed turbulence and spatial heterogeneity in hydraulic head, both of which drive hyporheic exchange.

2 Theories

2.1 Pseudo-first-order equations for hyporheic exchange

Here, we use pseudo-first-order equations (Wu et al., 2001) to quantify the impacts of the vegetation on the rate of solute exchange across the sediment-water interface. We hypothesized that Fick's first law governs the vertical hyporheic flux in vegetated channels with gravel flat beds, like the gas diffusion across a diffusive boundary layer. Thus, similar to gas transfer model based on the thin-film theory (Jørgensen & Revsbech, 1985; O'Connor & Hondzo, 2008), the rate of hyporheic exchange can be quantified by an effective hyporheic exchange velocity V_H. Note that here we focus on the hyporheic exchange between the surface water and the top sediment layers. We do not consider the variation in diffusivity with depth within deeper sediment as discussed in Chandler et al. (2016) and the longitudinal dispersion discussed in Bottacin-Busolin (2017). Below we describe how we use V_H and the pseudo-first-order equations to predict the release of solutes from the pore water of the top sediment layers to the surface water in a recirculating flume. In Section 3, we describe how we use flume experiments to validate the model.

First, at the beginning of the experiment, a solute is uniformly distributed in the pore space of the top several layers of sediment with concentration C_s. Due to hyporheic exchange, the solute in the sediment is transported into the surface water through a mixing layer, such that C_s decreases with time t. Once solute leaves the sediment bed, it is quickly mixed with the surface water with

a uniform concentration C_w. For simplicity, we assume that the solute concentrations in the top sediment layers and in surface water are both uniformly distributed, with volume $V_{ol,s}$ and $V_{ol,w}$, respectively. We hypothesize that the exchange between surface and subsurface water at the sediment-water interface can be characterized by a pair of pseudo-first-order equations with an effective hyporheic exchange velocity V_H. Therefore, based on mass balance between the surface water and subsurface water:

$$\frac{dC_s}{dt} = -V_H \frac{A_{SWI}\phi_s}{V_{ol,s}}(C_s - C_w) \quad (1)$$

$$\frac{dC_w}{dt} = -V_H \frac{A_{SWI}\phi_s}{V_{ol,w}}(C_w - C_s). \quad (2)$$

Here ϕ_s is the sediment porosity; A_{SWI} is the horizontal area of the sediment-water interface (m^2), and V_H is the effective hyporheic exchange velocity ($\mathrm{m/s}$), which is defined as $V_H = D_e/\delta_D$. D_e is the effective diffusion coefficient (m^2/s) and δ_D is the mixing layer thickness (m). If the solute concentration in the surface water is negligible ($C_s \gg C_w$), the analytical solution of Eq. 1 is $C_s(t) = C_{s0}e^{-V_H A_{SWI}\phi_s t/V_{ol,s}}$, which predicts an exponential decrease in the solute concentration in the pore space of the sediment. Here C_{s0} indicates the initial solute concentration in the sediment. The schematic diagram of the proposed model is shown in Fig. S1 in the Supplementary Information. The fitting of this model (Eqs. 1 and 2) to our experimental results are discussed in Section 4.1. Note that effective diffusion coefficient D_e was defined differently using 1-D diffusion equation in other studies (Chandler et al., 2016; Grant et al., 2012; O'Connor & Harvey, 2008). Comparisons of the D_e based on their definition is discussed in Section 4.1.

2.2 Impact of emergent vegetation on hyporheic exchange

In-channel vegetation exerts drag on surface flow (Cheng & Nguyen, 2011; D'Ippolito et al., 2019) and converts kinetic energy of the mean flow to turbulent kinetic energy (Nepf, 1999; Tanino & Nepf, 2008). The drag force generated by vegetation can be expressed as follows (Cheng & Nguyen, 2011),

$$F_D = \frac{1}{2} a V_{ol,v} C_D \rho_w U^2 \quad (3)$$

Here a is the frontal area per unit volume (m^{-1}) which can be estimated as $a = nd_v$ for cylindrical vegetation (Yang & Nepf, 2018); n is the stem density ($\mathrm{stem/m}^2$); d_v is the diameter of model vegetation stem (m); C_D is the drag coefficient of the vegetation; $V_{ol,v}$ is the volume of water with vegetation canopy (m^3); ρ_w is fluid density ($\mathrm{kg/m}^3$), and U is the flow velocity ($\mathrm{m/s}$). The drag exerted by the emergent vegetation generates spatial heterogeneities in the near-bed mean flow velocity, and further generated the hydraulic head that induces the hyporheic exchange (Yuan et al., 2021). In addition, the vegetation-generated turbulent kinetic energy k_{tv} can be estimated by the energy extracted from the mean flow due to vegetation drag (Tanino & Nepf, 2008; Yang et al., 2016):

$$k_{tv} = 1.2\left[C_D \frac{\phi_v}{(1-\phi_v)\,\pi/2}\right]^{2/3} U^2. \quad (4)$$

Here ϕ_v is the solid fraction of the vegetation. For cylindrical dowels, $\phi_v = \pi a d_v/4$ (Yang & Nepf, 2018). The total near-bed turbulent kinetic energy k_t then can be approximated as the sum of bed-generated k_{tb} and vegetation-generated k_{tv} (Yang et al., 2016; Yang & Nepf, 2018, 2019),

$$k_t = k_{tb} + k_{tv}. \quad (5)$$

Here $k_{tb} = C_f U^2/0.19$; C_f is bed drag coefficient. The vegetation generated turbulence is a result of vegetation drag and as thus correlates with the spatial heterogeneity in hydraulic head which is also induced by vegetation drag. We hypothesis that near-bed turbulent kinetic energy k_t reflects the compound effect of vegetation-drag-induced spatial heterogeneity in near-bed hydraulic head and near-bed turbulence on hyporheic exchange and thus k_t can be applied to predict the vegetation-induced hyporheic exchange.

3 Materials and Methods

3.1 Experimental setup

Hyporheic exchange experiments were conducted in a horizontal race-track flume at the University of Minnesota's St. Anthony Falls Laboratory. The flume is 14-m-long and 60-cm-wide and has a 150-cm-long by 60-cm-wide straight test section (Figs. 1 and S2). The water depth in all experiments was 20.0 ± 0.1 cm. The flow in the flume was driven by a propeller. The flow velocity was directly measured by a side-looking Acoustic Doppler Velocimeter (Nortek Vectrino, Norway, Fig. S5).

The bottom of the test section (60 cm × 150 cm) was removed, and the space underneath was filled with transparent hydrogel beads (5.6 ± 0.6 mm in diameter) to simulate a gravel bed. Method to make the hydrogel beads developed by Ma et al. (2019) is described in Text S1 in the Supplementary Information. To keep the hydrogel beads in place and the sediment bed flat, a black polyester mesh (4 mm pore size) was placed on the top of the beads. While the bed was mostly flat without obvious bedform, one of the downstream corners of the mesh tilted and formed a small lateral slop of 1/150 and 1/60 in streamwise direction and spanwise direction, respectively. This structure was roughly the same in both cases with and without vegetation. We anticipate this small structure would not affect our results, because we focus on the difference in hyporheic exchange between channels with and without vegetation.

To investigate the impact of rigid emergent vegetation on the flow, the translucent and cylindrical acrylic dowels with $d_v = 6.4 \pm 0.1$ mm diameter were inserted in a staggered pattern (Fig. S5) on a PVC board fixed under the sediments. The dowels extended through the whole water column and entire sediment depth. The solid volume fraction of vegetation ϕ_v in this study is 0.05, in the range of typical values found in marshes (Nepf, 2012; Yang et al., 2016). The stem density n is 1,514 $\mathrm{stems/m^2}$, and the spanwise center-to-center distance between two dowels $2ds$ is 2.6 cm (Fig. S5). The vegetation frontal area per unit canopy volume $a = nd$ is 9.8 $\mathrm{m^{-1}}$. There are 1,363 dowls in the test section. In the area where images were processed, there were 47 dowels.

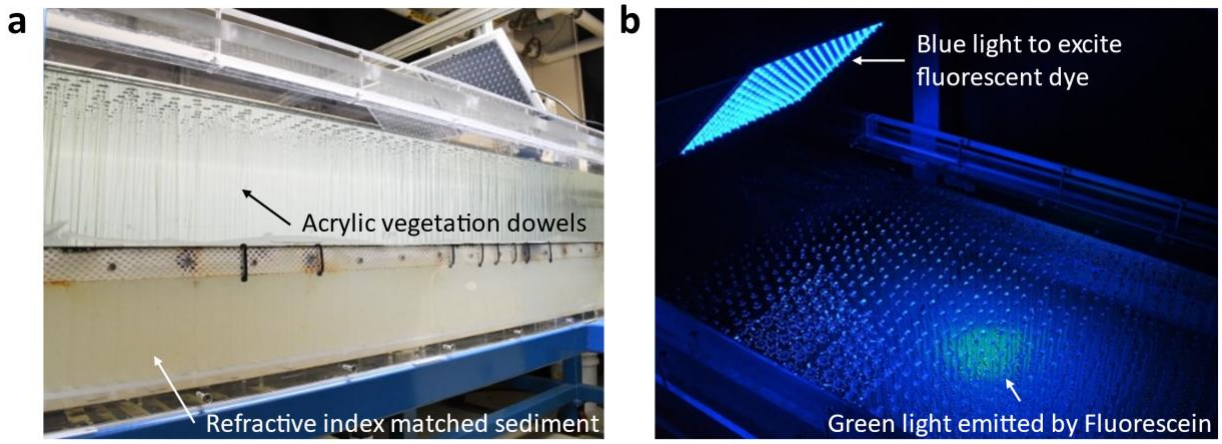

Figure 1. Experiments in a recirculating flume to visualize the exchange of fluorescent dye between surface and subsurface water. Refractive-index-matched sediment and translucent vegetation dowels were used. Green, fluorescent dye was injected into the sediment and a blue lamp was used to excite the dye.

Instantaneous flow velocity was measured using a side-looking Acoustic Doppler Velocimeter (ADV; Nortek Vectrino, Norway) mounted on a 2-D moving system with 200 Hz sampling rate for 2.5 minutes. Solid glass beads with specific gravity 2.6 and mean diameter 35 micrometers (3000 E-Spheriglass; Potters Industries Inc., Pennsylvania) were added to the water as seeding particles. Measurements with signal-to-noise ratio below 15 dB were removed from data analysis. A bivariate kernel density function was used to remove noise signals from velocity measurements (Islam & Zhu, 2013). For cases with vegetation, three dowels were removed to make space for the probe of the ADV. We anticipate that the ADV probe would not affect the velocity measurements, because the probe was 5 cm away from the measurement location (Fig. S5). Four velocity profiles were measured at the middle of test section to estimate spatial-weighted averaged velocities for each case. For cases without vegetation, profiles were 5, 13, 22, 30 cm away from the side wall, respectively. The measured locations and weighted average method for cases with vegetation can be found in Fig. S5.

The spatially averaged near-bed turbulent kinetic energy k_t was calculated from the instantaneous flow velocity measured 2 cm above the bed at the four representative locations using an ADV. Specifically, the local k_t at each location was calculated as $\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)/2$. Here u', v', and w' are flow velocity fluctuations in streamwise, spanwise, and vertical direction, respectively. The spatially averaged near-bed k_t was calculated using a spatial-average method justified in Yang et al. (2015) from local k_t at 4 locations as shown in Fig. S5. Location at 2 cm above bed was chosen because within 2 cm from the bed the sampling volume of the ADV is interfered by the boundary such that the signal-to-noise ratio became smaller than 15 dB. Previous studies using same model vegetation show that the vertical distribution of turbulent kinetic energy is uniform above a thin boundary layer (Nepf, 1999; Yang et al., 2015), thus, our measurement of k_t at 2 cm above the bed captures the impacts of vegetation on near-bed turbulent kinetic energy.

198 3.2 Fluorescent dye release experiments

199 Fluorescent dye release experiments were conducted to measure the rate of hyporheic
200 exchange. First, dye solution was prepared by adding fluorescein sodium salt (Sigma-Aldrich
201 F6377) to DI water at 0.002‰ weight ratio. The water depth in the flume was adjusted to 20.0 ±
202 0.1 cm. The fluorescent dye was injected into a 44 cm × 43 cm sediment area up to 5 cm deep
203 (accumulative dye concentration is $(1.286 \pm 0.006) \times 10^{-3}$ mg/cm^2) using a peristaltic pump (L/S
204 7550-50; Masterflex, Germany). The flow was stopped during the injection. The amount of dye
205 injected at each location was monitored by a scale during the injection process to make sure the
206 uniformly distribution of dye within the injection area. The dye emits green light at 520-nm
207 wavelength, when it is excited by blue light at 490-nm wavelength (Osenbroch et al., 2005). The
208 fluorescence intensity detected by downward-looking camera were calibrated against the dye
209 concentration in the sediment (Text S2 and Fig. S6 in the Supplementary Information). Our
210 measurements indicate that the fluorescence intensity is linearly proportional to the accumulative
211 dye concentration, i.e., mass per unit area (Fig. S6a). The picture of injection equipment and
212 injection locations can be found in Figs. S7-S8.

213 One square lamp (30 cm × 30 cm) with blue LED arrays were placed at the center of the
214 channel and 33 cm above the water surface. The angle between lamp and ground was 40°. The
215 light emitted from the dye was passed through a green light filter (FGV9S; Thorlabs, Newton) and
216 captured by a downward-looking industrial camera (BFS-U3-16S2C-CS; FLIR Systems,
217 Wilsonville) with a 6 mm focal length lens (ArduCAM, China) placed 120 cm above the sediment
218 bed. Afterwards, flow was recirculated in the flume using a propeller, and the fluorescence
219 intensity within the sediment bed was monitored every 5 minutes for a 16.6-hour duration. The
220 unsteady period of flow development at the beginning of the experiment is relatively short (few
221 minutes) compared to the time scale of whole experiment (> 16.6 hours) and the data at early stage
222 was not included in the model fits (Text S3 in the Supplementary Information). Experiments
223 without vegetation were conducted at mean flow velocities of 1.7, 4.0, 6.6, 15.4 cm/s. Experiments
224 with vegetation were conducted at flow velocities of 0.7, 1.6, 2.4, 3.6 cm/s. Each case was
225 conducted twice.

226 The effective hyporheic exchange velocity V_H was estimated by fitting the numerical
227 solution of the pseudo-first-order equation (Eq. 1) to the measured fluorescence intensity versus
228 time (Fig. 2). First, pixels occupied by vegetation and the mesh were removed, and the
229 fluorescence intensity of the light emitted by the dye in the sediment was estimated by averaging
230 the image intensity of pixels occupied by the pore space. From the series of images, the curve of
231 fluorescence intensity versus time, i.e., washout curve, can be obtained. Then, the proposed model
232 (Eqs. 1-2) were fitted numerically to the measured fluorescence intensity versus time (Fig. 2). The
233 effective hyporheic exchange velocity V_H and background image intensity was determined by
234 minimizing the root mean square error between the measured curve and the simulated curve. The
235 detail image processing method and fitting procedure can be found in Text S3 and Fig. S10 in the
236 Supplementary Information.

237 To compare the effective hyporheic exchange velocities V_H for the cases without and with
238 vegetation, we conducted the one-way analysis of covariance (ANOCOVA) using 'aoctool'
239 function in MATLAB, with p-value indicating the statistical difference (Philippas, 2014). When
240 $p < 0.05$, the difference between two data sets is often considered to be statistically significant.

Note that once dye leaves the sediment, it is quickly diluted in the surface water. Our experiments show that the dye in the surface water, whose concentration is much smaller than the dye concentration in the sediment, does not affect the results, i.e., the light captured by the camera above the water surface is mainly contributed by the dye in the sediment.

4 Results

4.1 Dye release experiments verify the proposed model

First, we use dye release experiments described in Section 3.2 to verify the proposed hyporheic exchange model (Eqs. 1-2). The fluorescence intensity at different times shows that the dye concentration in the sediment bed decreases over time (Fig. S9). The spatially averaged fluorescence intensity of the green light emitted by the fluorescent dye was plotted versus time to characterize the leaving of dye from the observed area. The method to identify the pixels related to the pore space can be found in Text S3 in the Supplementary Information. Fig. 2 shows two representative cases without and with vegetation at a similar spatially and temporally averaged flow velocity U measured by an ADV. The decrease in dye concentration occurred much faster in a channel with vegetation than in a channel without vegetation, indicating that the presence of vegetation increases the hyporheic exchange rate.

To capture the rate of exchange, we fit the spatially averaged fluorescence intensity versus time measurements with the proposed model (Eqs. 1 and 2) numerically (see Text S3 in the Supplementary Information for details). The fitted results (solid curves in Fig. 2) show an exponential decrease in fluorescence intensity. The predictions of the model are consistent with the data which were not included in the fitting of the effective hyporheic exchange velocity V_H (dash lines in Fig. 2), indicating that the proposed model can be used to characterize the hyporheic exchange observed in the experiments.

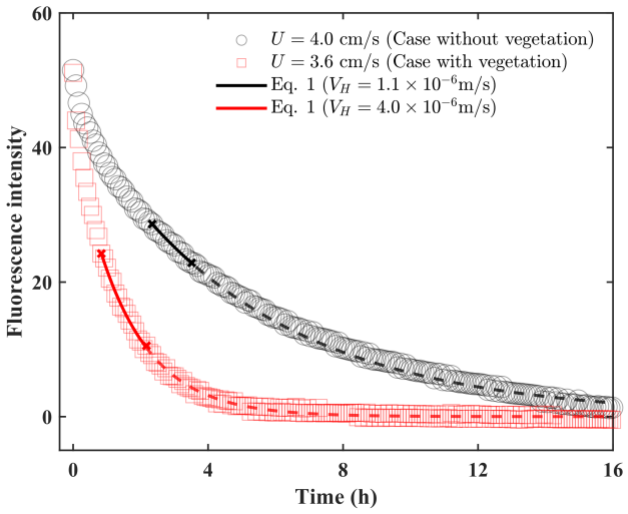

Figure 2. The concentration of the fluorescent dye in the sediment, represented by the fluorescence intensity of the emitted green light, decays over time. The flow was started at time = 0 hour. The black and red symbols represent the fluorescence intensities relative to the background image intensities in channels without vegetation and with vegetation of volume fraction $\phi_v = 0.05$, respectively, at a similar flow velocity 4 cm/s. The black and red solid curves represent the fits of

the measurements with the solution of Eq. 1 with both $R^2 = 0.99$. The model fits are conducted when the streamwise fluorescence intensity decrease uniformly (see Text S3 in the Supplementary Information for details). In the experiments, the horizontal area of the sediment-water interface $A_{SWI} = 0.19\ \mathrm{m}^2$; the sediment porosity $\phi_s = 0.3$; the volume of pore space in the sediment $V_{ol,s} = 1200 \pm 9$ mL, and the volume of surface water $V_{ol,w} = 2830$ L. The fitted parameters are V_H and background image intensity. Dash lines show the model predictions.

Note that in the complementary dye release experiments with a side-looking camera, we observed a streamwise elongation of dye plume. The velocity of the dye front is 1.0~1.5% of the velocity of overlying flow to the downstream in the sediment, which is not considered in the proposed model. On the other hand, the vertical mixing of dye in the sediment was not significant compared with the exchange of dye at the sediment-water interface (Text S4 in the Supplementary Information).

At a similar flow velocity around 4 cm/s, the effective hyporheic exchange velocity V_H of the case without vegetation is 1.1×10^{-6} m/s, about 4 times smaller than V_H of the case with vegetation which $V_H = 4.0 \times 10^{-6}\ \mathrm{m/s}$ (Fig. 2). In addition, the slope of regression line of cases with vegetation is 4 times higher than the slope of regression line of cases without vegetation (Fig. 3a). These results indicate that the presence of vegetation increases the rate of hyporheic exchange by a factor of 4 at the same mean flow velocity U.

Finally, we provide comparison of our results with pervious study. The effective diffusion coefficients D_e calculated using 1-D diffusion equation in our experiments are provided in Table S1 and are compared with the interfacial transport model proposed by Volermans et al. (2018a) in Fig. S12 in the Supplementary Information.

4.2 The scale of effective hyporheic exchange velocity with turbulent kinetic energy

By comparing V_H versus U and k_t for cases without and with vegetation, we exam whether the exchange rate at the sediment-water interface is controlled by mean flow velocity or turbulent kinetic energy. Based on ANOCOVA (see methods for details), the difference between lines V_H versus U measurements for cases without and with vegetation is statistically significant (with $p = 0$ smaller than statistical threshold value 0.05). In contrast, at $k_t < 6 \times 10^{-4}\ \mathrm{m^2/s^2}$, the difference between the slopes of lines V_H versus k_t measurements for cases without and with vegetation is not significant ($p = 0.26$; Fig. 3b). Note that the intercept of line V_H versus k_t without vegetation is statistically significantly bigger than the intercept of line with vegetation and V_H in the vegetated case with $k_t = 7.4 \times 10^{-4}\ \mathrm{m^2/s^2}$ deviates from the linear fitting for $k_t < 6 \times 10^{-4}\ \mathrm{m^2/s^2}$. These deviations are reflections of the complex interactions of flow and vegetation, especially at high turbulent conditions. Nevertheless, our results show that compared with mean flow velocity, turbulent kinetic energy is a better predictor of hyporheic exchange for channels with vegetation, especially at $k_t < 6 \times 10^{-4}\ \mathrm{m^2/s^2}$.

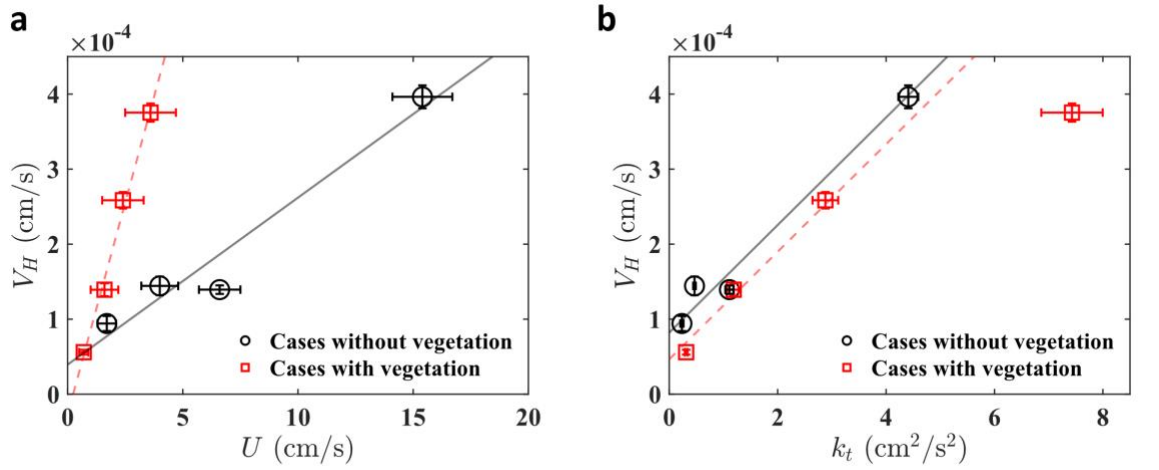

Figure 3. (a) The effective hyporheic exchange velocity V_H versus mean flow velocity U of cases without vegetation (black) and with vegetation of volume fraction $\phi_v = 0.05$ (red). The black solid line ($y = (0.2x + 0.4) \times 10^{-4}$) and red dash line ($y = (1.1x - 0.3) \times 10^{-4}$) represent linear fits to measurements without and with vegetation with $R^2 = 0.89$ and $R^2 = 0.95$, respectively. (b) V_H versus the total near-bed turbulent kinetic energy k_t of cases without vegetation (black) and with vegetation (red). The black solid line ($y = (7.2x + 8.2) \times 10^{-5}$) and red dash line ($y = (7.2x + 4.7) \times 10^{-5}$) represent linear fits of the measurements without and with vegetation with both $R^2 = 0.92$.

5 Conclusions

Vegetation has been acknowledged to enhance the exchange between surface and subsurface water in the aquatic habitats, yet the impacts of vegetation on hyporheic exchange have not been characterized. Here we propose a model to characterize the vegetation-induced hyporheic exchange in channels with vegetation. By conducting tracer experiments using fluorescent dye and refractive-index-matched sediment, we show that the vegetation-induced hyporheic exchange at the sediment-water interface can be characterized by the pseudo-first-order equations with an effective hyporheic exchange velocity V_H. We demonstrate that at the same spatially and temporally averaged flow velocity U, vegetation increases V_H by up to a factor of four when compared with channels without vegetation. We further demonstrate that V_H scales with the total near-bed turbulent kinetic energy k_t instead of U when $k_t < 6 \times 10^{-4}$ m^2/s^2. The results of the proposed hyporheic exchange model will enable quantitative analysis of the impacts of vegetation on the exchange of contaminants and nutrients in the hyporheic zone.

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Data Availability Statement

The raw data of the dye release experiments with a downward-looking camera has been deposited in The Data Repository for University of Minnesota (https://doi.org/10.13020/W282-JJ11). The raw data of the dye release experiments with a side-looking camera and dye calibration have been deposited on Zenodo (https://doi.org/10.5281/zenodo.6412364).

The codes used to process the images and fit the washout curves have been deposited on Zenodo (https://doi.org/10.5281/zenodo.6407198).

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