From Substrate to Surface: A Turbulence-based Model to Predict Interfacial Gas Transfer across Sediment-water-air Interfaces in Vegetation Streams with Sediments

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Abstract

Turbulence generated by aquatic vegetation plays a vital role in the interfacial transfer process at the air-water interface and sediment-water interface (AWI and SWI), impacting the dissolved oxygen (DO) level, a key indicator of water quality for aquatic ecosystems. We investigated the influence of vegetation, under different submergence ratios and plant densities, on the interfacial gas transfer mechanisms. We conducted laboratory experiments in a unidirectional recirculating flume with simulated rigid vegetation on a sediment bed. Two-dimensional planar Particle Image Velocimetry (2D-PIV) was used to characterize the mean flow field and turbulent quantities. Gas transfer rates at the AWI were determined by monitoring the DO concentration during the re-aeration process in water. SWI interfacial transfer fluxes were estimated by measuring the DO concentration difference between the near-surface and near-bed values. Compared to previous observations on a smooth bed without sediment, the presence of sediment enhances the bottom roughness, which generates stronger bed-shear turbulence. The experimental result shows that turbulence generated from the bed does not affect the surface transfer process directly. However, the near-bed suspended sediment provides a negative buoyancy term that reduces the transfer efficiency according to the predictions by a modified Surface Renewal model for vegetated flows. The measured interfacial transfer fluxes across the SWI show a clear dependence on the within-canopy flow velocity, indicating that bed shear turbulence and within-canopy turbulence are critical indicators of transfer efficiency at SWI in vegetated flows. A new Reynolds number dependence model using near-bed turbulent kinetic energy as an indicator is proposed to provide a universal prediction for the interfacial flux across the SWI in flows with aquatic vegetation. Our study provides critical insight for future studies on water quality management and ecosystem restoration in natural water environments such as lakes, rivers, and wetlands.

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Abstract

- Turbulence generated by aquatic vegetation can alter flow structures throughout the whole water column, affecting gas transfer mechanisms across the air-water and sediment-water interfaces (Fig. 1).

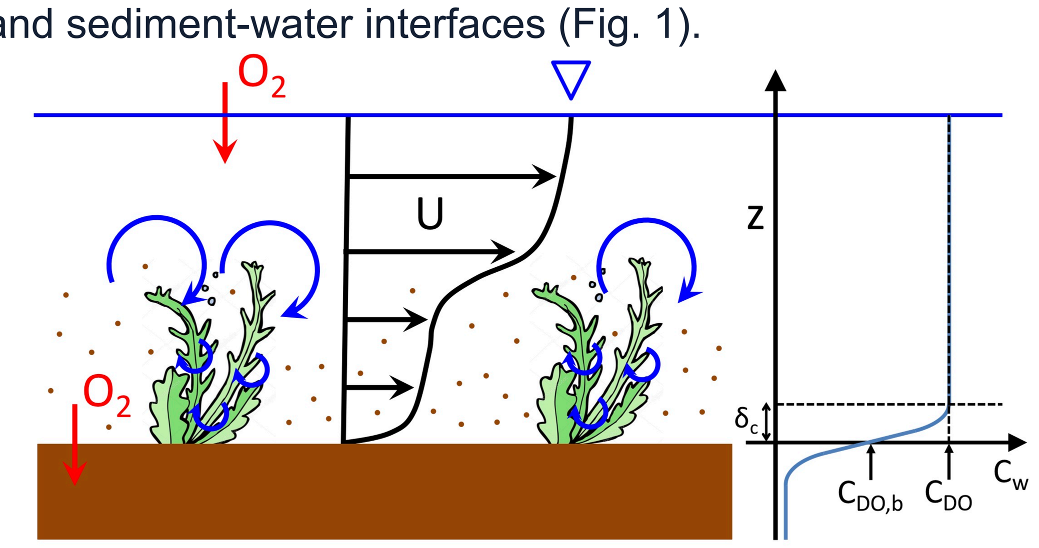
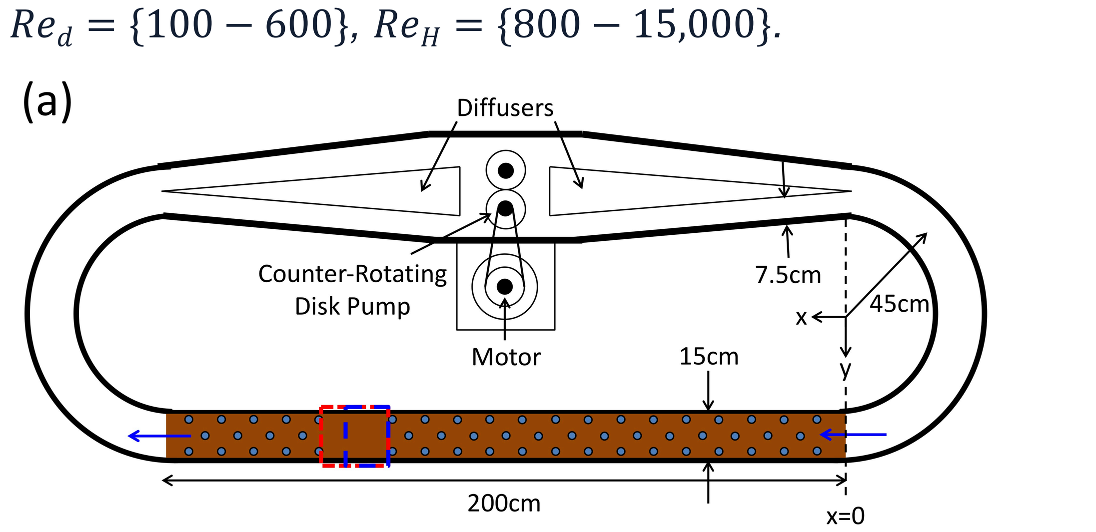


Figure 1. Sketch of interfacial gas transfer in vegetated flows and the associated dissolved oxygen concentration profile.

- The experiment result shows that turbulence generated from the bed does not affect the surface transfer process directly, but the near-bed suspended sediment reduces the gas transfer efficiency.
- A new Reynolds number dependence model using near-bed turbulent kinetic energy as an indicator is proposed to provide a universal prediction for the interfacial flux across the SWI in vegetated flows.

Methodology

- Experiments were conducted in a recirculating race-track flume with staggered arrays of rigid cylinders ($d = 0.64\ cm$) to mimic aquatic vegetation (Fig. 2).
- 2D-PIV is used to characterize the flow field (PIV-5W CW Laser, 5MP CCD camera).
- Flow conditions vary from emergent to fully submerged arrays, $h/H = \{1, 0.5, 0.25\}$ and from sparse to dense, $ah = \{0.1, 0.5\}$.
- A frequency controlled ($10-40\ Hz$) disk pump drives the flow for a velocity range $U = \{2-25\}\ cm/s$, yielding $Re_d = \{100-600\}$, $Re_H = \{800-15{,}000\}$.



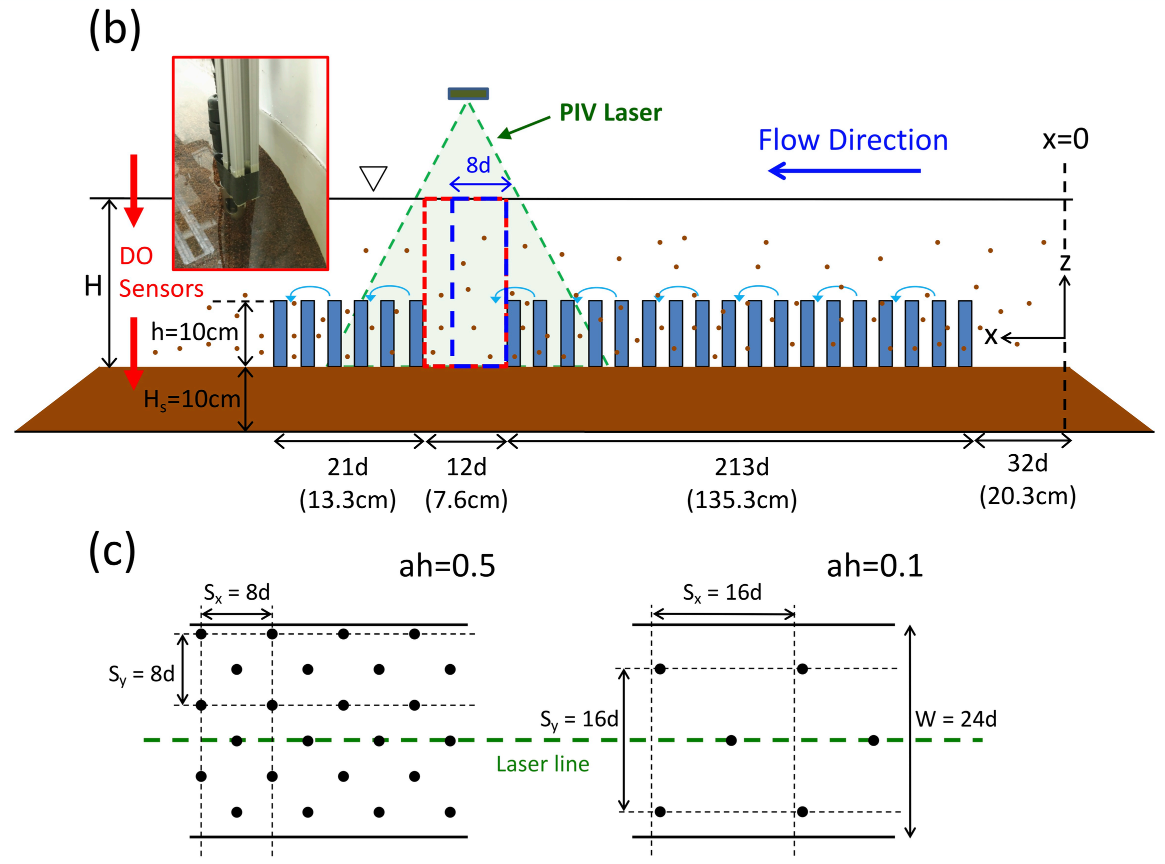


Figure 2. (a) Top-view sketch of the recirculating flume. (b) Side-view sketch of the test section (not to scale). (c) The vegetation array configuration, where the green dashed line shows the location of the PIV laser slice focusing on the center of the

- By using Sodium Sulfite (Na_2SO_3) as an oxygen depletion agent, surface gas transfer rates can be fitted by DO re-aeration curves in water.

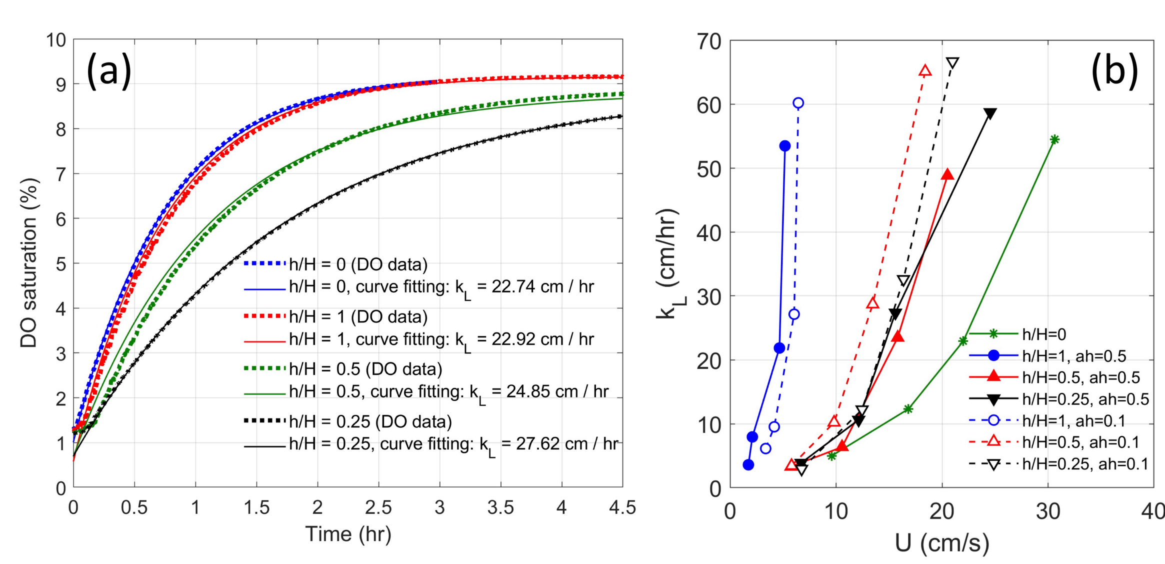


Figure 3. (a) The fittings of re-aeration process for the surface gas transfer rate, k_L, estimation. (b) The relation between surface gas transfer rate, k_L, and time-averaged mean flow velocity, U.

- Interfacial transfer fluxes across sediment-water interface were estimated by measuring the DO concentration difference between the near-surface and near-bed values (Fig. 4).

$$J_{SOD} = -D\left.\frac{\partial C}{\partial z}\right|_{z=0} = -D\frac{C_{DO} - C_{DO,b}}{\delta_c}$$

$$C_{DO} - C_{DO,b} = C_{DO,sat}\exp\left(-\frac{k_L}{H}t\right)\left[\exp\left(\frac{k_L}{H}\Delta t\right) - 1\right]$$

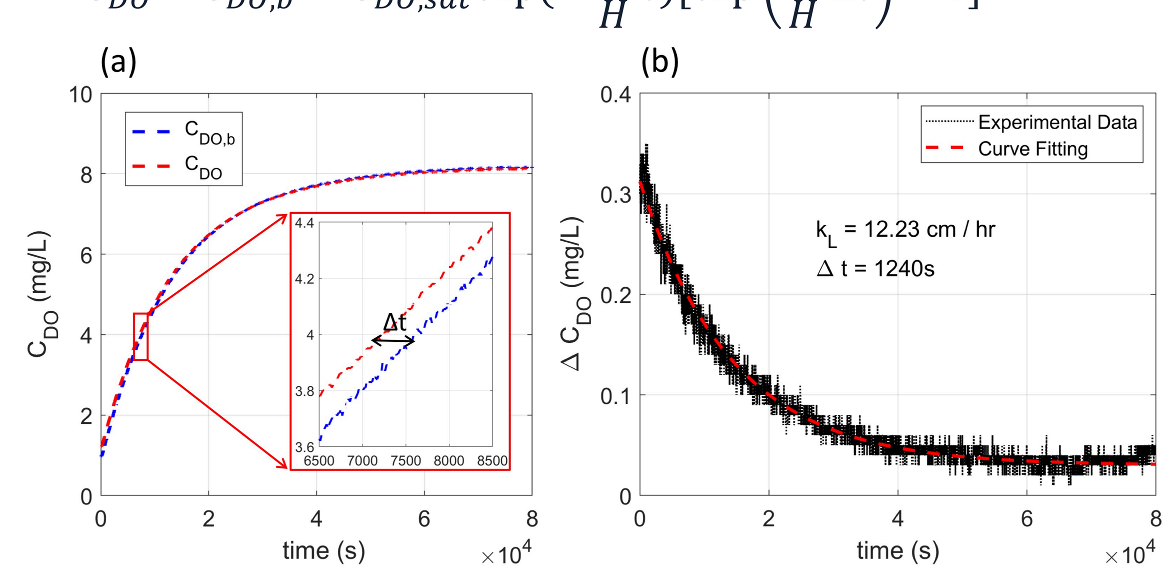


Figure 4. (a) The re-aeration curves obtained from the DO measurements near the bed (blue dashed line) and the surface (red dashed line) under flume pump frequency, f = 20 Hz, with ah = 0.1 and h/H = 0.25. (b) The fitting result of the time lag, Δt, based on Equation 1 and the surface gas transfer rate, k_L, under flume pump frequency, f = 20 Hz, with ah = 0.1 and h/H = 0.25.

Results and discussion

- **Flow turbulence structure:**
  - TKE production, $P = -\langle u'w' \rangle \frac{\partial \langle u \rangle}{\partial z}$.
  - Bulk mean shear velocity $u_b^* = \sqrt{-\langle u'w' \rangle_b}$.
    Maximum shear velocity $u_{max}^* = \sqrt{-\langle u'w' \rangle_{max}}$.
  - Stem-scale turbulence dominates the mixing and exchange processes within the canopy.
  - Canopy-scale turbulence dominates the mixing and exchange processes above the canopy.

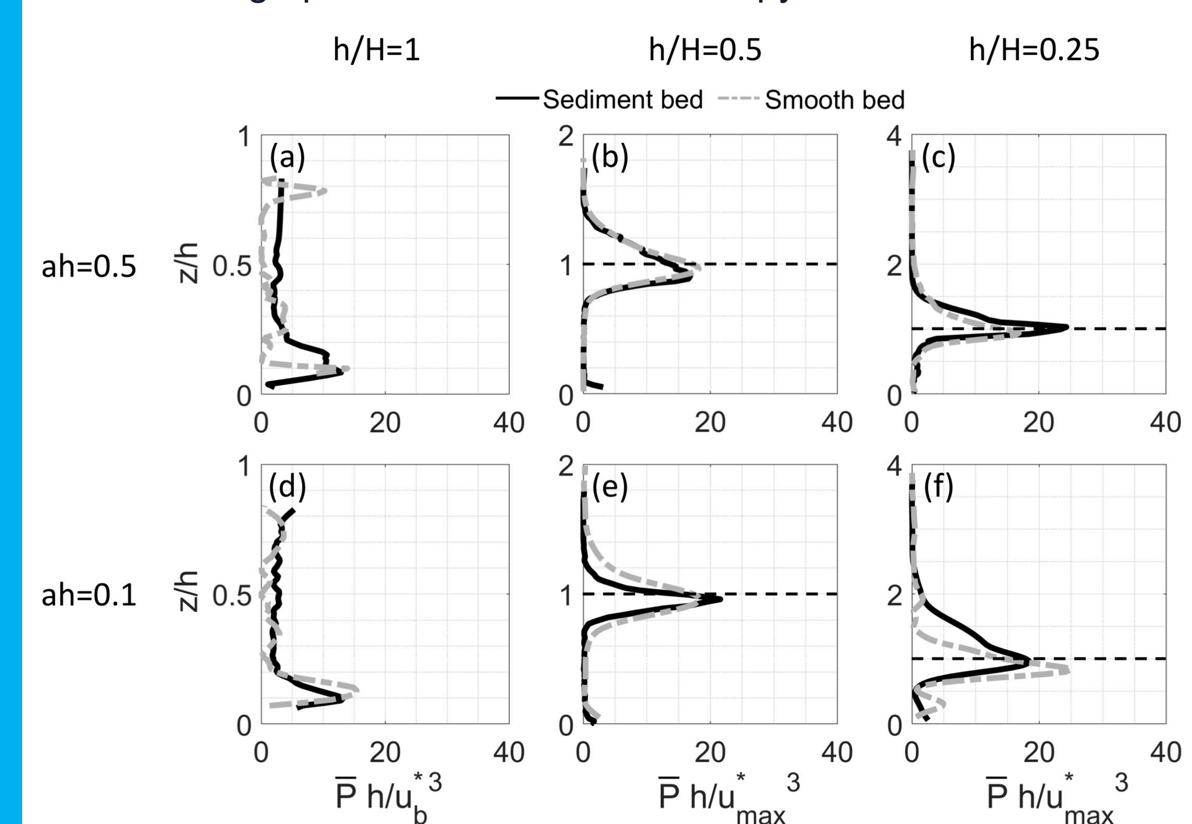


Figure 5. The normalized mean TKE production profile under different roughness density, ah, and submergence ratio, h/H, with smooth bed (from Tseng & Tinoco, 2020) and sediment bed. The pump inverter frequency of these cases are f = 40 Hz. The corresponding U and mean flow Reynolds number, Re_H, for cases (a) to (f) are: U = {6.6; 14.2; 20.0; 11.8; 18.9; 22.1} cm/s, and Re_H ={2269; 7967; 12, 270; 4331; 9392; 13, 283} on the smooth bed; U = {5.2; 20.5; 24.5; 6.4; 18.4; 21.0} cm/s, and Re_H ={2220; 11, 189; 15, 500; 2760; 10, 041; 13, 257} on the sediment bed. The black dashed line represents the height of the vegetation canopy.

- **Gas transfer across air-water interface:**
  - General form: $k_L = \alpha\sqrt{L^+ \frac{DP_*^{1/2}}{\nu^{1/2}}}$.
  - Emergent cases: $P_* = P_b$, $L^+ = L_{eme}^+ = Re_d^{1/2}\frac{H^{1/2}}{d^{1/2}}\frac{u_b^{*1/2}}{u_b^{1/2}}$.
  - Submerged cases: $P_* = \bar{P}_{max}$, $L^+ = L_{sub}^+ = Re_H^{1/2}\frac{L_{up}^{1/2}}{H^{1/2}}\frac{u_{max}^{*1/2}}{u_h^{1/2}}$.

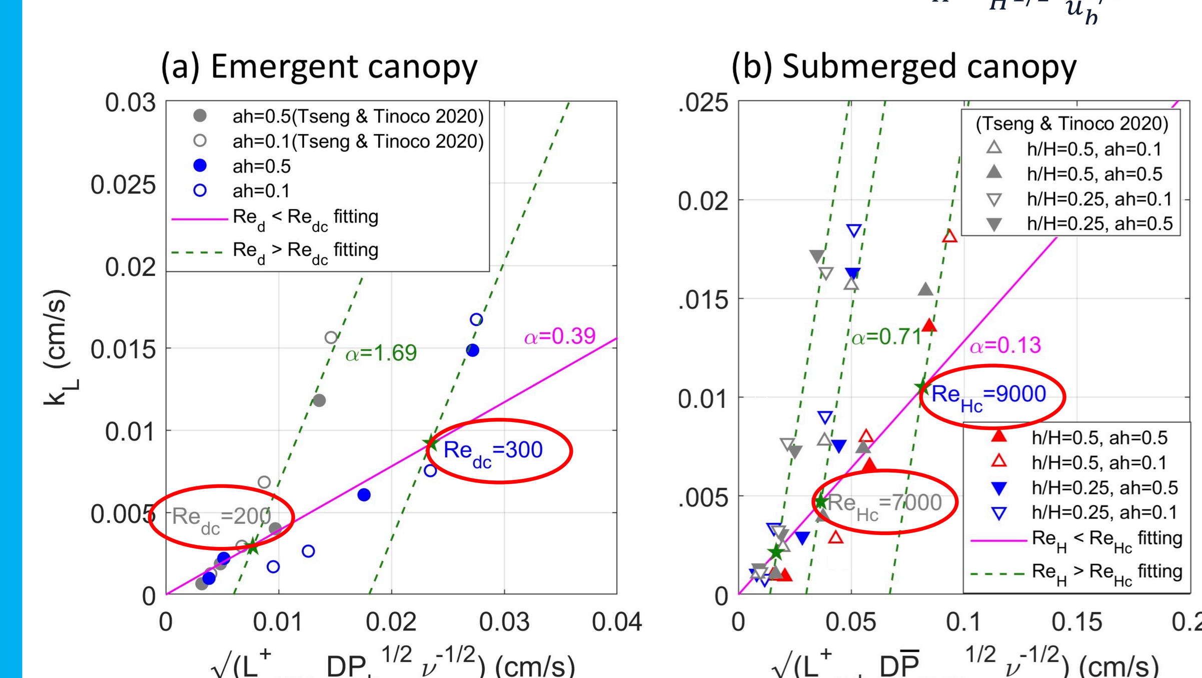


Figure 6. The linear fitting results of the emergent (left) and submerged (right) canopy data by the modified SR model. The critical stem-scale Reynolds number, Re_{dc}, for the emergent case shifts from 200 on a fixed smooth bed (Tseng & Tinoco, 2000) to 300 on a sediment bed, while the critical mean flow Reynolds number, Re_{Hc}, shifts from 7000 on a fixed smooth bed (Tseng & Tinoco, 2000) to 9000 on a sediment bed.

- **Gas transfer across sediment-water interface:**
  - $Re_K = \frac{u^*\sqrt{K}}{\nu}$ → $Re_{TKE} = \frac{\sqrt{k_t}\sqrt{K}}{\nu}$
  - $k_t = k_{tb} + k_{tv} + k_{cs}$ → bed shear + vegetation + non-linear
  - $D_{eff} = D_m + D_d + D_t$ → molecular + dispersive + turbulent

$$\begin{cases} \text{molecular regime}: & Re_{TKE} \le 0.05, & D_{eff}/D \approx D/D = 1 \\ \text{dispersive regime}: & 0.05 < Re_{TKE} < 2.3, & D_{eff}/D \approx D_d/D \approx \gamma_d Re_{TKE}^{\ 2} Sc \\ \text{turbulent regime}: & Re_{TKE} \ge 2.3, & D_{eff}/D \approx D_t/D \approx \gamma_t Re_{TKE}^{\ 2} Sc \end{cases}$$

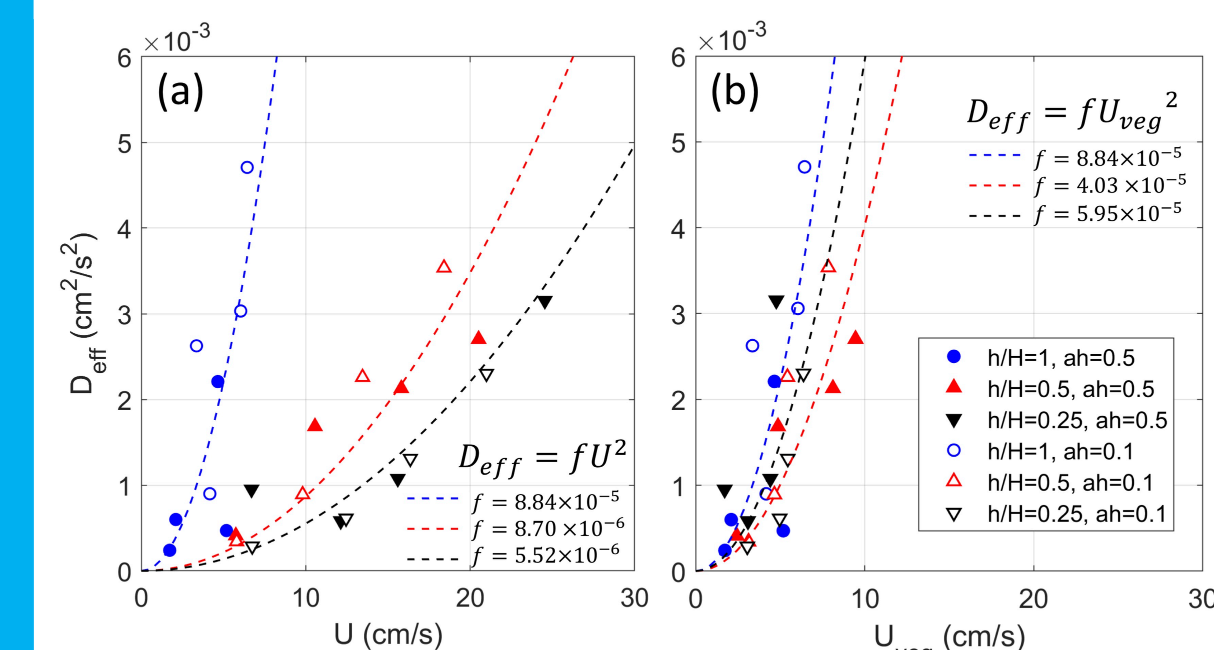


Figure 7. The relation between effective sediment-water gas transfer diffusion coefficient, D_{eff}, and (a) the time-averaged mean flow velocity, U; (b) the time-averaged mean flow velocity within the vegetation canopy, U_{veg}, under different submergence ratios (U =0.25, 0.5, and 1) and array roughness densities (ah =0.1 and 0.5). Trendlines are parabolic fits to both sparse and dense conditions for each submergence ratio.

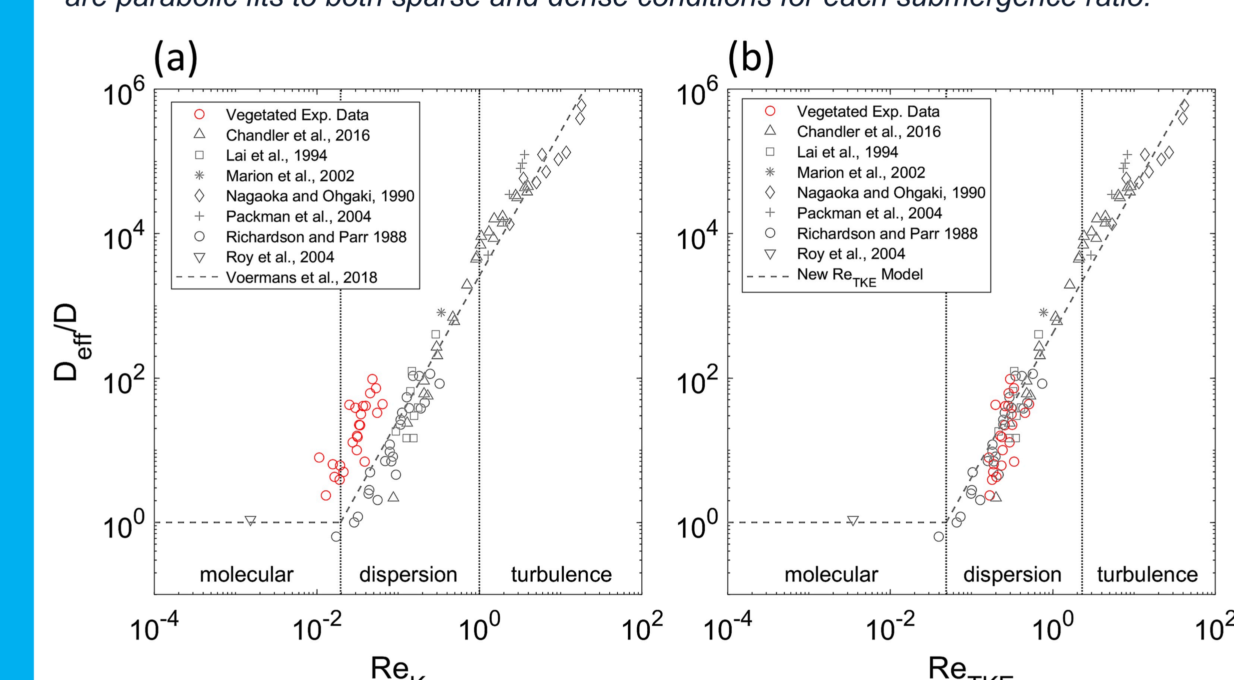


Figure 8. Comparison of (a) Re_K-dependence model (Voermans et al., 2018) (b) the proposed Re_{TKE}-dependence model for the sediment-water interfacial gas transfer diffusion coefficient, D_{eff} with previous observation data (bare-bed open-channel flows) and the current experimental data (vegetated flows). The three regimes: molecular, dispersion, and turbulence are separated by the dotted vertical lines. The current experimental data in vegetated flows are represented by the color markers (red circles).

Conclusions

- Vegetation-generated turbulence drives both air-water and sediment-water interfacial gas transfer.
- The near-bed suspended sediment concentration due to higher turbulent kinetic energy reduces surface gas transfer rates.
- A new Reynolds number dependence model based on turbulent kinetic energy provides consistent predictions for sediment-water interfacial gas transfer fluxes.

Reference:

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- Voermans, J. J., Ghisalberti, M., & Ivey, G. N. (2018). A model for mass transport across the sediment-water interface. Water Resources Research, 54(4), 2799- 2812.