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Longitudinal dispersion affected by willow patches

Kaisa Västilä[1], Jungsun Oh[2], Fred Sonnenwald[3], Un Ji[2], Juha Järvelä[1], Inhyeok Bae, Ian Guymer[3]

[1] Department of Built Environment, Aalto University, Espoo, Finland

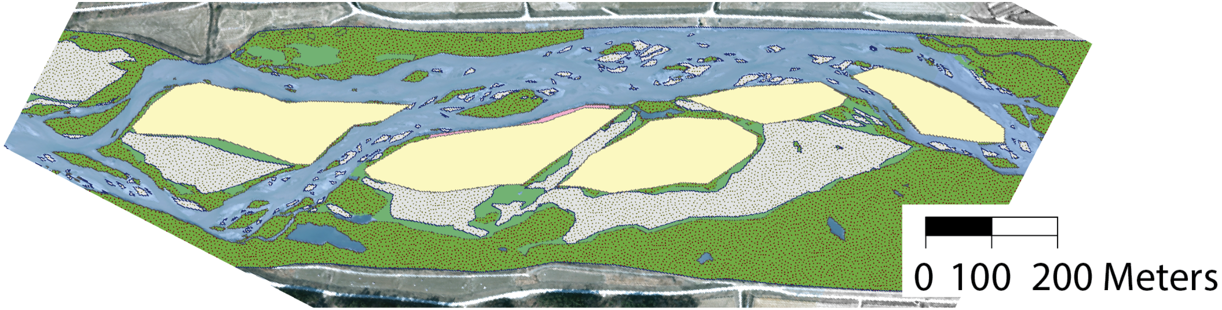
[2] Korea Institute of Civil Engineering and Building Technology, Goyang-Si, Korea

[3] Department of Civil and Structural Engineering, University of Sheffield, UK

[4] Department of Civil Engineering, Kunsan National University, South Korea

Motivation & objectives

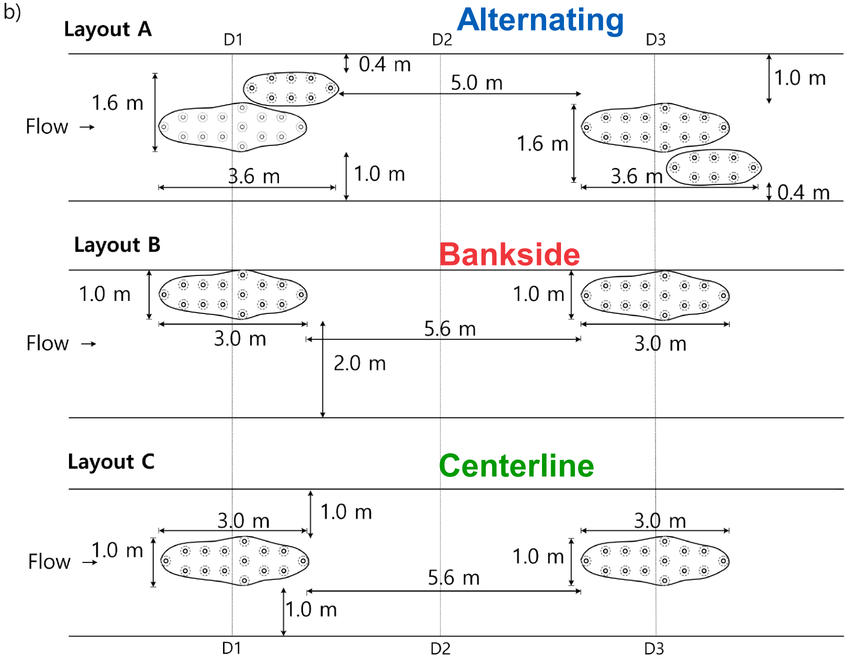
- Vegetation significantly controls the transport of soluble compounds influencing e.g. the fate of nutrients
- Focus mostly on non-vegetated or fully vegetated flows, at small scale or with simplified vegetation
- Limited understanding from the reach scale with vegetation patches
- We aim at
  1) investigating longitudinal dispersion in a reach with real-scale flexible woody vegetation patches and
  2) evaluating selected predictors for D_X under patchy vegetation conditions



Prototype-scale 80 m long study reach with natural-like patches

- Outdoor experiment channel at KICT-REC in Korea
- Artificial emergent foliated plants resembling *Salix subfragilis*
- 3 patch layouts with 1-1.6 m wide and 3-4 m long patches
- Coverage, plant density, and spatial distribution of patches was varied
- Flow field measured with ADCP

Key properties of the vegetation patches



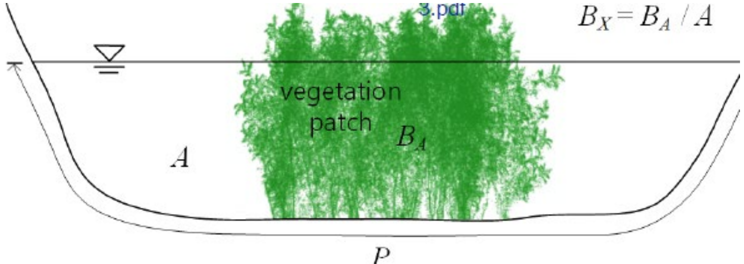
Leaf area index A_L/A_B=1.8-4.9

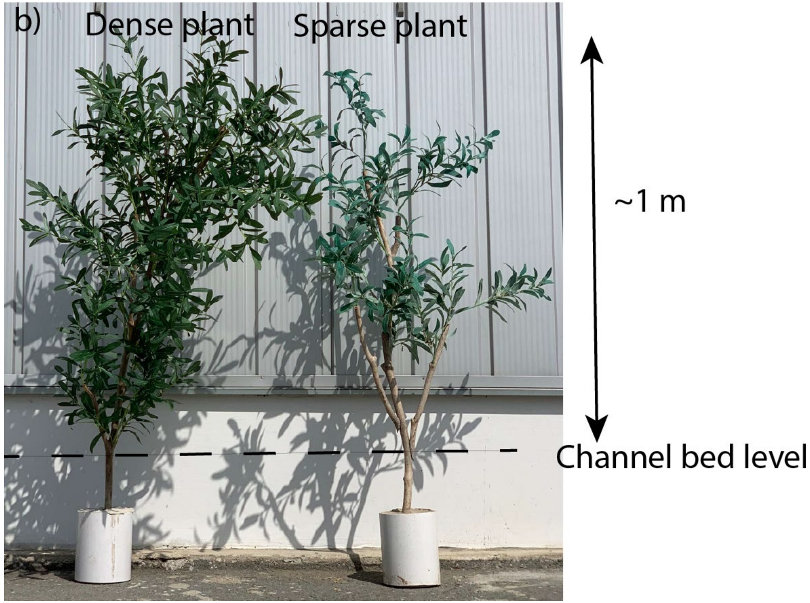
Areal/volumetric coverage

V_P/V_W=0.06-0.11

Cross-sectional blockage factor

B_x=0.28-0-40





8 experimental runs with salt tracing

7 vegetated + 1 unvegetated reference run, incl. repetitive traces

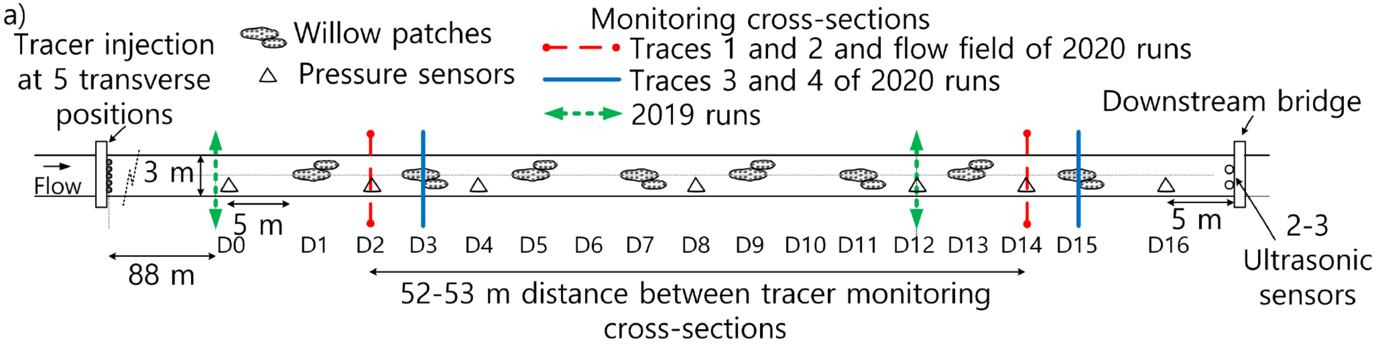
Mean flow velocities: 0.33-0.62 m/s

Flow depths: 0.73-0.94 m

Wetted surface widths: 5.8-6.7 m

Near-instantaneous slug injection with complete lateral mixing before study reach

1-3 EC sensors in 2 cross-sections



Deriving ADE and ADZ parameters

Longitudinal dispersion coefficient D_x through Advection-dispersion Eq. routing:

$$S(x_2,t) = \int_{\gamma=-\infty}^{\infty} \frac{S(x_1,\gamma)U}{\sqrt{4\pi D_x \bar{t}}} \exp\left[-\frac{U^2(\bar{t}-t+\gamma)^2}{4D_x\bar{t}}\right] d\gamma \quad \textbf{(1)}$$

where $S(x_1,t)$ is the observed upstream temporal concentration profile at time instant t, $S(x_2,t)$ is the observed downstream temporal concentration profile, U is mean longitudinal velocity, and $\bar{t}$ is mean travel time (Rutherford 1994).

Aggregated dead zone model (ADZ) routing:

$$\hat{S}^m = \exp(-\alpha\Delta t)S^{m-1} + (1-\exp(-\alpha\Delta t))S_u^{m-\delta-1} \qquad \textbf{(2)}$$

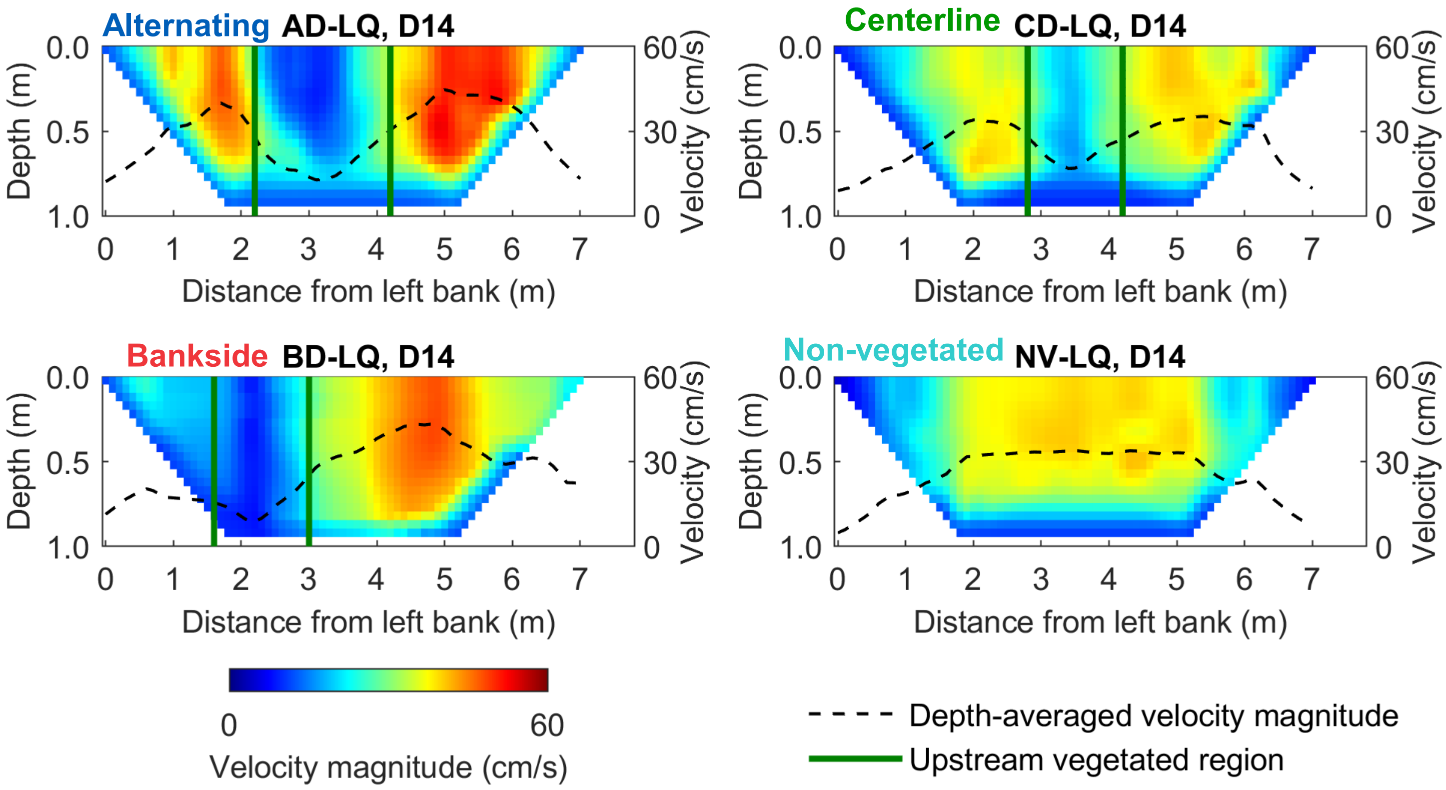
where S^m and S^{m-1} are concentrations at times $m\Delta t$ and $(m-1)\Delta t$, α is cell time constant and $\delta = \text{floor}(\tau/\Delta t)$ (Rutherford 1994).

-> dispersive fraction (volume contributing to dispersion per total reach volume)

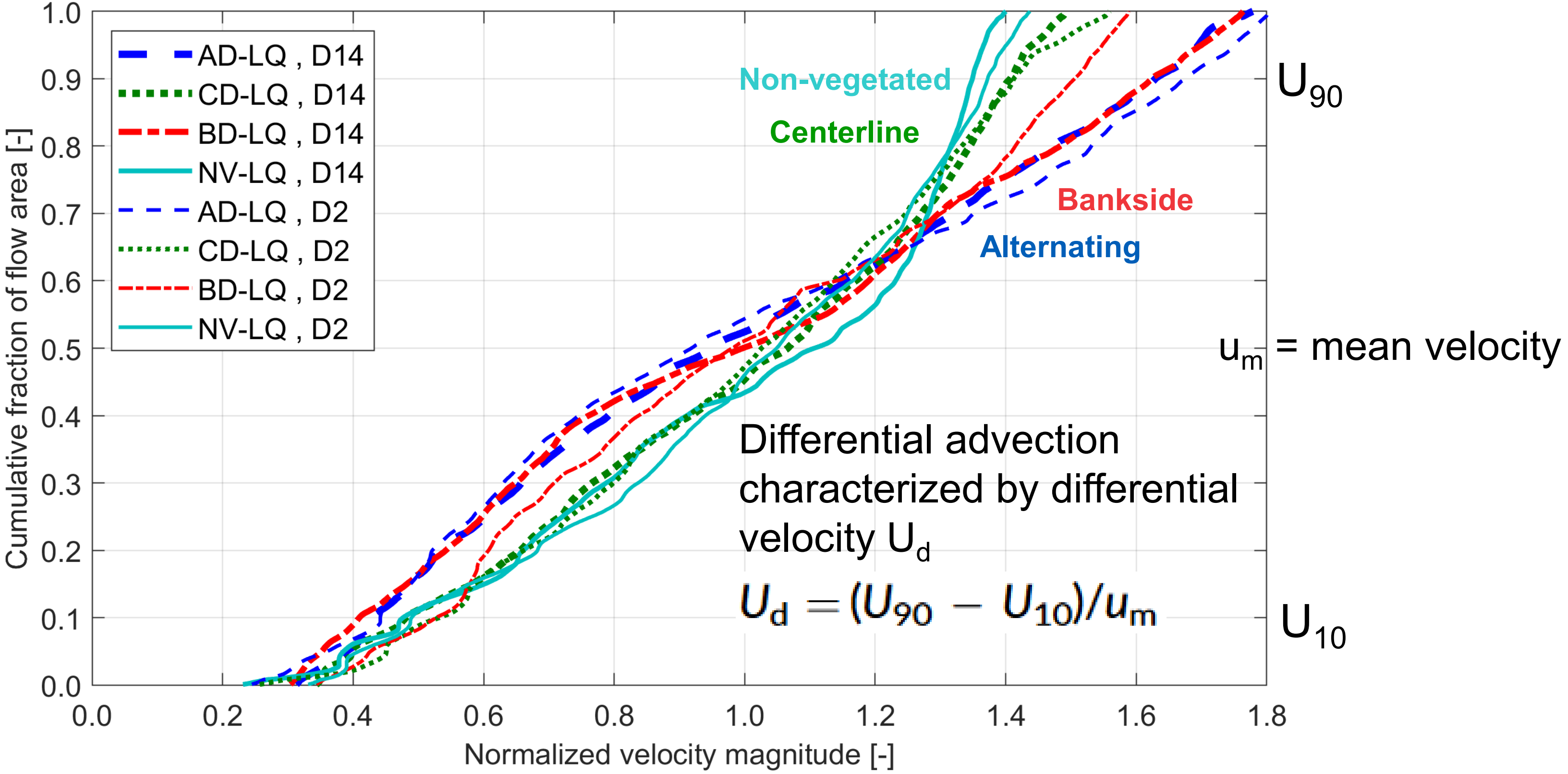
$$D_f = 1/(\alpha\bar{t}_{\text{ADZ}})$$

Vegetation patches diverted the flow to unvegetated parts of the cross-section

$$U = \sqrt{u^2 + v^2 + w^2},$$

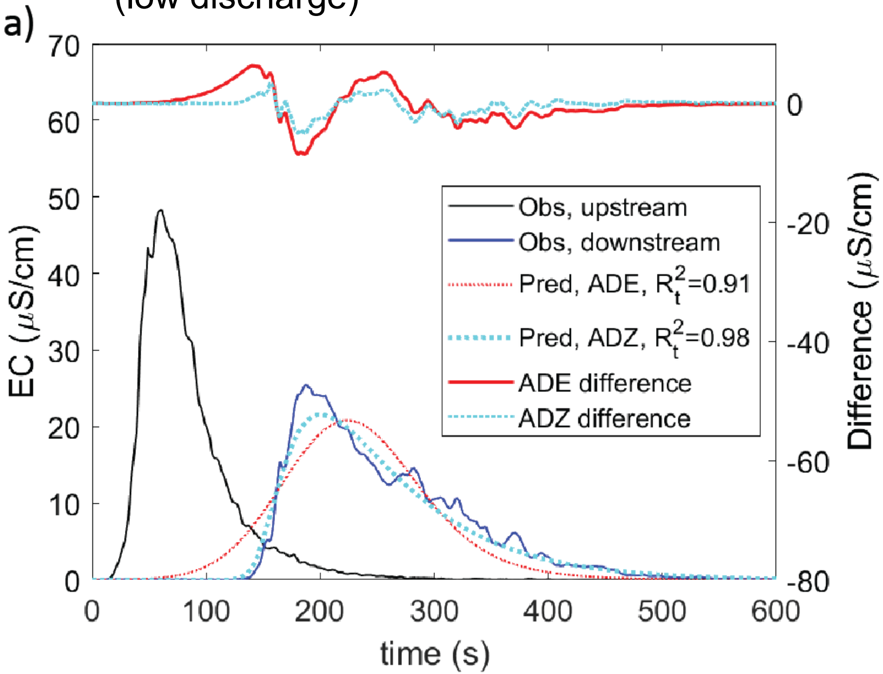


Dense and high-blockage patches increased the highest velocities and the differential advection

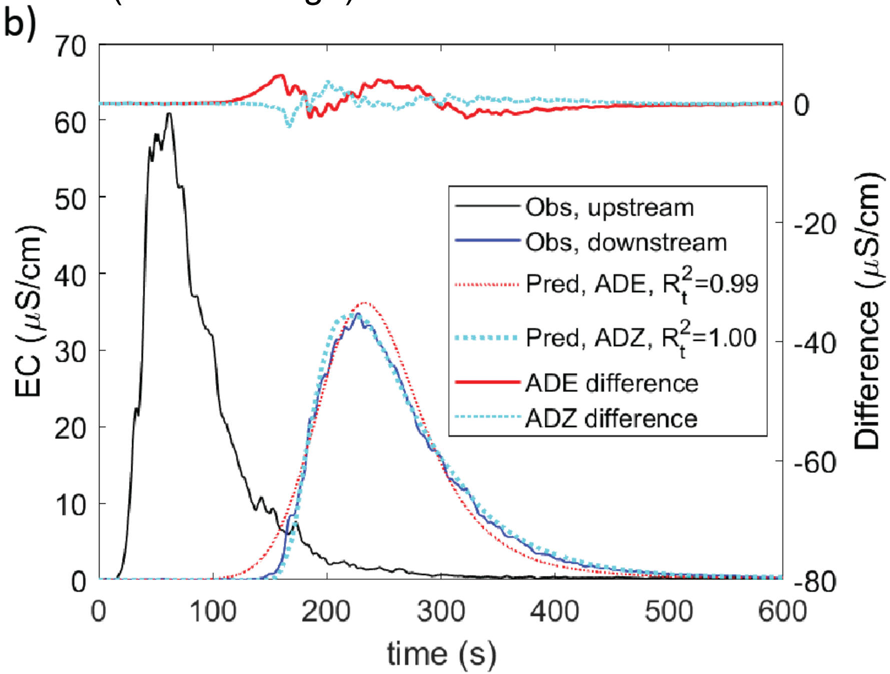


Both ADE and ADZ approaches could be fitted at least satisfactorily to all runs

Weakest ADE fit for bankside patches (low discharge)

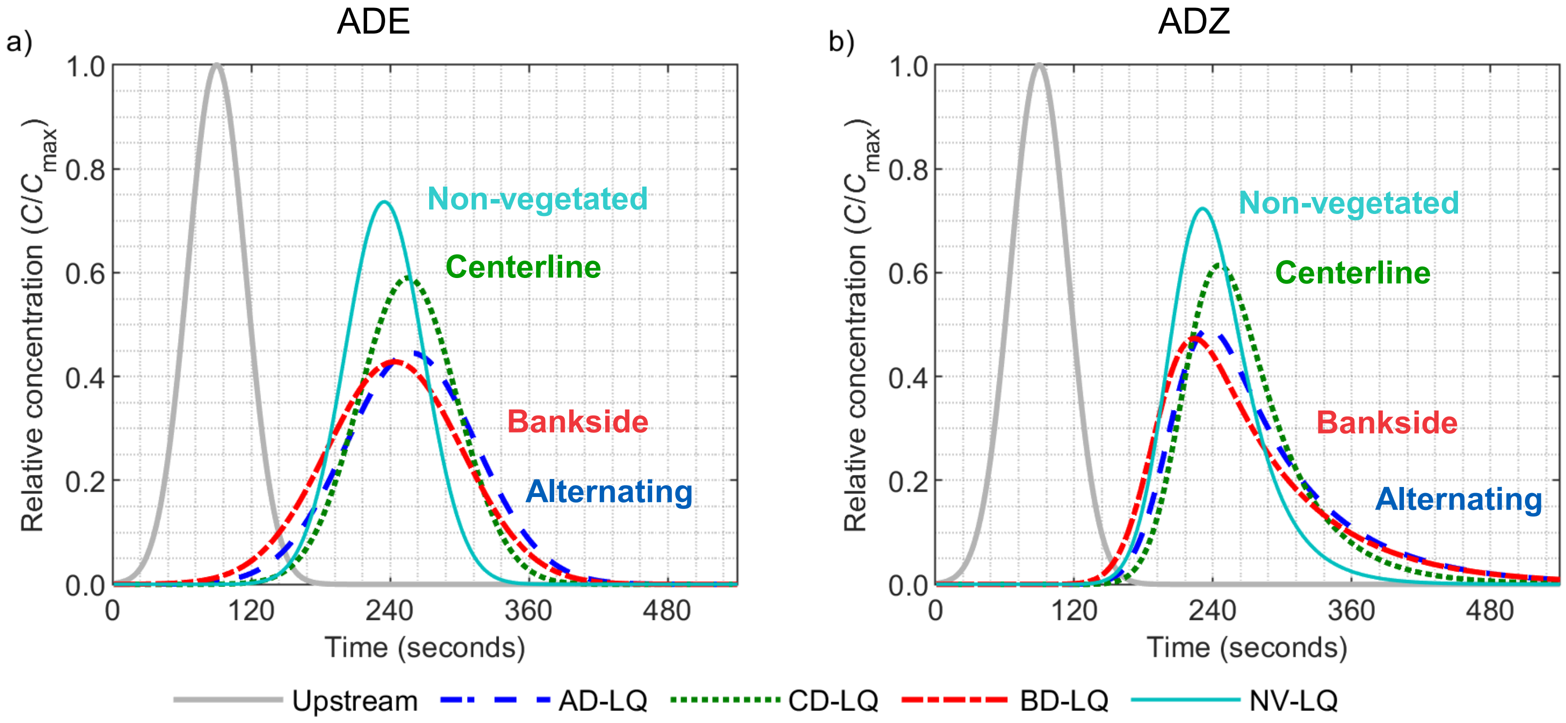


Best overall fits for centreline patches (low discharge)

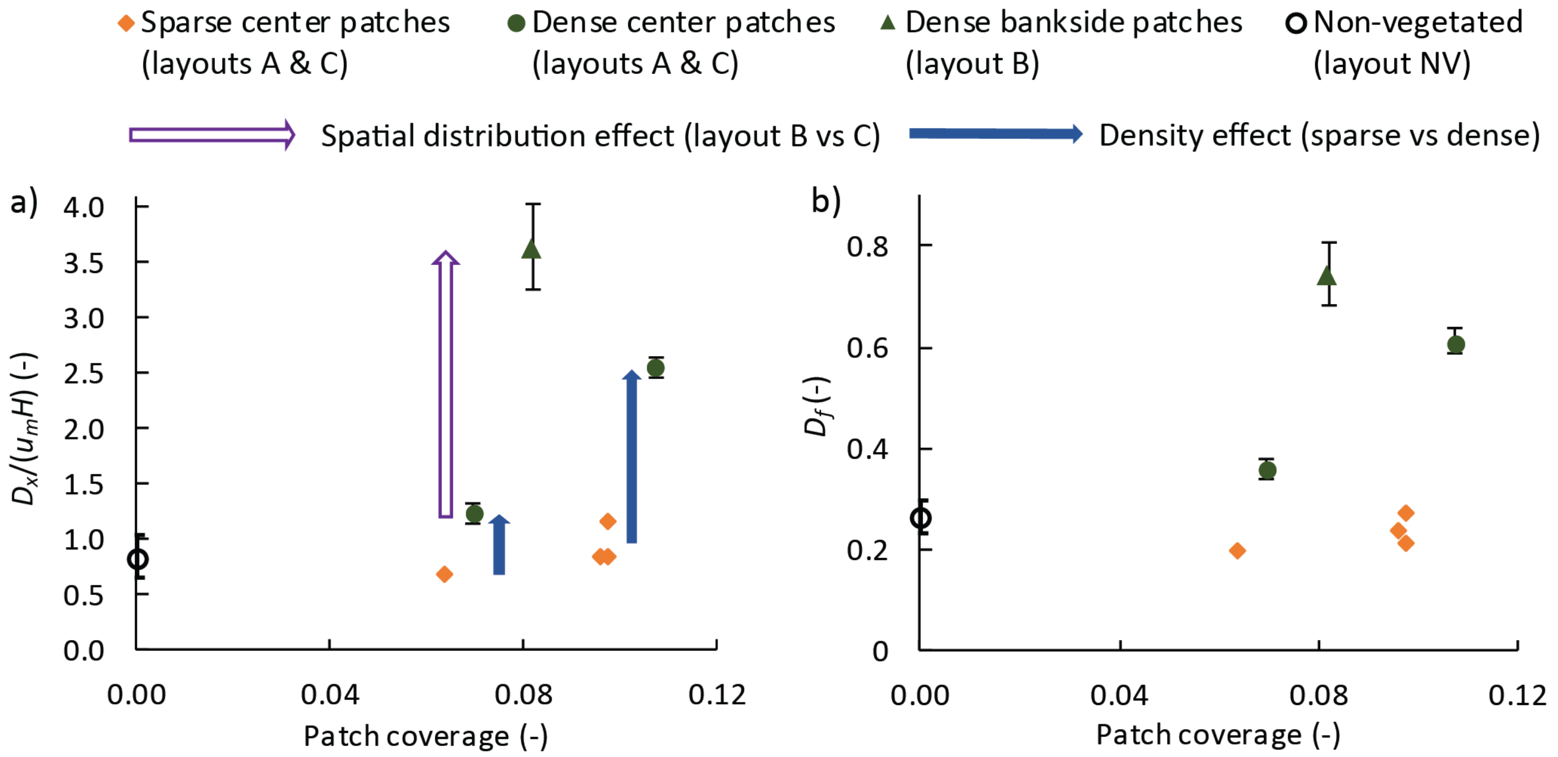


Plant patches decreased peak concentrations and increased residence times compared to non-vegetated conditions

Synthetic upstream concentration profile and predicted downstream concentrations



The patches influenced dispersion via their plant density, volumetric coverage and spatial distribution



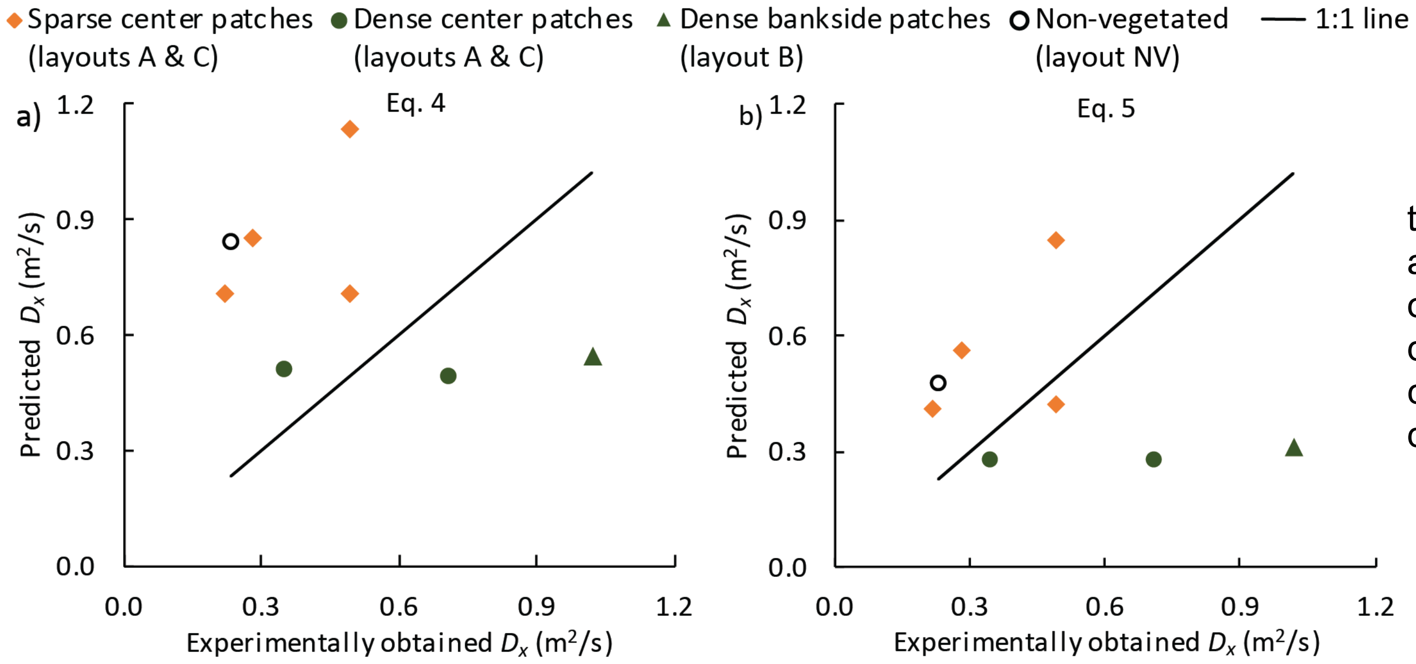
The influence of vegetation patches on dispersion is opposite than for uniform vegetation

Analytical models for non-vegetated and fully vegetated flows could not predict the patch effects on dispersion

Lightbody & Nepf (2006) and Sonnenwald et al. (2019a) for fully vegetated flows predicted 1-2 orders of magnitude too low values

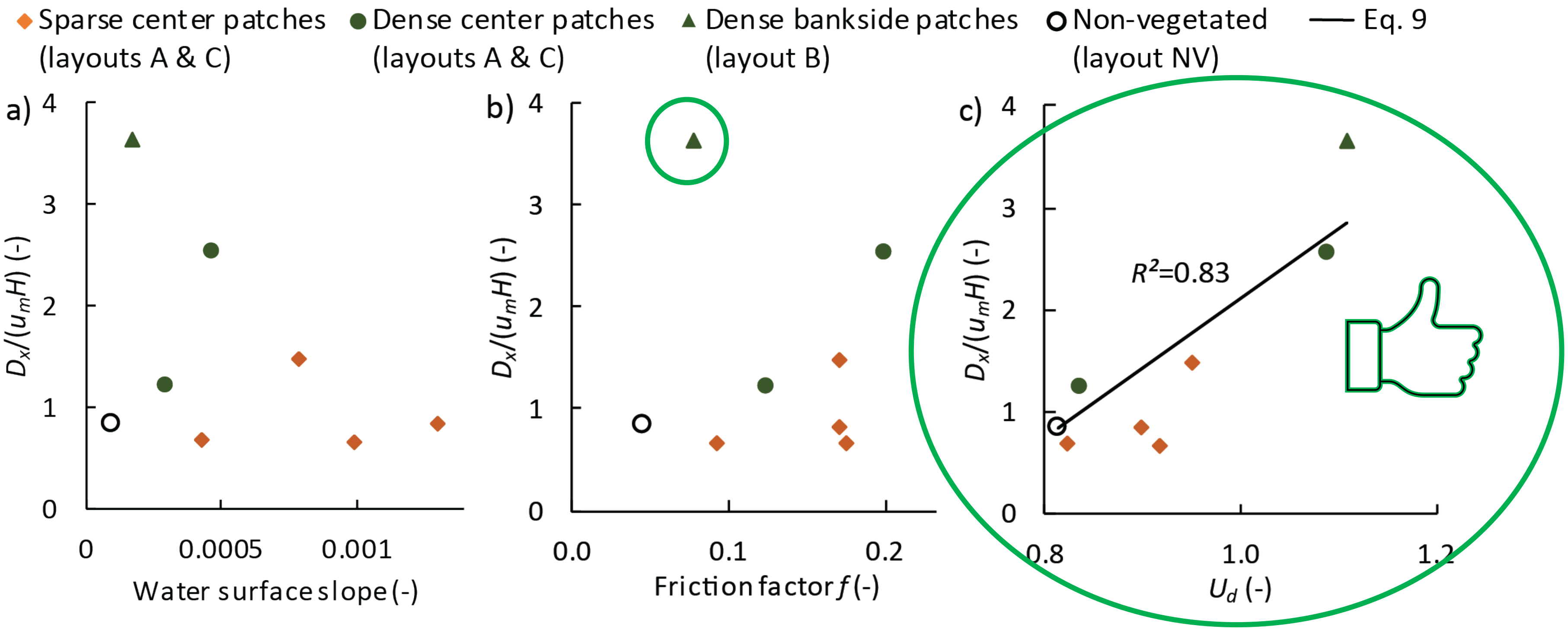
Fischer (1975)

Wang & Huai (2016)



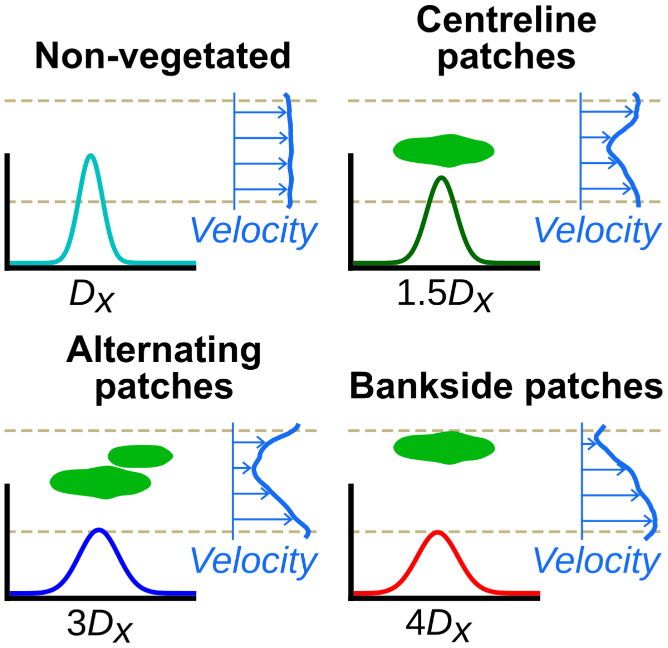
the widely applied analytical models for open channel flows do not describe the changes in the differential advection

Other examined predictors of D_X



Dependence on f/LAI and standardized Morisita index also weak

New findings on describing the patch effects on reach-scale dispersion



Longitudinal dispersion D_X is controlled by the lateral velocity differential, which depends on vegetation patch layout.

$$\frac{D_x}{u_m H} = \frac{D_{x,NV}}{u_{m,NV} H_{NV}} + \varepsilon\left(U_d - U_{d,NV}\right)$$

values in vegetated conditions

values in non-vegetated conditions

influence of U_d
(ε is a scaling factor)

Conclusions & future work

- Low-coverage, dense vegetation patches notably increased dispersion
- We proposed differential velocity as a new basic estimator of the dispersion coefficient under patchy vegetation
- Such rare full-scale analyses will improve the predictions of the transport and retention of pollutants in real vegetated flows and help optimize NbS
- Further experiments with lower (and higher) mean velocities and medium patch coverages of ~20-50% would help in extending the observed relationships

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