CFD Study of Mixing within Random Cylinder Arrays

(RandoSticks – Mostly in pics!)

Virginia Stovin

Professor of Green Infrastructure for Stormwater Management

The University of Sheffield

ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE

10.1029/2021WR030396

Key Points:

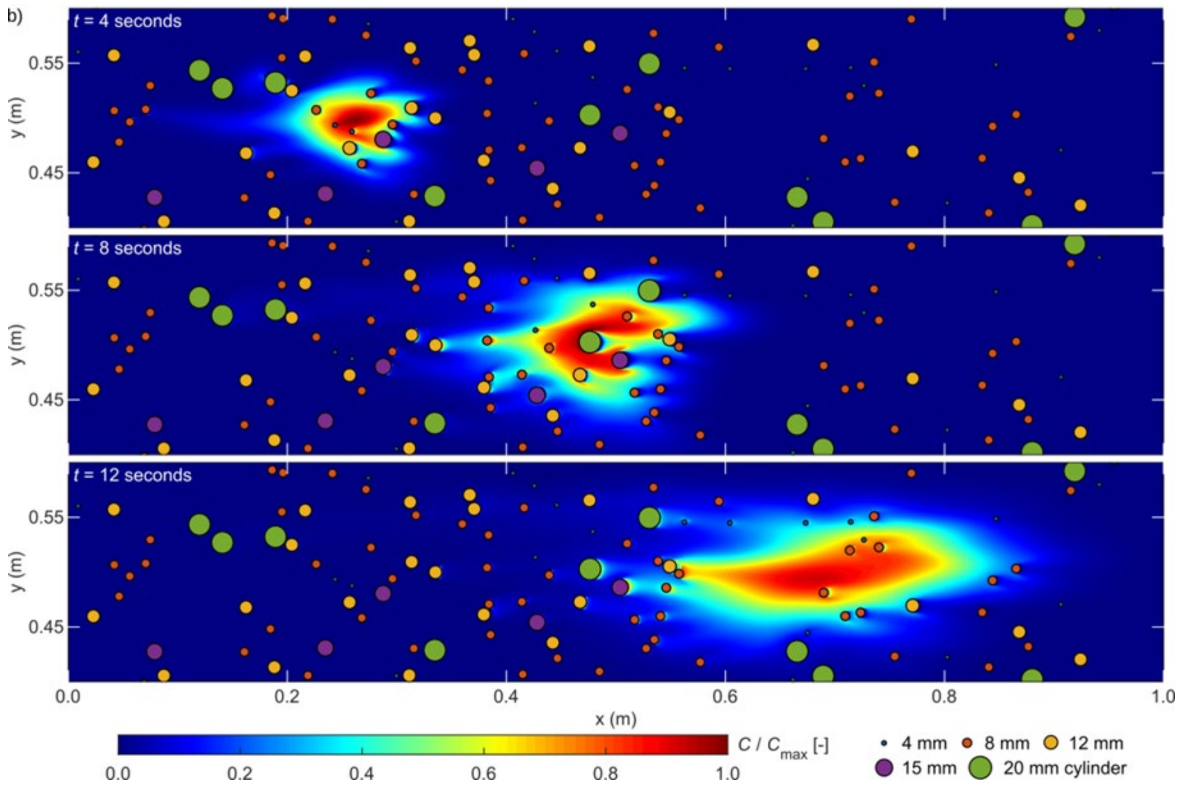
- New dispersion data for non-uniform and uniform cylinder diameter distributions have been generated using a two-dimensional numerical model
- Non-dimensional dispersion coefficients are unaffected by cylinder diameter distribution
- Both longitudinal and transverse dispersion coefficients can be modeled as linear functions of cylinder diameter and cylinder spacing

The Impact of Cylinder Diameter Distribution on Longitudinal and Transverse Dispersion Within Random Cylinder Arrays

V. R. Stovin[1], F. Sonnenwald[1], M. Golzar[1], and I. Guymer[1]

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

Abstract Numerous studies focus on flow and mixing within cylinder arrays because of their similarity to vegetated flows. Randomly distributed cylinders are considered to be a closer representation of the natural distribution of vegetation stems compared with regularly distributed arrays. This study builds on previous work based on a single, fixed, cylinder diameter to consider non-uniform cylinder diameter distributions. The flow fields associated with arrays of randomly distributed cylinders are modeled in two dimensions using the ANSYS Fluent Computational Fluid Dynamics software with Reynolds Stress Model turbulence



AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2016WR019937

Transverse and longitudinal mixing in real emergent vegetation at low velocities

F. Sonnenwald[1], J. R. Hart[2], P. West[2], V. R. Stovin[1], and I. Guymer[2]

[1]Department of Civil and Structural Engineering, The University of Sheffield, Sheffield, UK, [2]School of Engineering, University of Warwick, Coventry, UK

Key Points:

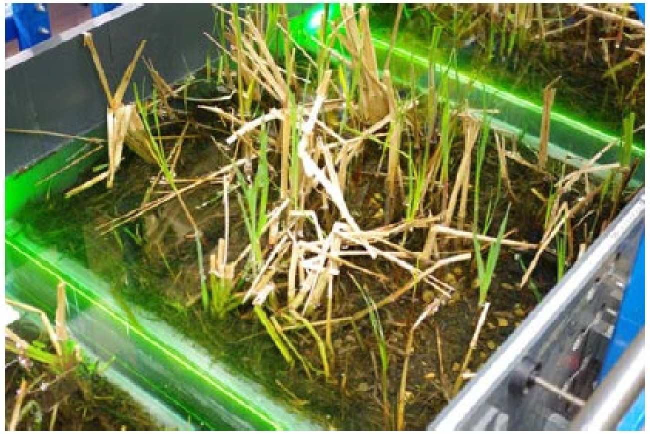
- A new lab data set describes transverse and longitudinal dispersion in real emergent vegetation
- New and existing data have been compared with models for predicting dispersion
- Current dispersion models relying on mean stem diameter do not describe real vegetation well

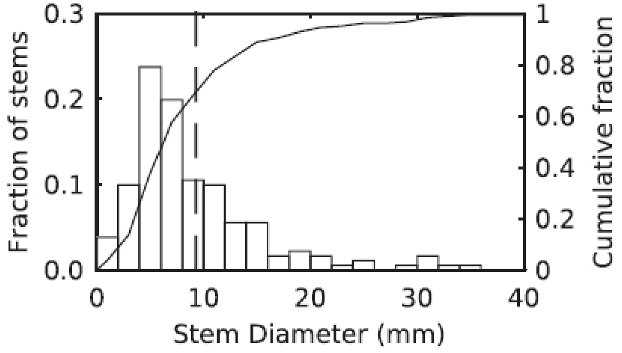
Correspondence to:
F. Sonnenwald,
f.sonnenwald@sheffield.ac.uk

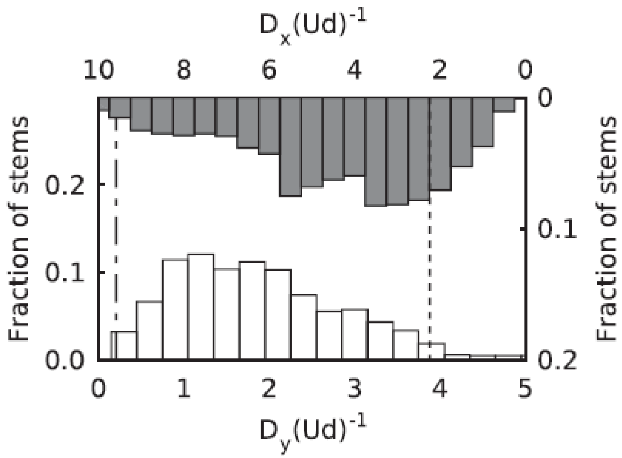
Citation:
Sonnenwald, F., J. R. Hart, P. West, V. R. Stovin, and I. Guymer (2017), Transverse and longitudinal mixing in real emergent vegetation at low velocities, *Water Resour. Res.*, *53*, doi:10.1002/2016WR019937.

Received 13 OCT 2016

Abstract Understanding solute mixing within real vegetation is critical to predicting and evaluating the performance of engineered natural systems such as storm water ponds. For the first time, mixing has been quantified through simultaneous laboratory measurements of transverse and longitudinal dispersion within artificial and real emergent vegetation. Dispersion coefficients derived from a routing solution to the 2-D Advection Dispersion Equation (ADE) are presented that compare the effects of vegetation type (artificial, *Typha latifolia* or *Carex acutiformis*) and growth season (winter or summer). The new experimental dispersion coefficients are plotted with the experimental values from other studies and used to review existing mixing models for emergent vegetation. The existing mixing models fail to predict the observed mixing within natural vegetation, particularly for transverse dispersion, reflecting the complexity of processes associated with the heterogeneous nature of real vegetation. Observed stem diameter distributions are utilized to highlight the sensitivity of existing models to this key length-scale descriptor, leading to a recommendation that future models intended for application to real vegetation should be based on probabilistic descriptions of both stem diameters and stem spacings.



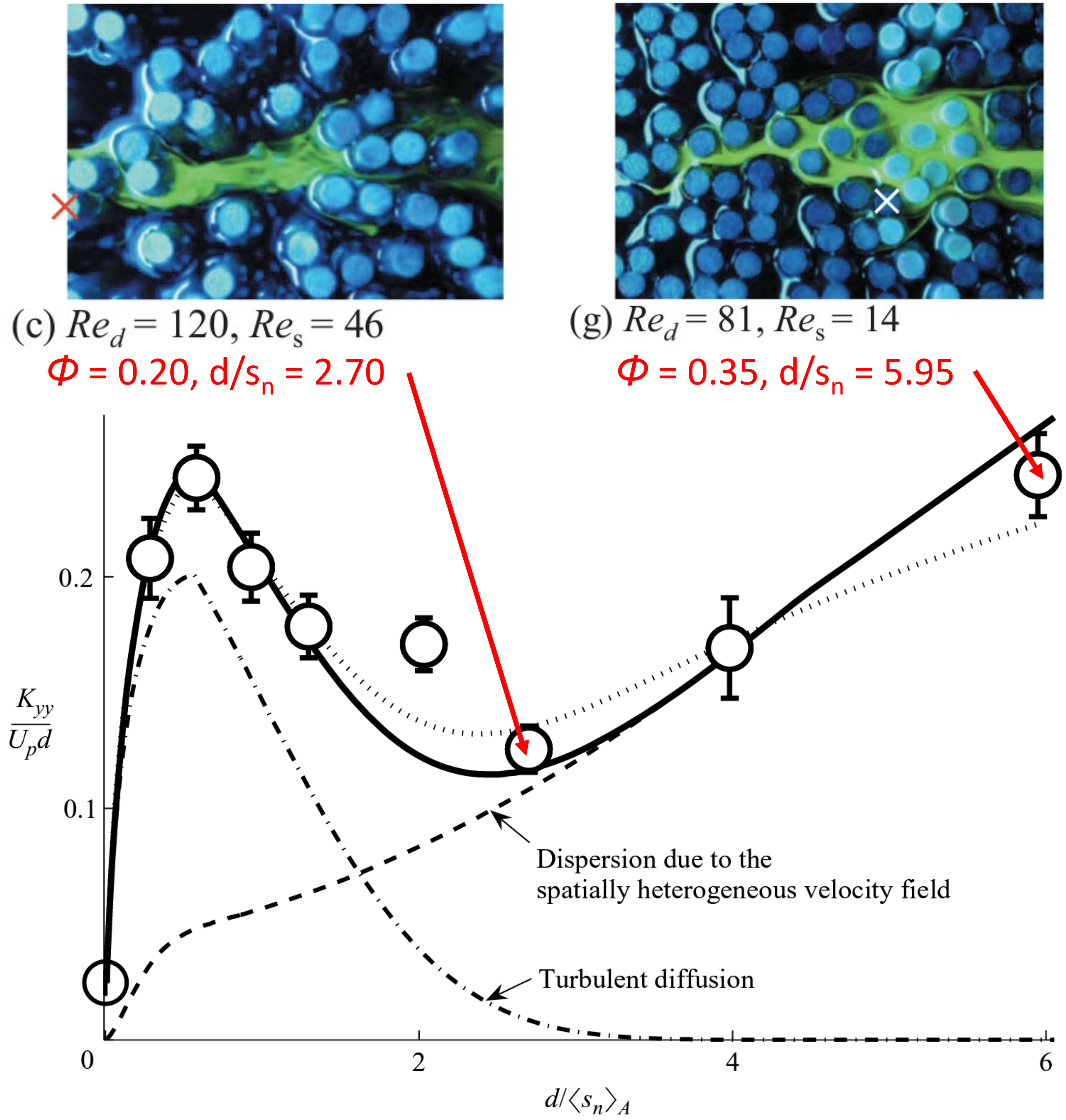




The challenge

Tanino and Nepf (2008) model for transverse/lateral dispersion

- Can we reproduce this in CFD?
- Can we then use CFD to explore effects due to non-uniform stem diameters?
- Can we utilise CFD outputs to better understand the controlling physical processes?

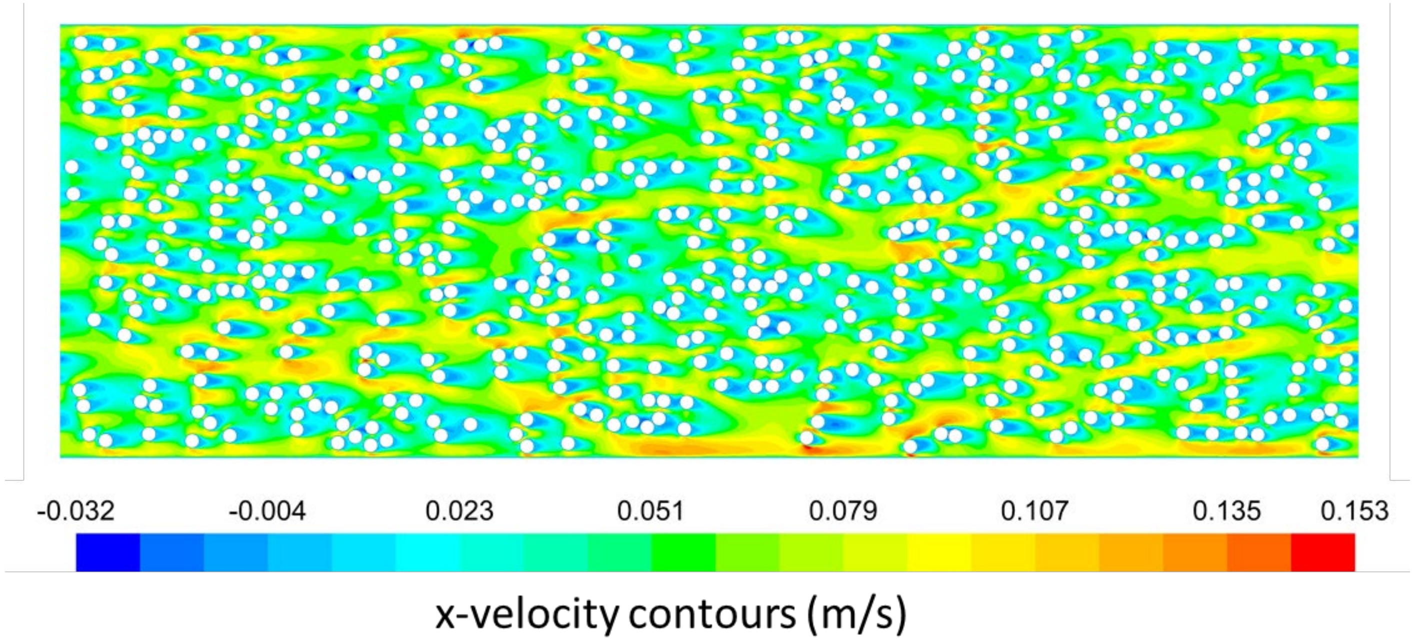


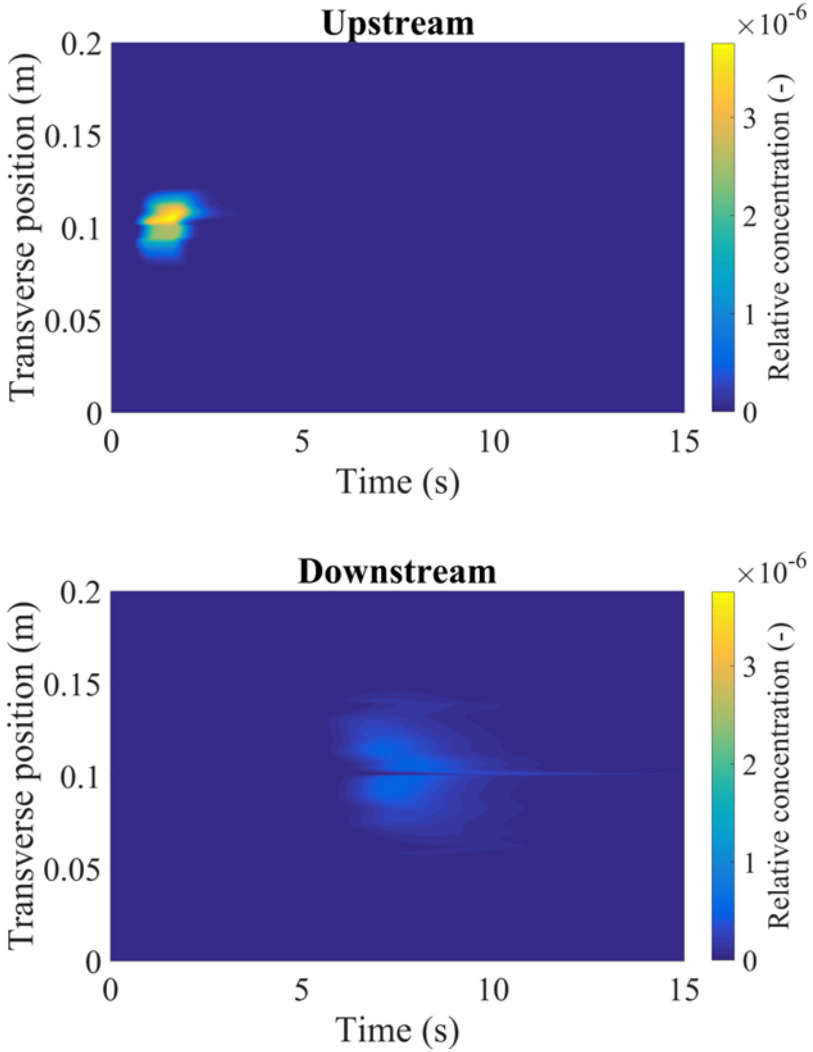
Tanino, Y, & Nepf, H.M. (2009) "Laboratory investigation of lateral dispersion within dense arrays of randomly distributed cylinders at transitional Reynolds number." *Physics of Fluids* 21.4 (2009): 046603-10.

Tanino, Y. & Nepf, H.M. (2008) "Lateral dispersion in random cylinder arrays at high Reynolds number" *J. Fluid Mech*. 600, 339–371.

Mahshid Golzar PhD

Confirmed the feasibility of directly simulating flow and solute transport through stem arrays using desktop CFD tools
Potential to evaluate D_x and D_y simultaneously





RandoSticks CFD – Non-uniform stem diameters, with random spacing

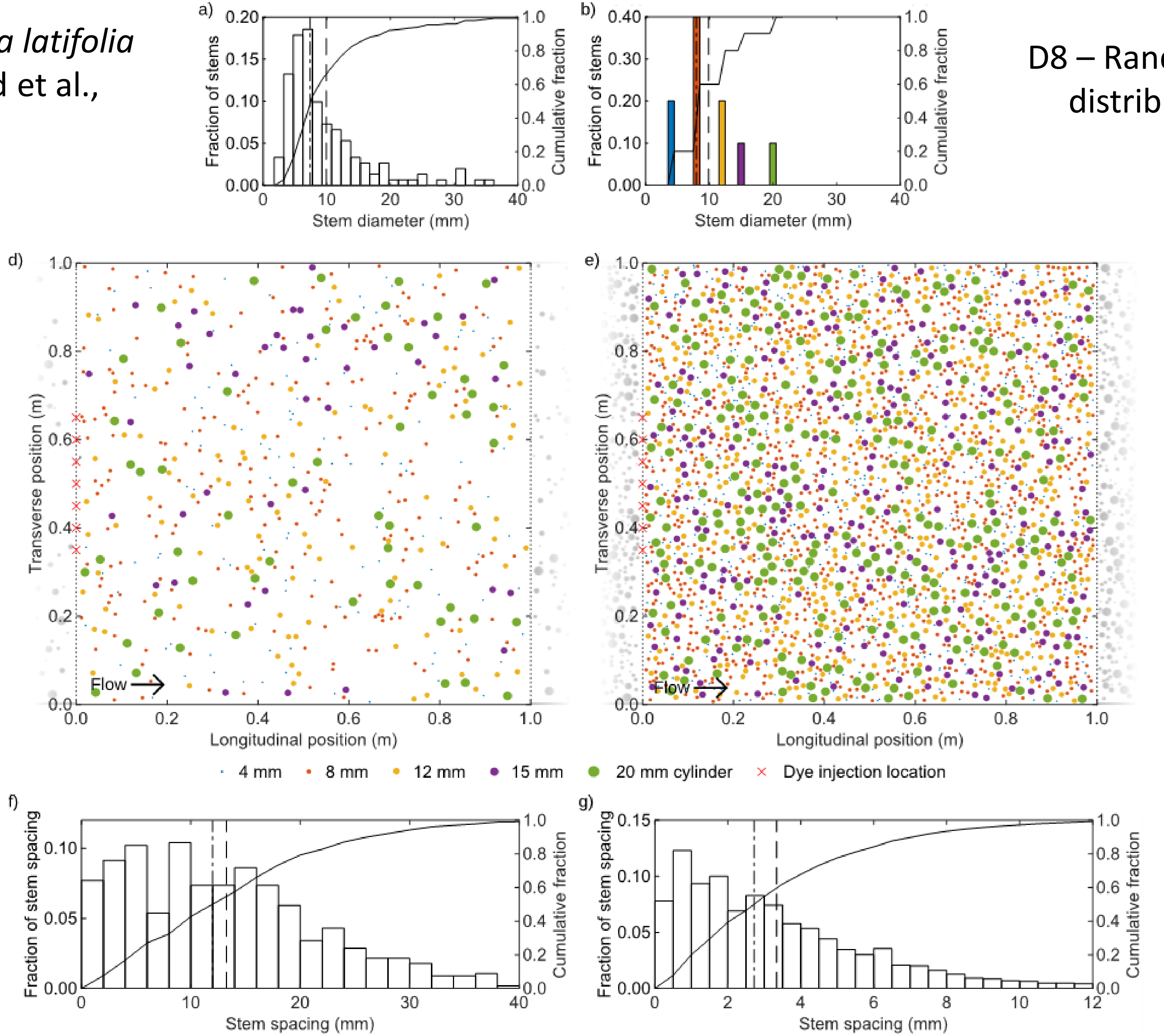
Label	Cylinder Diameter	Reason
D1	Uniform 6.35 mm	Direct comparison with Tanino and Nepf (2008).
D2	Uniform 4 mm	Component of D8, matches previous experimental work (Sonnenwald et al., 2017; Sonnenwald et al., 2019a).
D3	Uniform 8 mm	Component of D7 and D8, matches previous experimental work (Sonnenwald et al., 2019a).
D4	Uniform 12 mm	Component of D8.
D5	Uniform 15 mm	Component of D7 and D8.
D6	Uniform 20 mm	Component of D7 and D8. Largest consistently observable stem size in experimental real vegetation (Sonnenwald et al., 2017).
D7	8 and 15 mm stems; d_{50} = 8 mm, d = 10.8 mm	3:2 bimodal cylinder diameter distribution.
D8	4, 8, 12, 15, and 20 mm stems; d_{50} = 8 mm, d = 9.9 mm	2:4:2:1:1 distribution based on winter Typha latifolia (Sonnenwald et al., 2017).

- 1 m x 1 m tiles (chained together for solute transport simulations)
- 20 different solid volume fractions ($0.005 < \phi < 0.350$)
- 7 different transverse injection locations (0.35 m < y < 0.65 m) (equivalent to different geometries)
- $Re_{d50} = 500$
- Re_d = 675 for D7 and 619 for D8

- 2D CFD model – ANSYS Fluent
- RSM turbulence closure
- Mesh 1 mm, 0.1 mm at stems

Winter *Typha latifolia* (Sonnenwald et al., 2017)

D8 – RandoSticks distribution

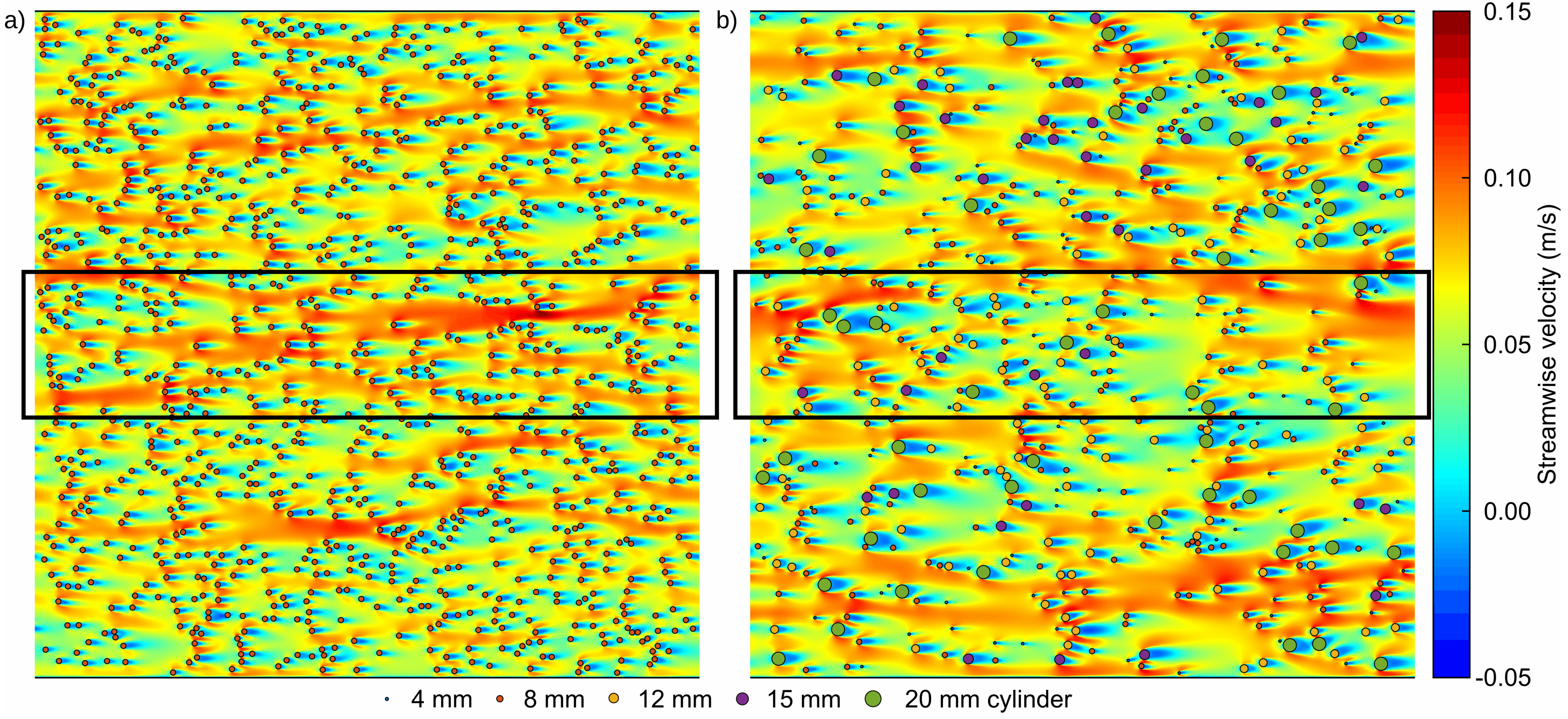


ϕ = 0.05

ϕ = 0.25

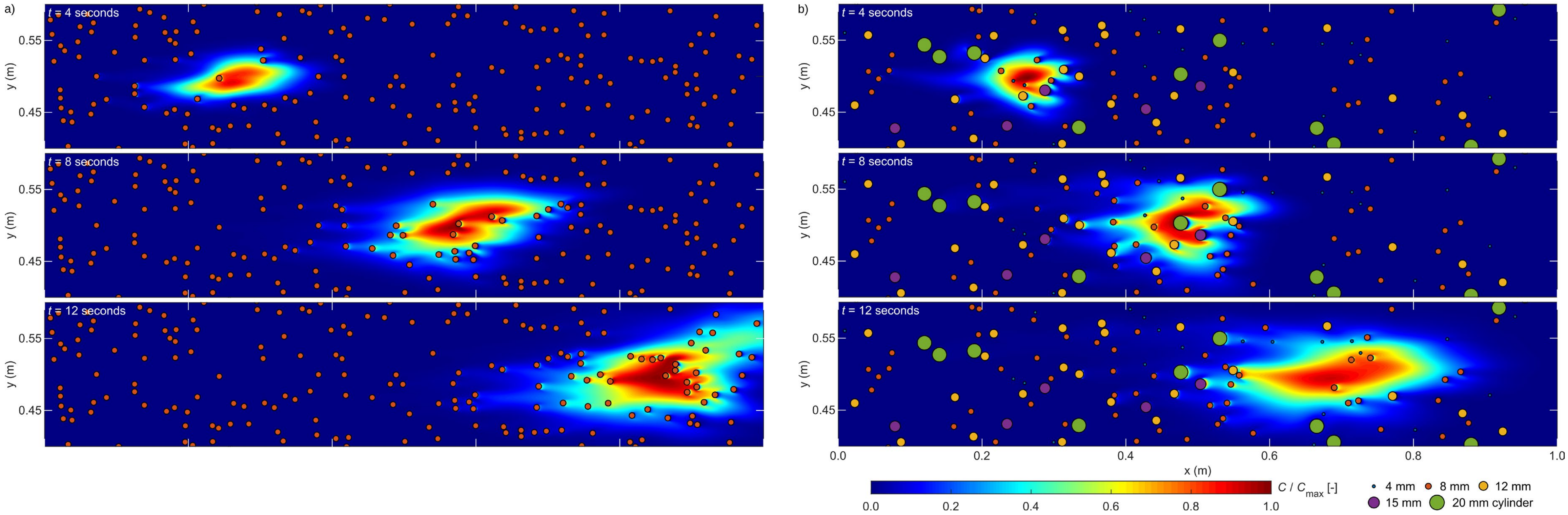
Flow fields

ϕ = 0.05: (a) D3 (8 mm uniform) and (b) D8 (RandoSticks)



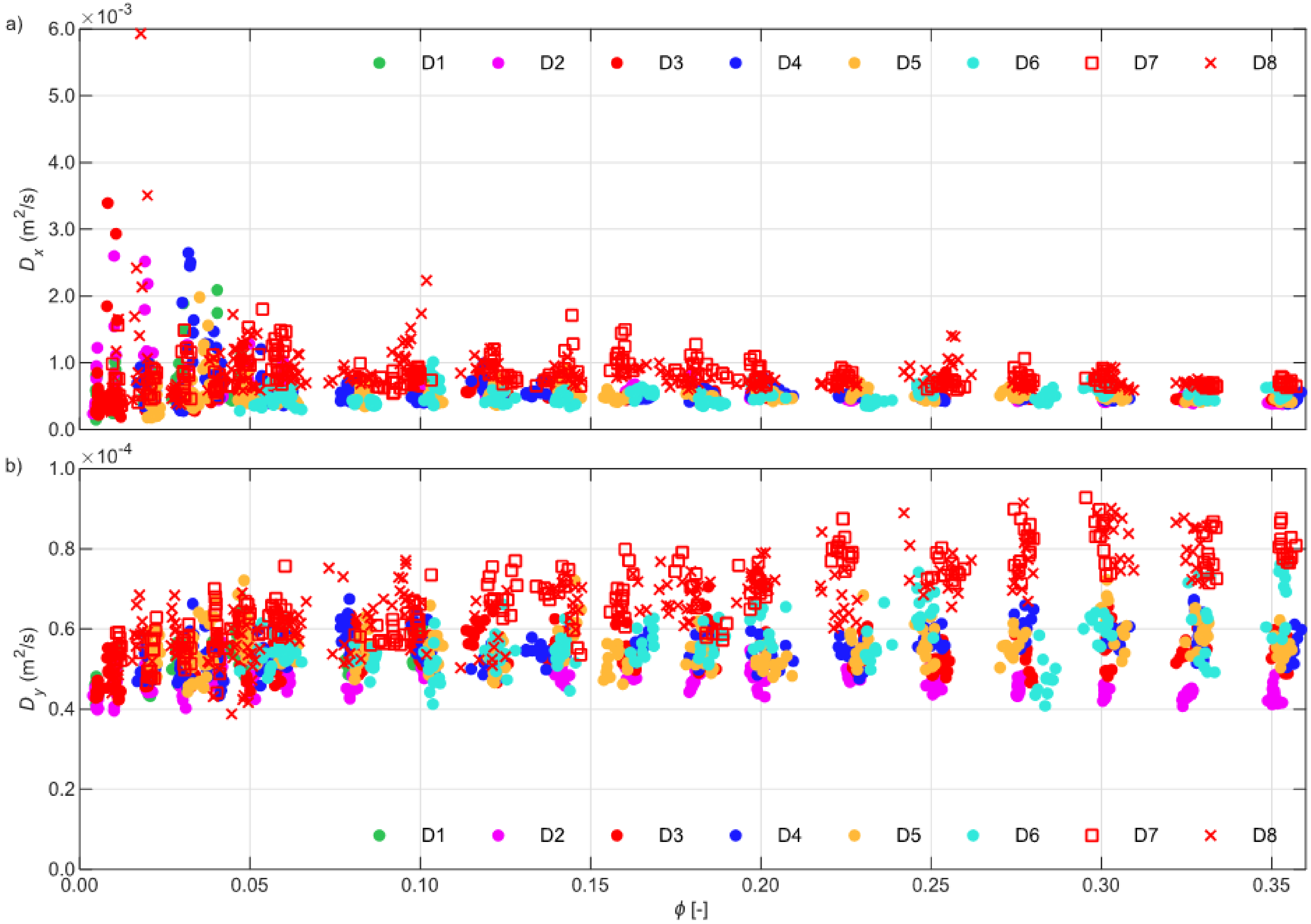
Simulated Dye Trace

ϕ = 0.05: (a) D3 (8 mm uniform) and (b) D8 (RandoSticks)



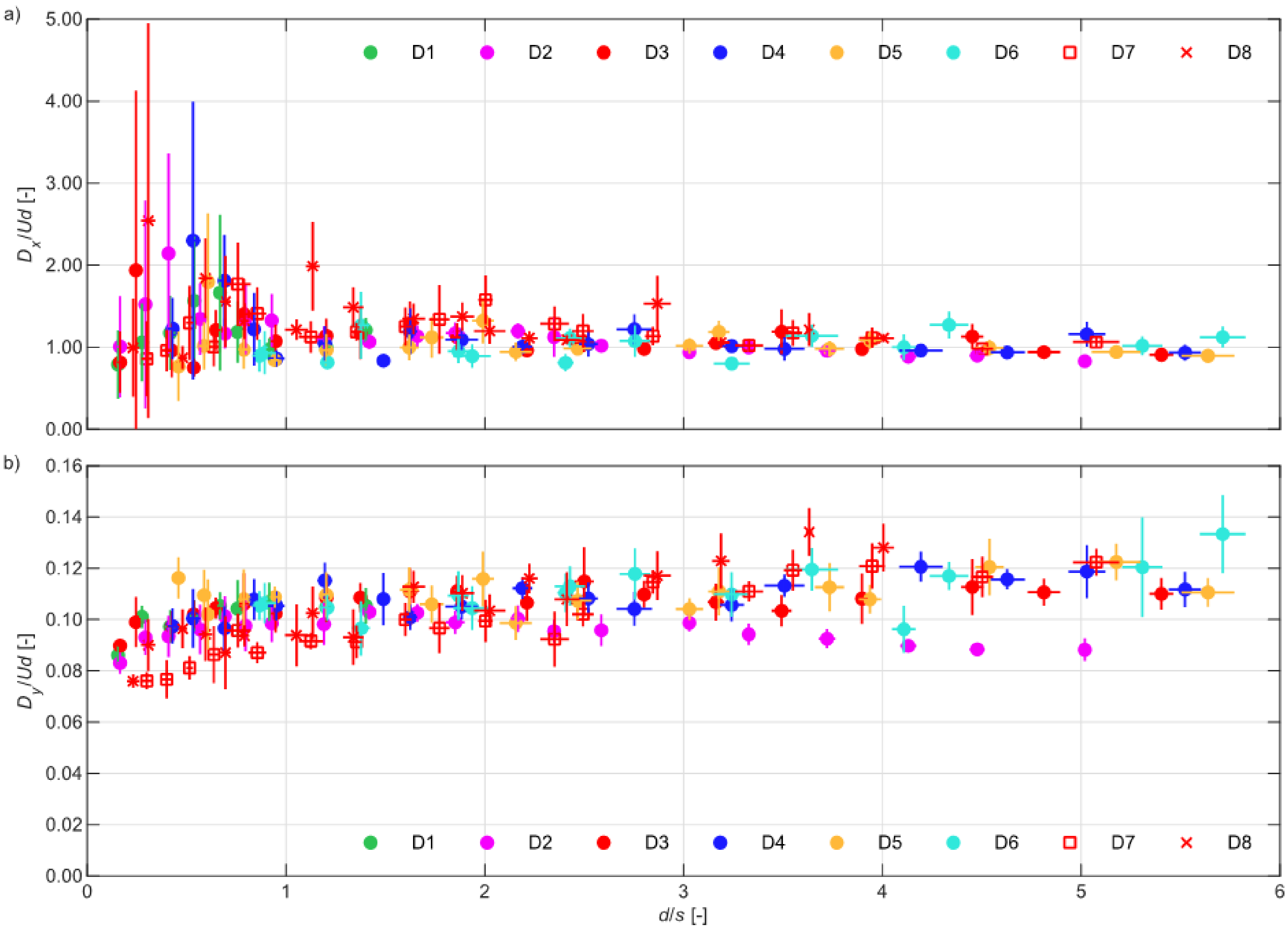
Raw data

- Red cases all have the same d_{50}
- Configurations D7 and D8, with non-uniform stem diameter distributions, show higher values of D_y compared with the uniform stem diameter configurations
- Significant variation in D_x at low ϕ, due to the random occurrence of preferential flow paths
- D_x & D_y both appear to be essentially independent of ϕ
- D_x is approximately one order of magnitude greater than D_y



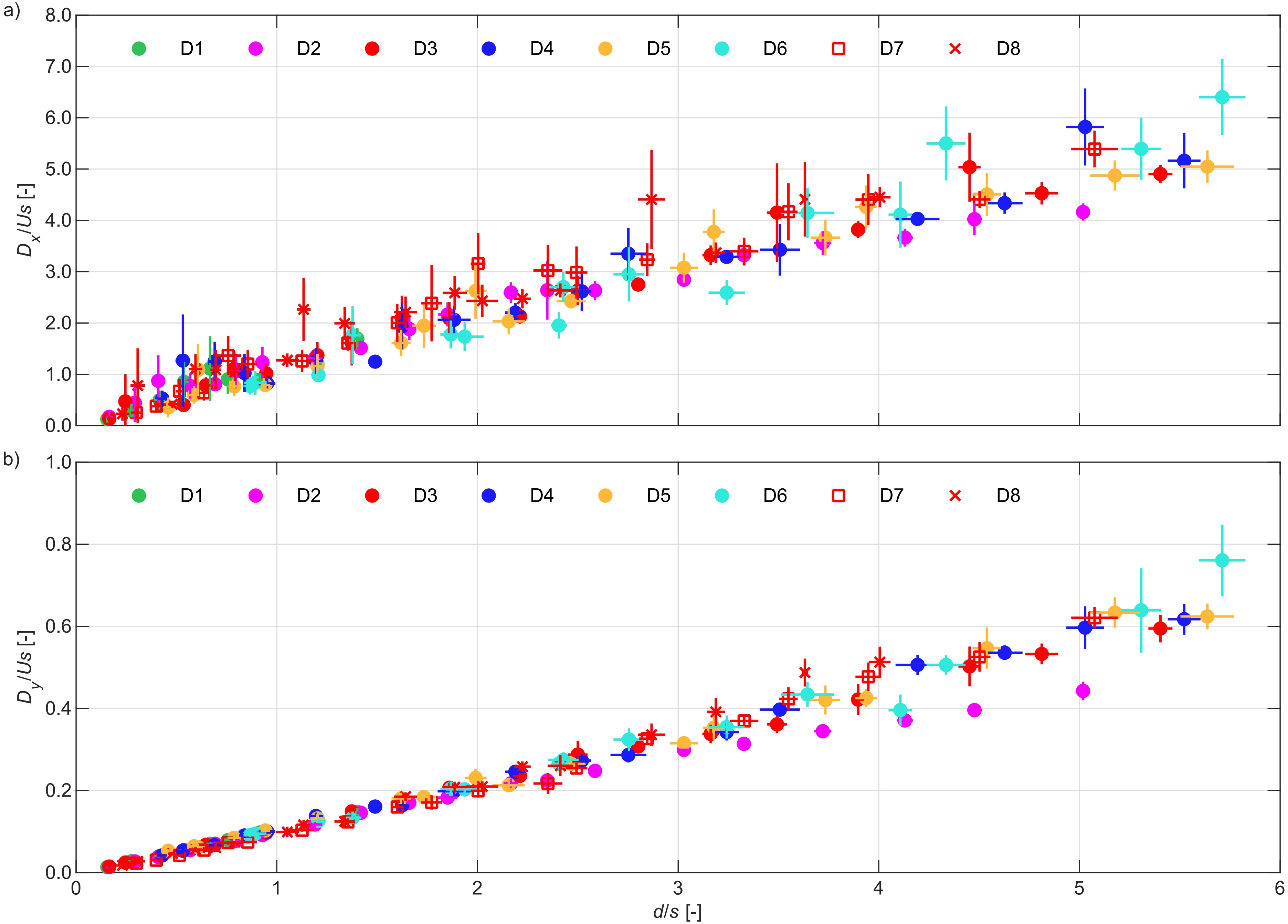
Normalised data

- Y-axis – divide by Ud (as Re_d varied)
- X-axis – d/s replaces ϕ
  - Permits direct comparison with Tanino and Nepf (2008)
  - Discriminates better between configuration with similar values of ϕ, but very different stem sizes and stem spacings
- The apparent enhanced dispersion due to diameter non-uniformity disappears.
- The fundamental dispersion characteristics associated with a vegetated flow are unaffected by the uniformity (or otherwise) of the stem diameter distribution.
- The new CFD-derived transverse dispersion coefficients do not show the characteristic 'N' or 'hump' shape of the Tanino and Nepf (2008) model



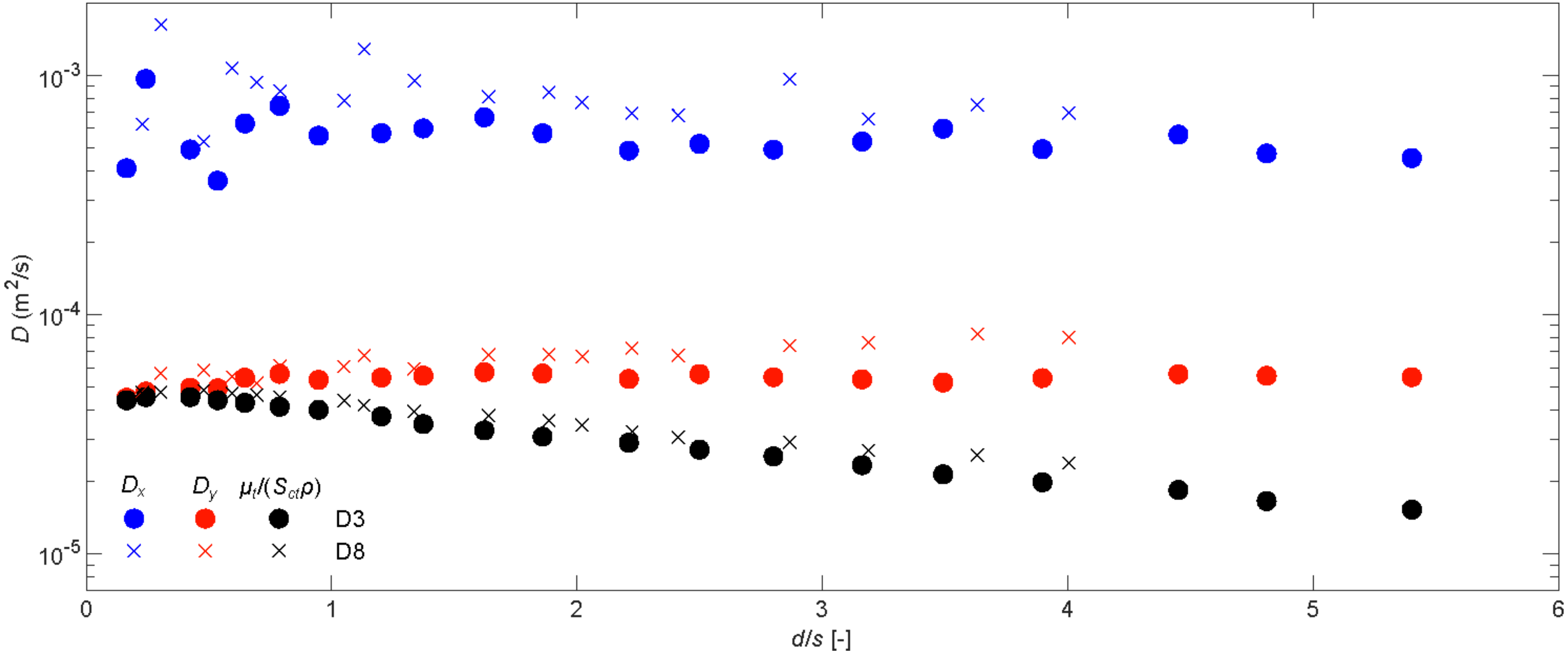
Normalised data

- Y-axis – divide by Us (as Re_d varied)
- D_x/Us and D_y/Us both collapse reasonably well onto a single line
- No evidence of stem diameter distribution effects
- Eliminated the variation in D_x observed at low solid volume fractions
- D2 probably a bit dodgy!

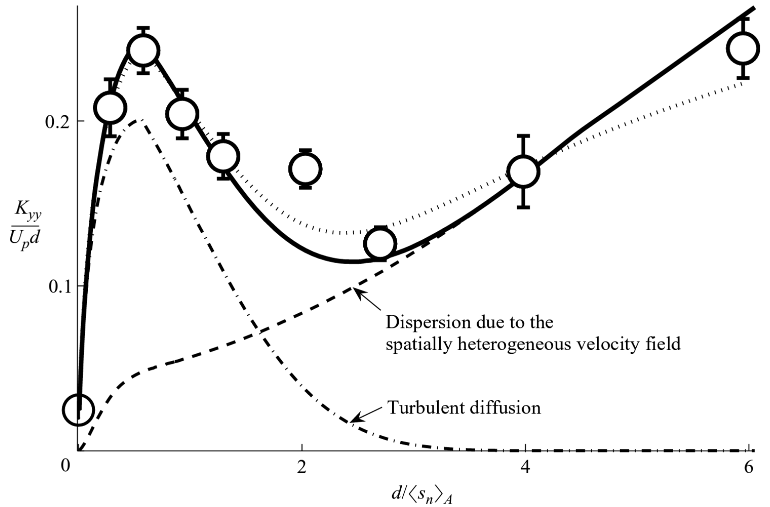


Components

- Relative contribution of turbulent diffusion ($\mu_t/(S_{ct}\rho)$) to overall reach-scale D_x and D_y
- Isotropic
- Turbulent diffusion is a minor component of longitudinal dispersion throughout the range of solid volume fractions
- In contrast, as noted by Tanino and Nepf (2008), its contribution to transverse dispersion is significant, particularly at low solid volume fractions

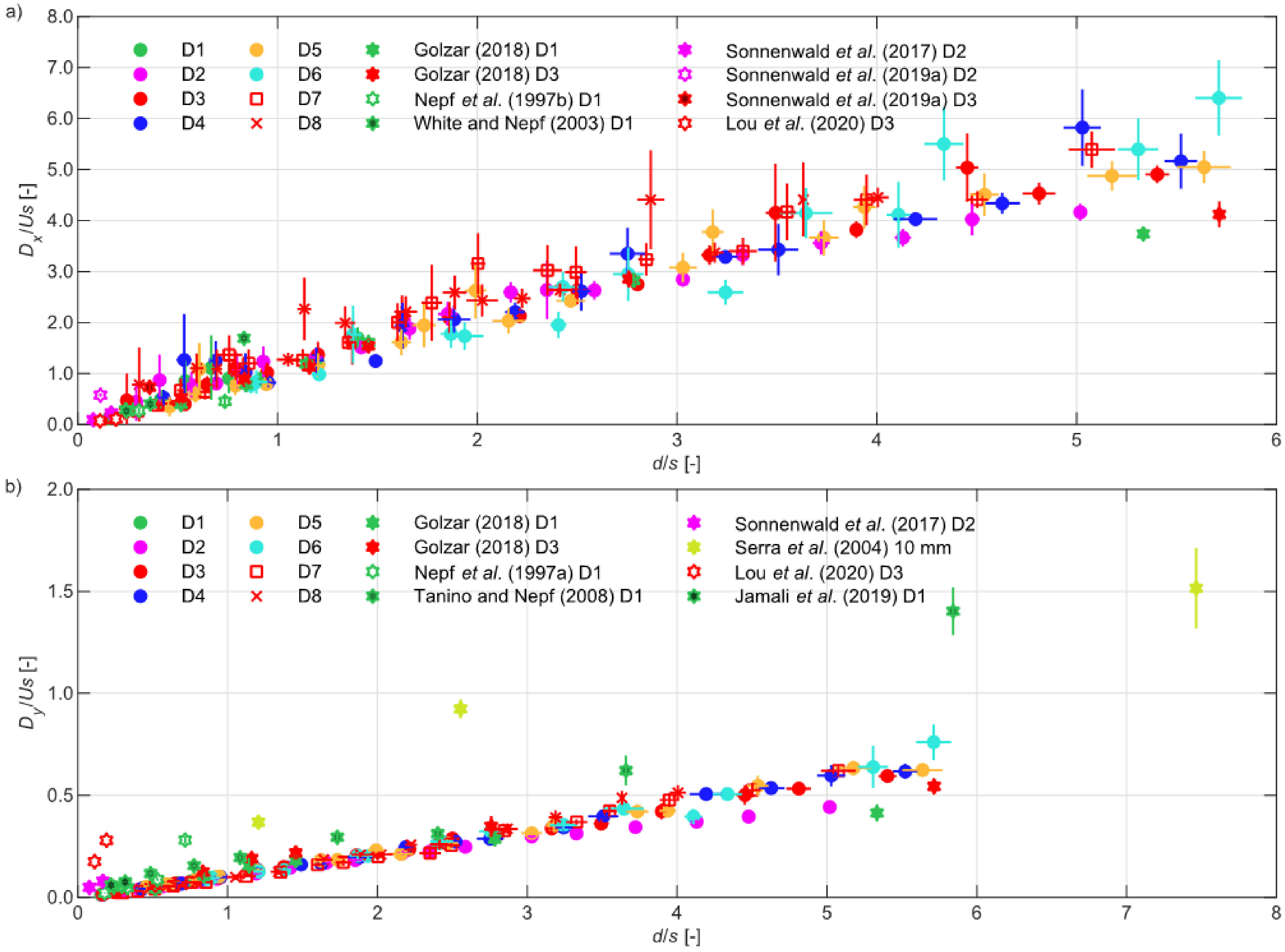


Our data challenges the Tanino and Nepf (2008) model's expectation that turbulent diffusion reduces to zero at *d/s* values greater than approximately 3.0 (ϕ > 0.25)



Comparison with previously reported data

- Generally highly consistent



Conclusions

- CFD-generated dispersion coefficients are largely independent of solid volume fraction.
- Non-dimensional dispersion coefficients for vegetation with a non-uniform stem diameter distribution are in agreement with those for vegetation with a uniform stem diameter. Stem diameter distribution does not affect the mixing processes associated with vegetated flows simulated using cylinder arrays.
- Non-dimensionalising by stem spacing reveals a linear relationship between dispersion and d/s that is consistent with previously reported laboratory studies. This confirms that stem spacing – rather than stem diameter – is the relevant length scale for turbulent mixing processes in vegetated flows.
- Subsequent in-house experimental work will permit further validation.