Solute Mixing
from Estuaries to Pipes

“travelling upstream from estuaries, through rivers, sewers, & into pipes, simplifying as we go ……….”

Ian Guymer

University of Sheffield, UK

University of Sheffield

40th International School of Hydraulics
Kąty Rybackie, Poland

- Transport, fate and effect of soluble pollutants
- Laboratory and field studies to identify and quantify mixing processes
- Estuarine, coastal, rivers, urban drainage and pipes

Where, when & what concentration?

- Diffusion; turbulence; velocity shear
- Advection & dispersion
- Spatial scale: from millimetres (turbulence) to several hundred kilometres (catchments)
- Temporal scale: from milliseconds to months

How to integrate all these processes

within 1D network models?

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Established Career Fellowship
"Modelling Mixing Mechanisms in 1D Water Network Models"

UKRI Engineering and Physical Sciences Research Council

Contents

- Why quantify longitudinal dispersion (D_x) and can we predict D_x?
- 1D networks:
  - estuaries/rivers/sewers/pipes
- Hydraulic conditions:
  - Uniform; steady; straight; turbulent; density
- Processes:
  - f(x) and f(t)
- How do cross-sectional (transverse) processes affect longitudinal processes?
- Comments & conclusions

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Why needed?

Accidental spills & storm overflows produce time varying water quality discharges

Models needed to describe the temporal concentration distributions

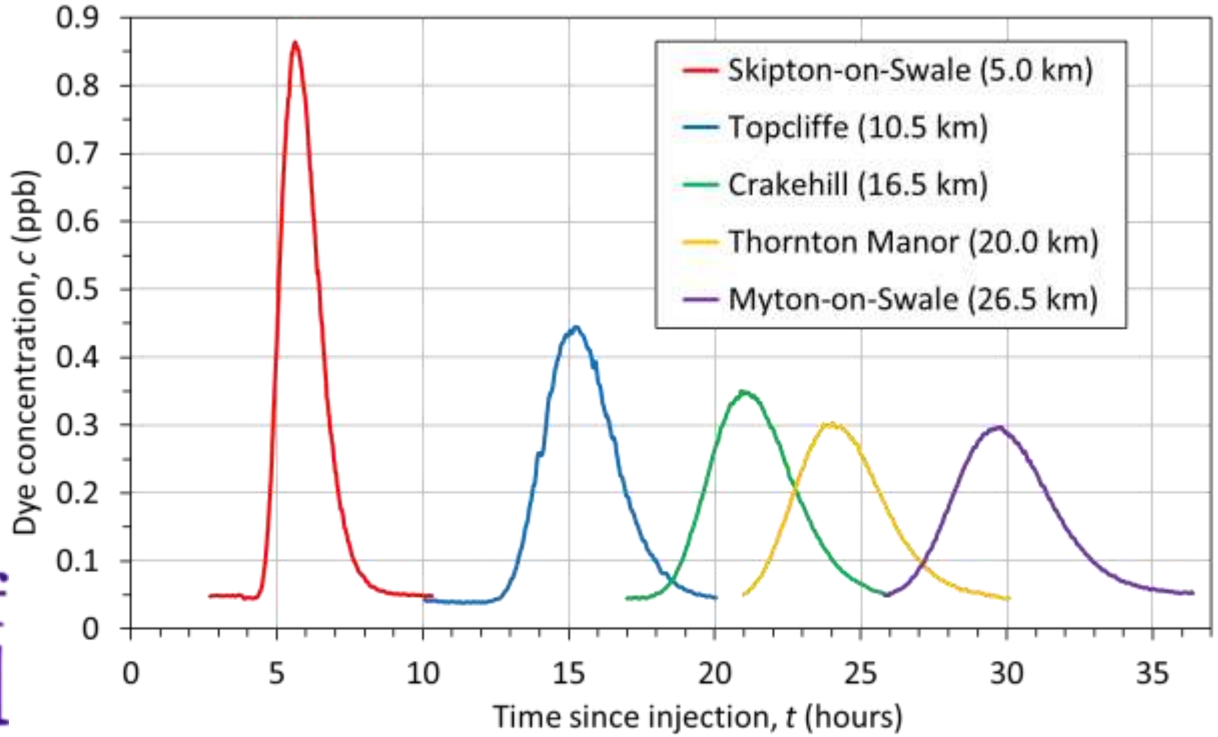
e.g. impact of contaminated highway runoff on receiving water ecology

UK Environment Agency - Time of Travel Database

- 196 data sets, 27 different rivers
- Physical data recorded:

  reach slope, catchment areas, discharge

  (instantaneous, annual mean, daily mean, Q95)



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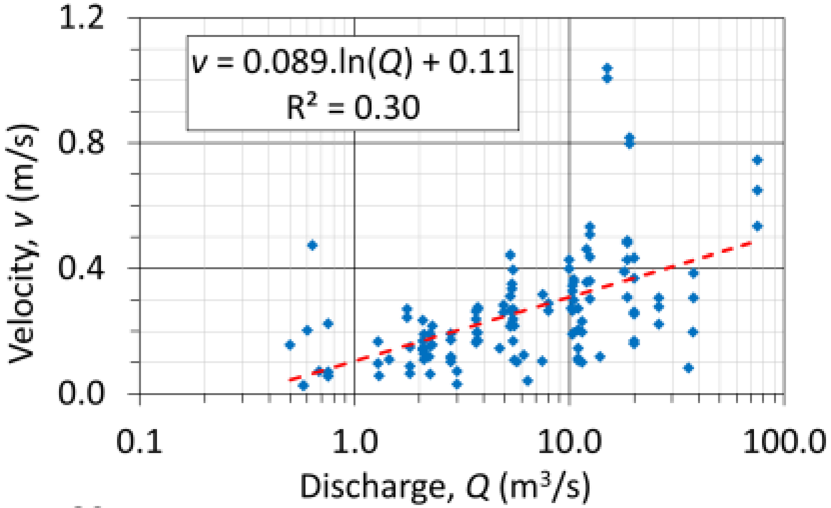
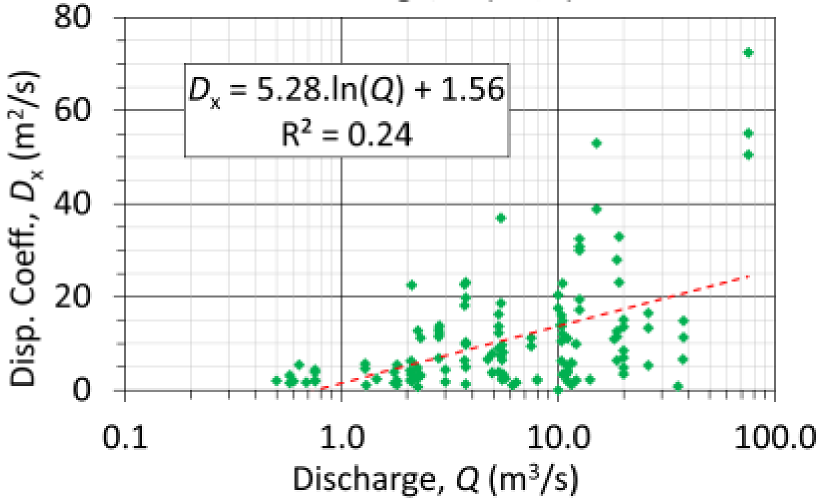
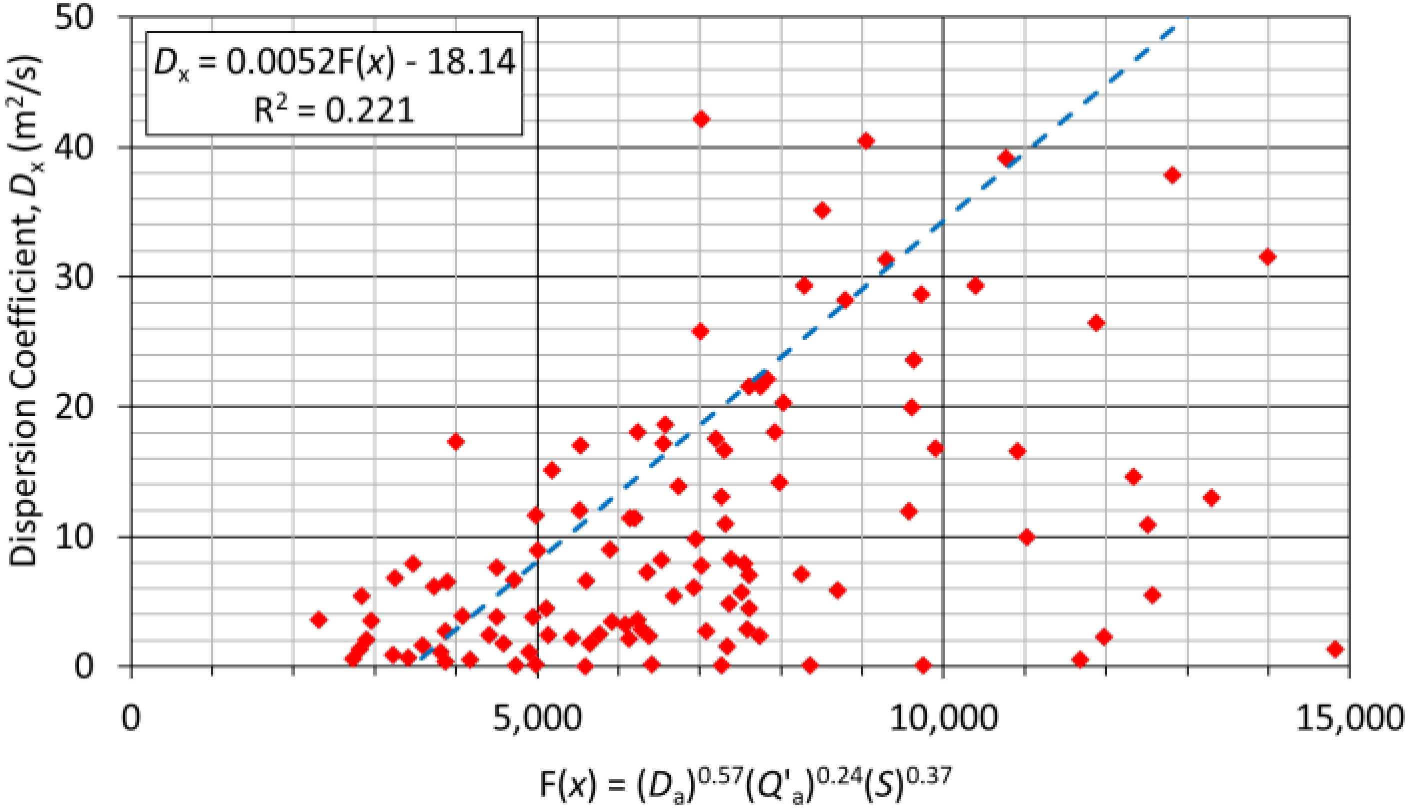
Environment Agency

EA Database – Velocity & Dispersion trends







- Multiple processes affecting longitudinal dispersion
- What are the contributing components?

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Mixing Processes

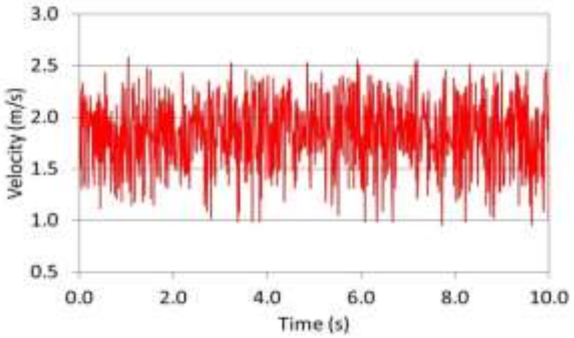
Diffusion

Relative magnitude of mixing processes

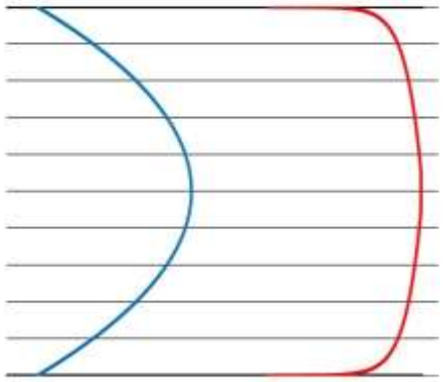
Molecular diffusion	e	10^{-10} to 10^{-9} m^2/s
Turbulent diffusion	ε	10^{-3} to 10^{-1} m^2/s
Shear dispersion	D_x	1 to 10^3 m^2/s

Differential Advection

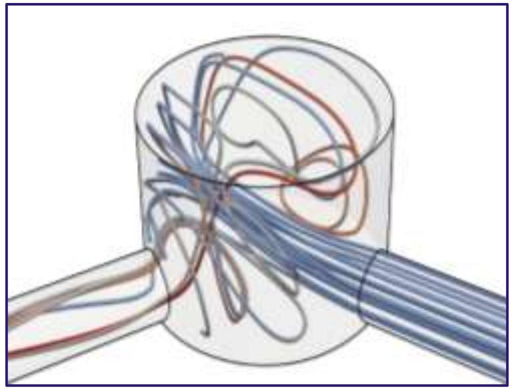
Turbulence



Shear flow



3D flow field



Transient Storage

Dead Zones,
trapping effects,
secondary circulation

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Advection-dispersion Equation

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} = D_x\frac{\partial^2 c}{\partial x^2}$$

Dispersion of soluble matter in solvent flowing slowly through a tube

By Sir Geoffrey Taylor, F.R.S.

(*Received* 31 *March* 1953)

$D_x = a^2u^2/48D_m$

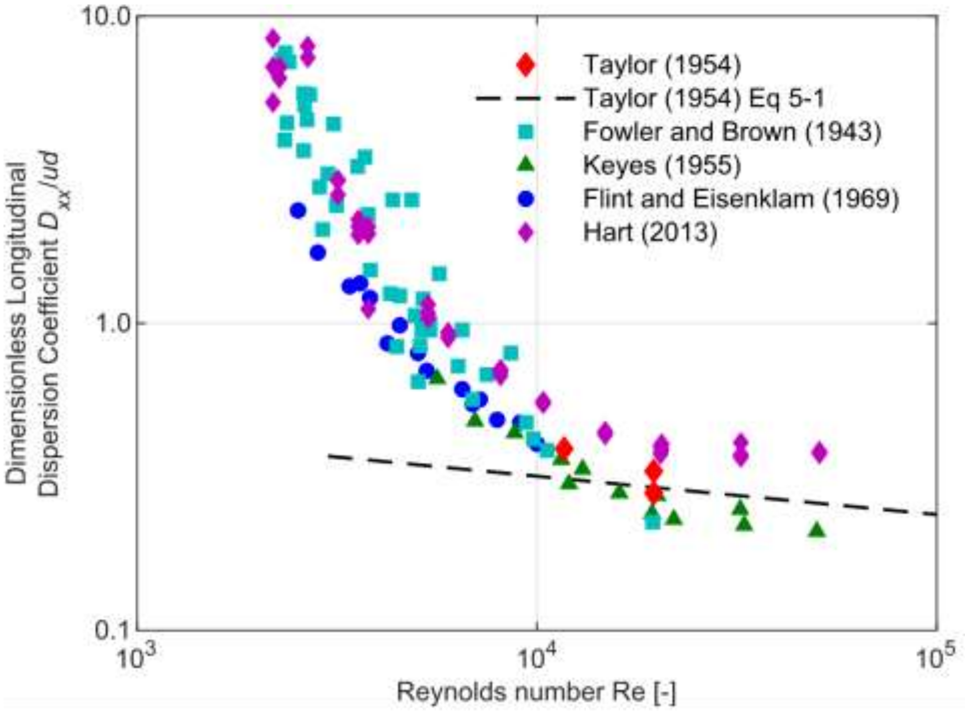
The dispersion of matter in turbulent flow through a pipe

By Sir Geoffrey Taylor, F.R.S.

(*Received* 24 *December* 1953—*Read* 11 *March* 1954)

$D_x = 10.1au^*$

How to obtain a value of D_x?



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Hart, J.R., Guymer, I., Sonnenwald, F. and Stovin, V.R. (2016) "Residence Time Distributions for Turbulent, Critical and Laminar Pipe Flow" ASCE J. of Hydraulic Eng.

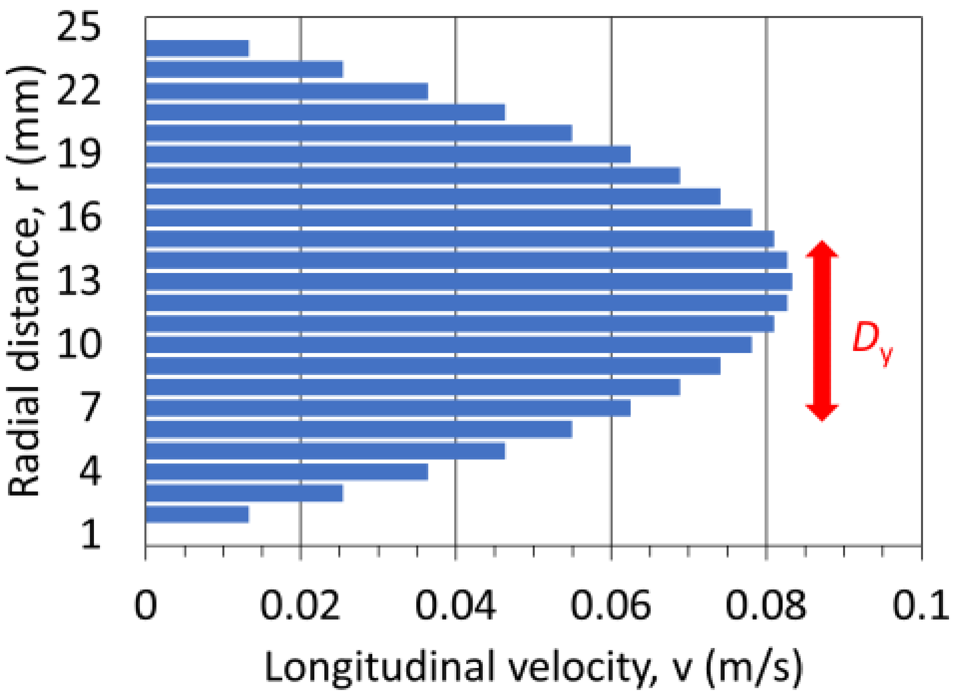
Estimating the Longitudinal Dispersion Coefficient

Fischer (1967), extended by Chickwendu (1986):

$$D_x = \sum_{j=1}^{N-1} (q_1 + q_2 + \cdots + q_j)^2 [1 - (q_1 + q_2 + \cdots + q_j)]^2 \frac{[u_{12\ldots j} - u_{(j+1)\ldots N}]^2}{b_{j(j+1)}}$$

$$b_{j(j+1)} = \frac{2D_{yj(j+1)}}{h^2(q_j + q_{j+1})}$$

D_x is the estimate of longitudinal dispersion for N zones based on geometry, longitudinal velocity profile and transverse dispersion coefficient profile.



	D_y (m²/s)	$1.00.10^{-9}$
D_x (m²/s)	Re = 1,000	8.47
	Re = 10,000	39.1

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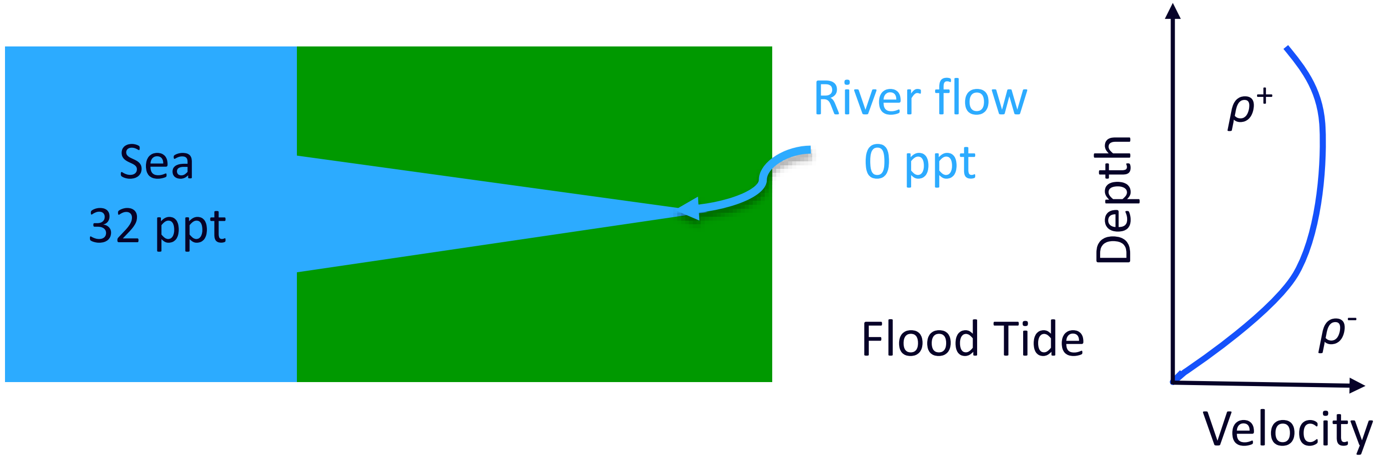
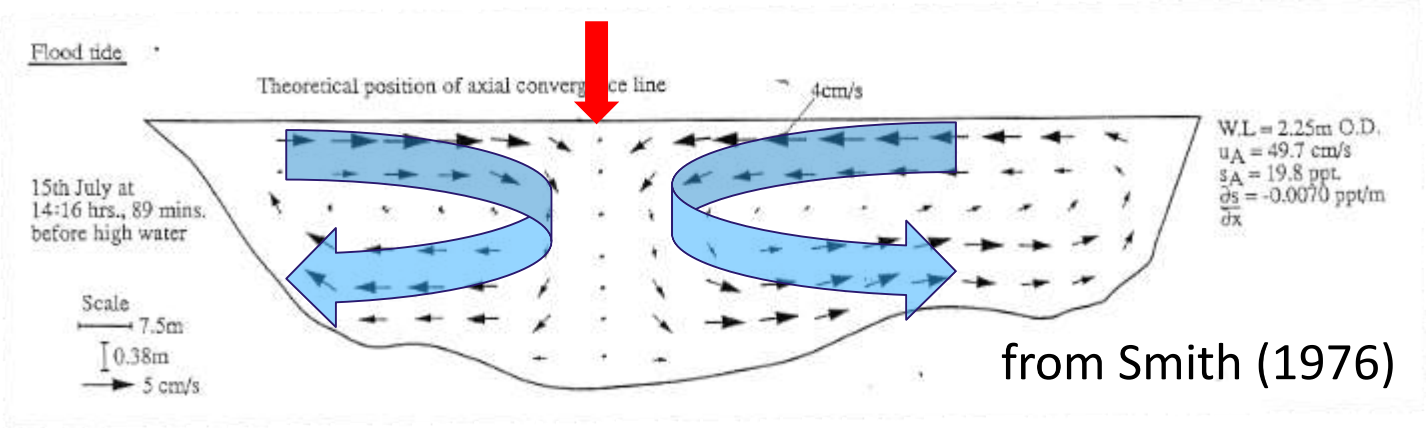
Chickwendu, S. C. (1986) ''Calculation of longitudinal shear dispersivity using an *N*-zone model as $N \rightarrow \infty$'' *J. Fluid Mech.*, 167, 19–30.

Estuarine Mixing Processes





from Smith (1976)

Guymer, I. (1985) 'Some Aspects of Solute Transport Processes in the Conwy Estuary', PhD, University of Birmingham, UK.

Smith, R. (1976). "Longitudinal dispersion of a buoyant contaminant in a shallow channel." *J. Fluid Mech.*, 78(4), 677-688.

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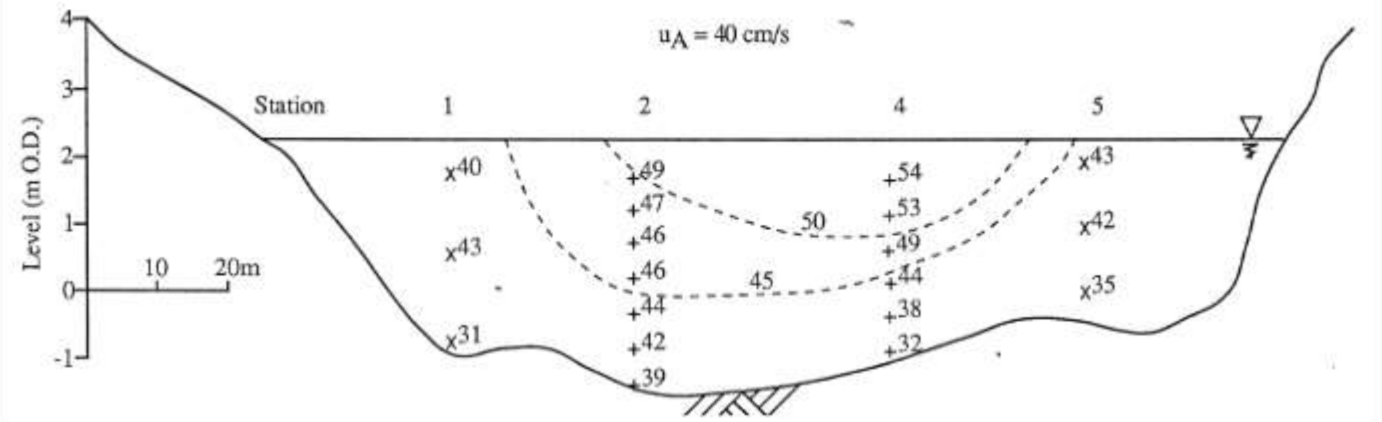
Estuarine Mixing Processes

Velocity measurements



- Longitudinal density gradients, combined with vertical velocity profiles, create strong secondary circulations on the flood tide, reducing the longitudinal dispersion, D_x
- *"Bends appear to be influential, due either to channel asymmetry promoting transverse effects in long bends or secondary flow induced intense mixing in short, sharp bends, thus decreasing dispersion effects"*

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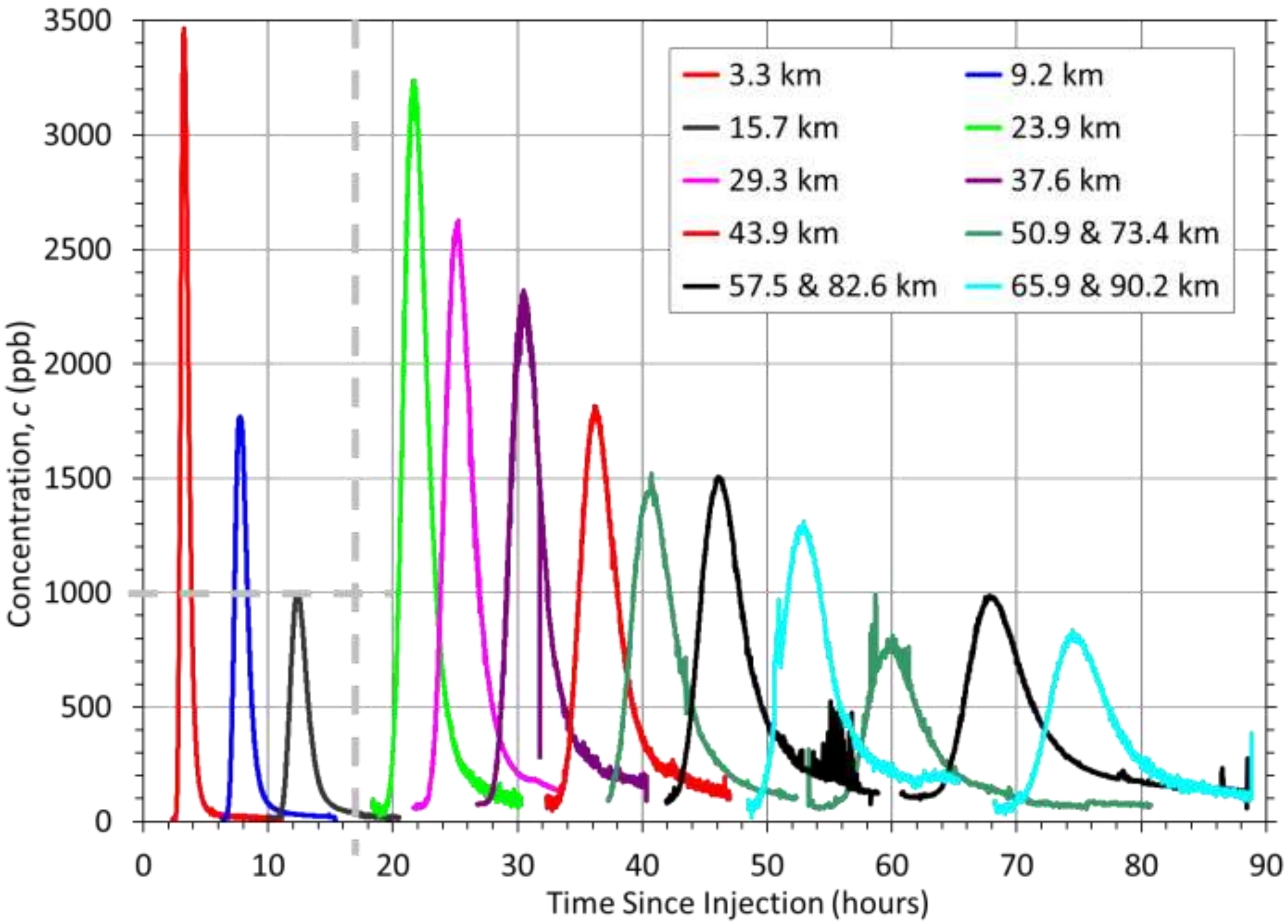
Guymer, I. and West, J.R. (1992) "Longitudinal Dispersion Coefficients In An Estuary"
ASCE Journal of Hydraulic Engineering, 118(5), 718-734.

Planform Curvature – field studies



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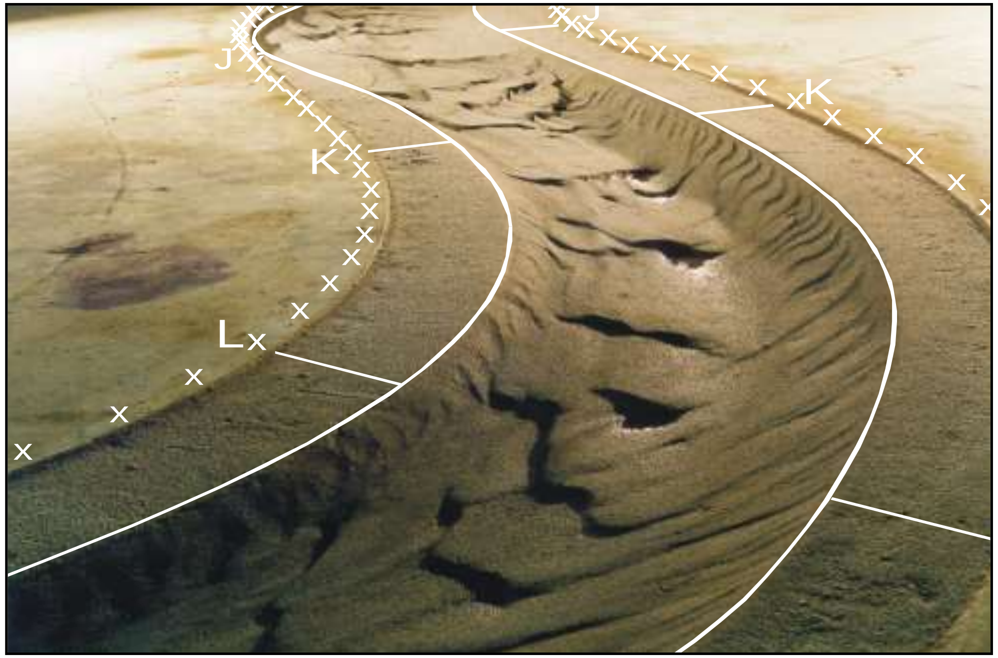
Rowinski, P.M., Guymer, I. and Kwiatkowski, K. (2008) "Response to the slug injection of a tracer – large scale experiment in a natural river", *Hydrological Sciences*, 53(6), 1300- 1309.

Planform Curvature – laboratory studies

60° fixed bed channel
Trapezoidal and change in shape
Longitudinal dispersion



25 l/s natural formed channel
Longitudinal and transverse mixing

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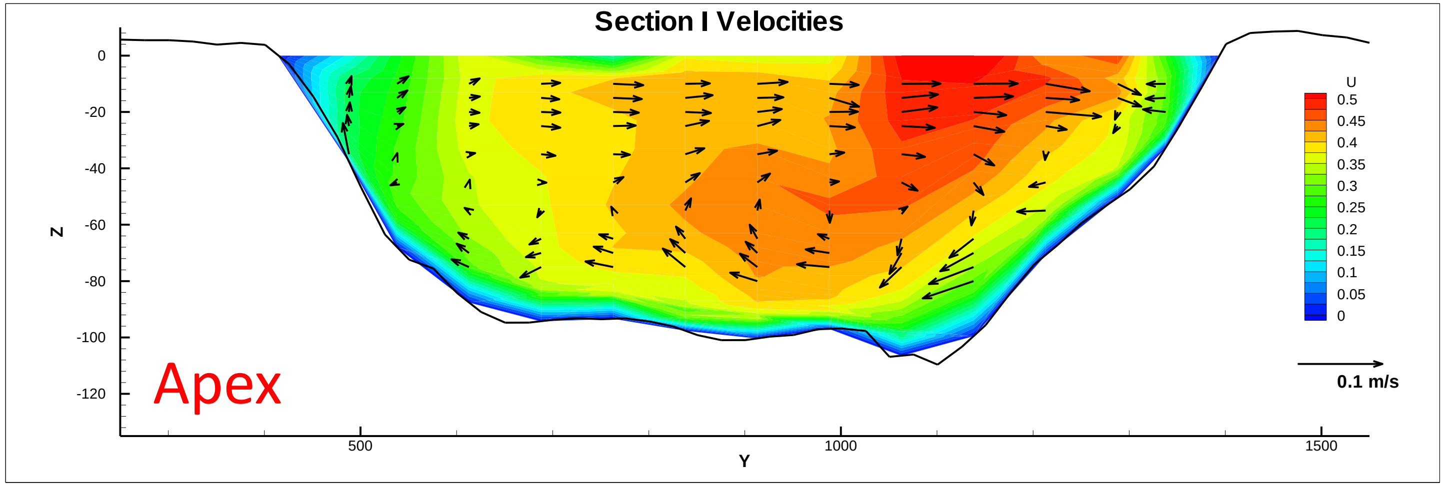
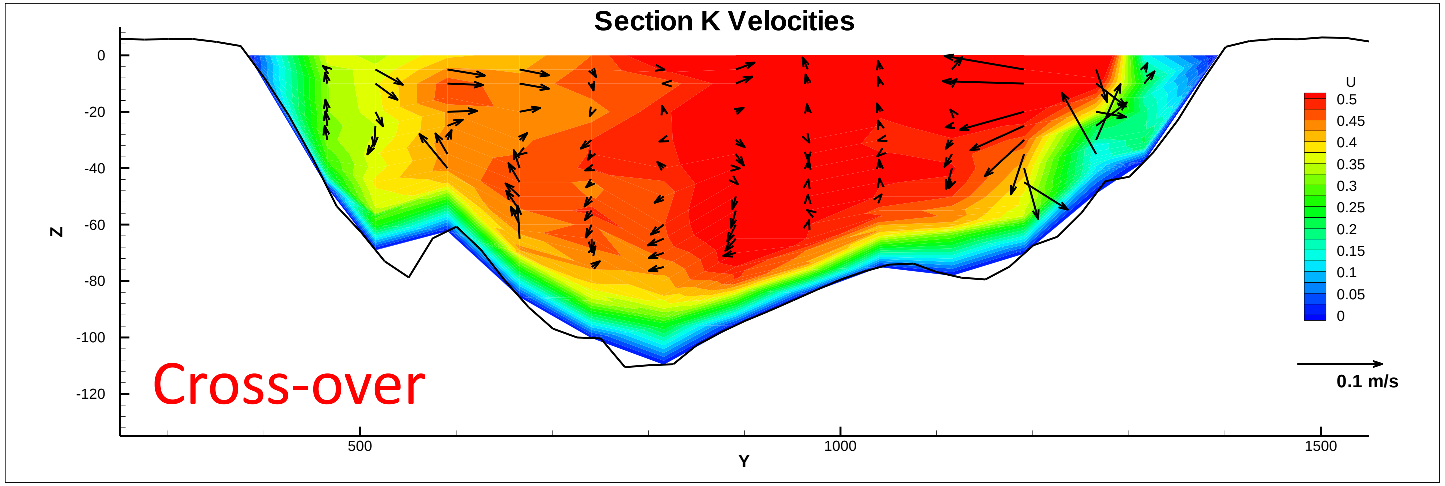
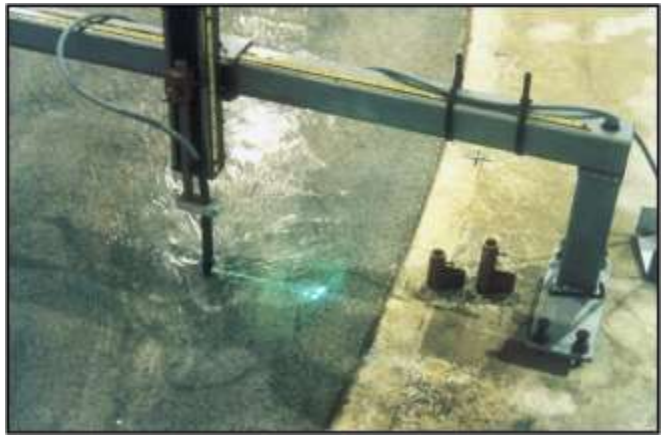
Guymer, I. (1998) "Longitudinal Dispersion in a Sinuous Channel with Changes in Shape" *ASCE Journal of Hydraulic Engineering*, 124(1), 33-40.

Planform Curvature – laboratory studies







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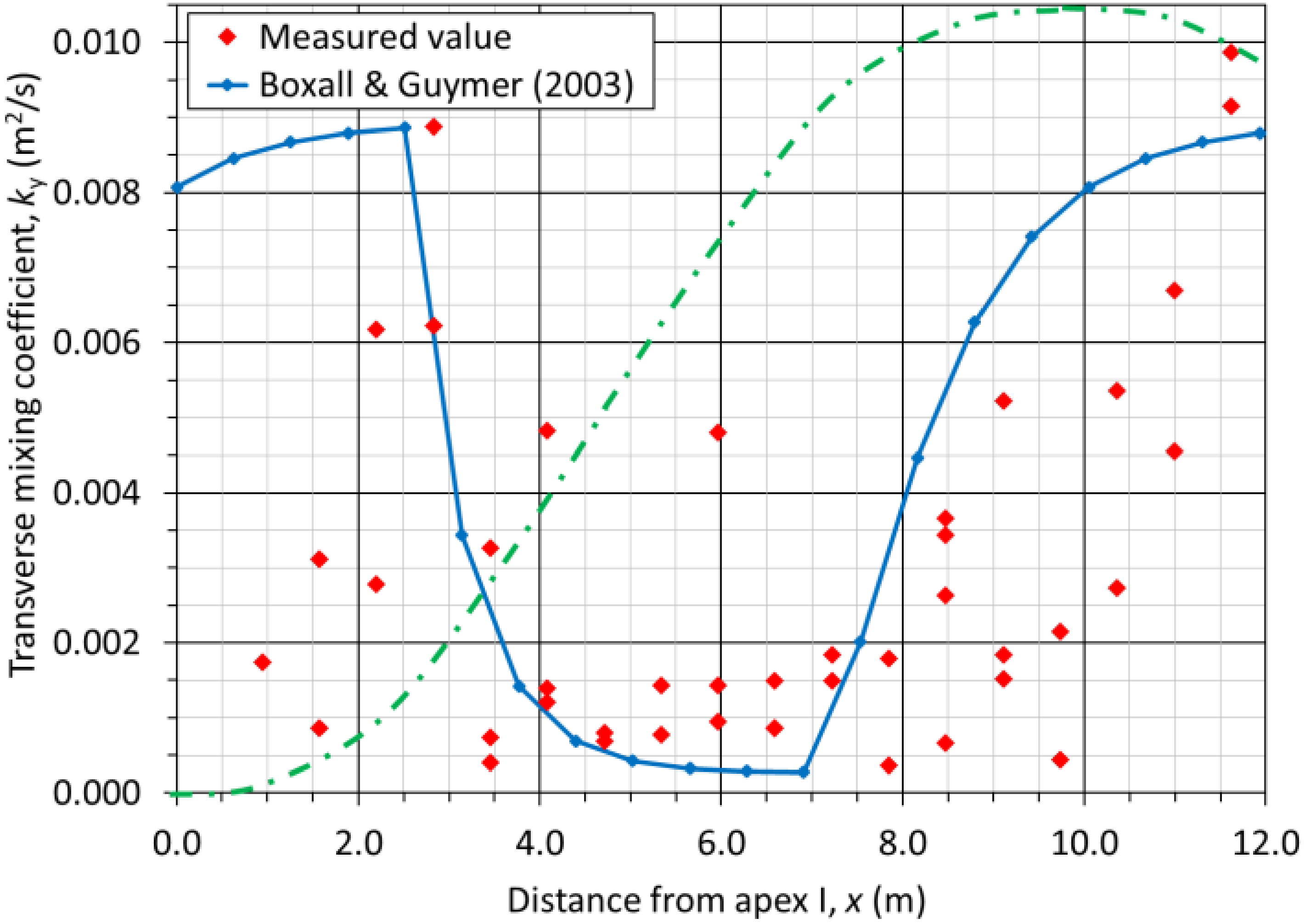
Boxall, J.B., Guymer, I. and Marion, A. (2003) “Transverse mixing in sinuous natural open channel flows”, *J. of Hydraulic Research*, 41(2), 153-165.

Planform Curvature – transverse mixing



- Rozovskii (1961) analytical prediction of secondary flows due to planform curvature
- Employ increase in transverse mixing within Chickwendu (1986)
- Relate transverse to longitudinal mixing

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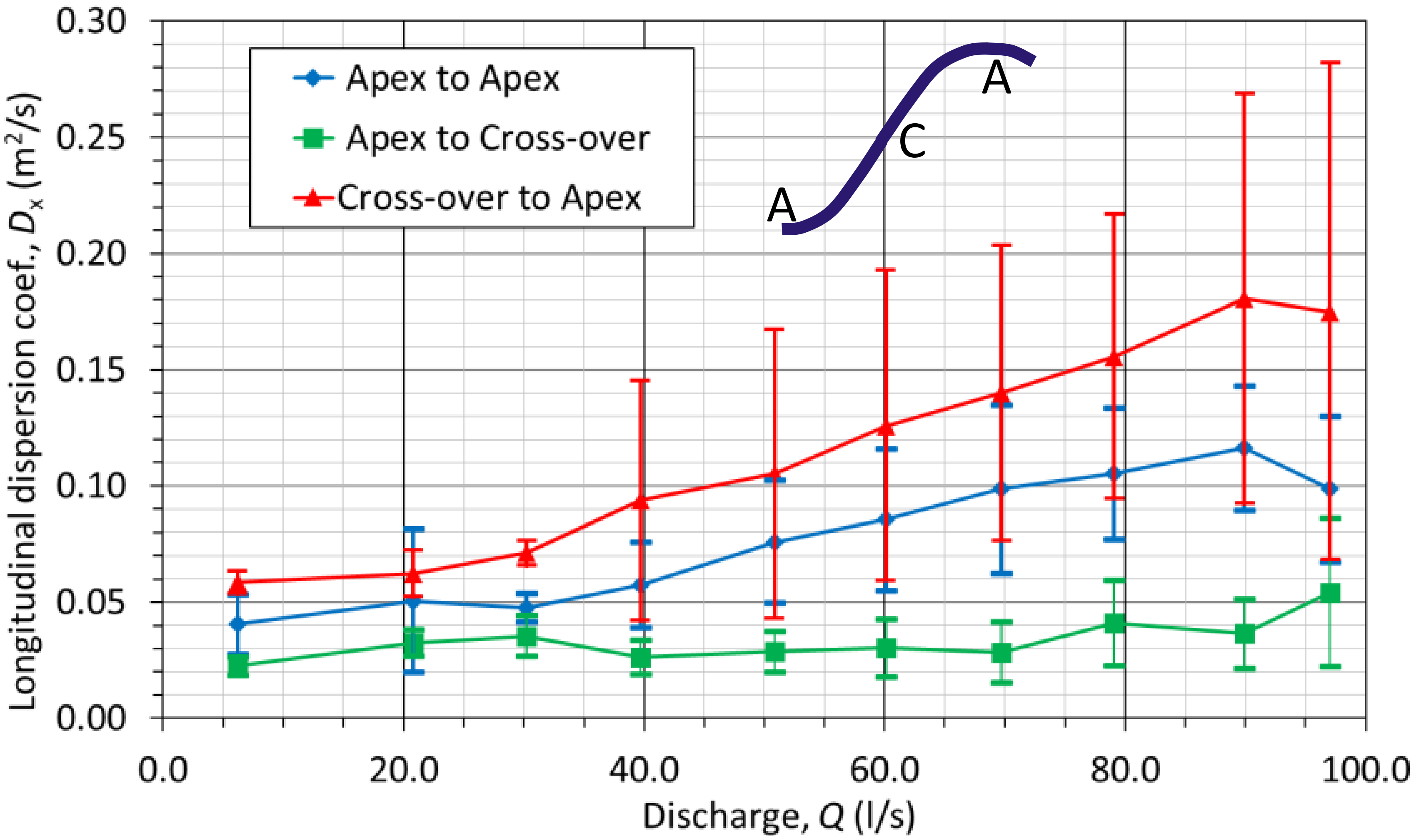
Boxall, J.B. and Guymer, I. (2003) "Analysis and Prediction of Transverse Mixing Coefficients in Natural Channels", *ASCE Journal of Hydraulic Engineering*, 129(2), 129-139.

Planform Curvature – longitudinal dispersion



- Bends induce secondary flows
- increase transverse mixing
- reduce influence of longitudinal differential advection
- reduce longitudinal dispersion

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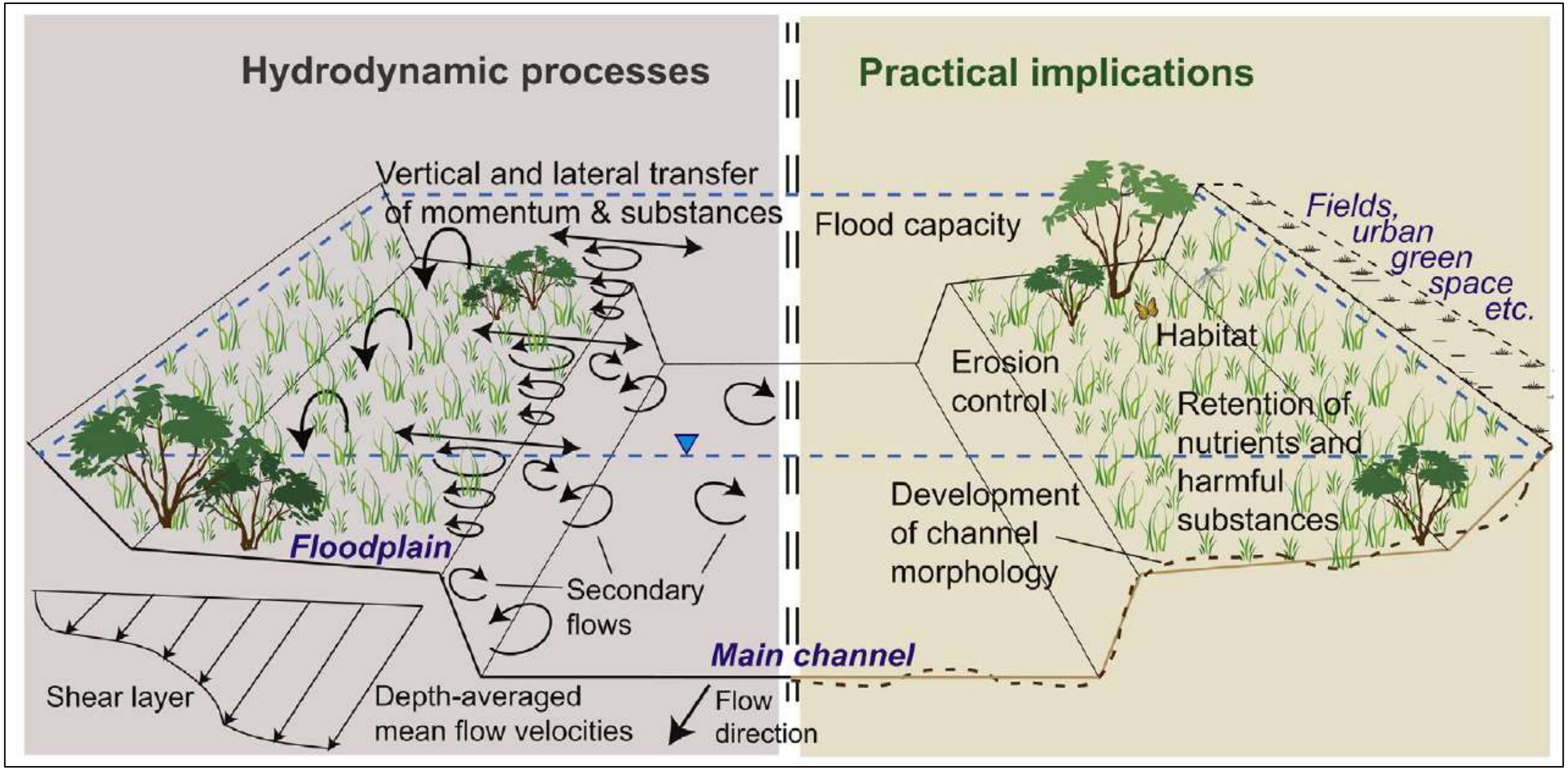
Boxall, J.B. and Guymer, I. (2007) "Longitudinal mixing in meandering channels: new experimental data set and verification of a predictive technique." *Water Research*, 41(2), 341-354

Compound Channels – transverse shear effects



Rowinski, P.M.; Västilä, K.; Aberle, J.; Järvelä, J. and Kalinowska, M.B. (2018) How Vegetation Can Aid in Coping with River Management Challenges: A Brief Review. *Ecohydrology Hydrobiology* 18, 345–354.

Compound Channels – transverse shear effects

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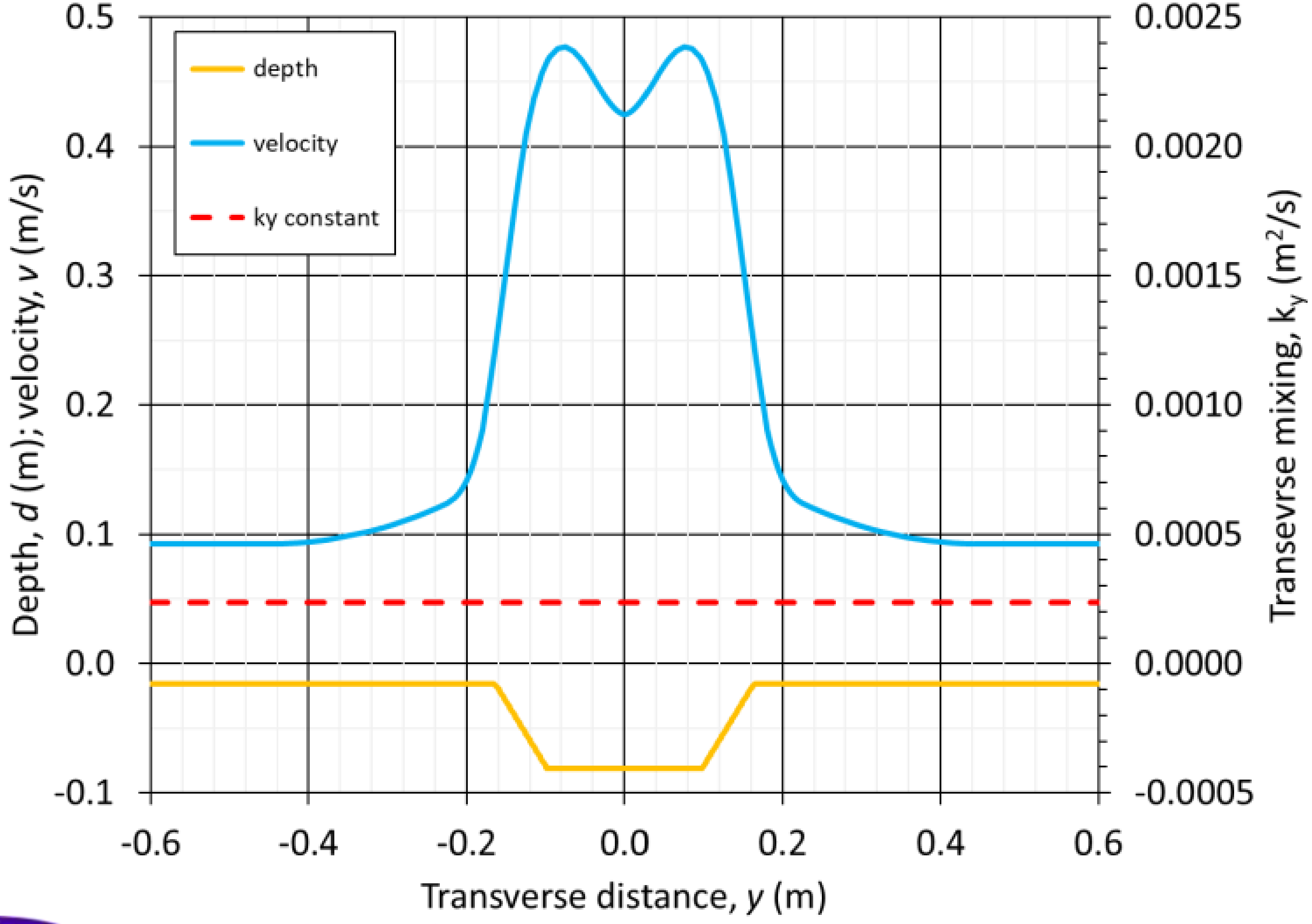
Spence, K.J., Sonnenwald, F.S. & Guymer, I. (**STILL** in preparation) “Spatial variation of transverse mixing in compound channels”

Compound Channels – transverse shear effects



- Spatial variation of transverse mixing, k_y
- Effect on longitudinal dispersion, D_x, evaluated using Chickwendu (1986)

	D_x (m^2/s)
Uniform	0.65

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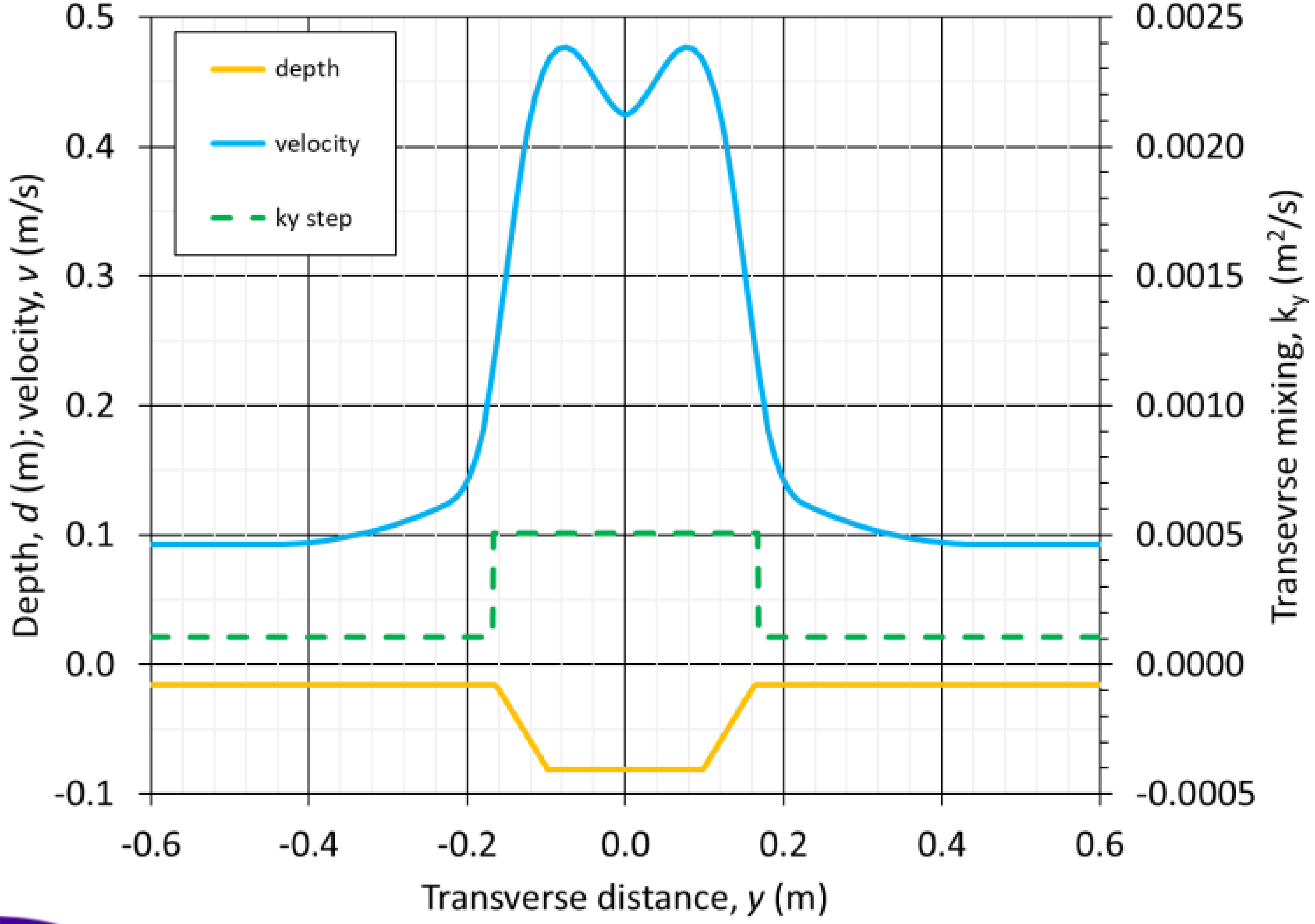
Spence, K.J., Sonnenwald, F.S. & Guymer, I. (**STILL** in preparation) "Spatial variation of transverse mixing in compound channels"

Compound Channels – transverse shear effects



- Spatial variation of transverse mixing, k_y
- Effect on longitudinal dispersion, D_x, evaluated using Chickwendu (1986)

	D_x (m^2/s)
Uniform	0.65
Step	4.30

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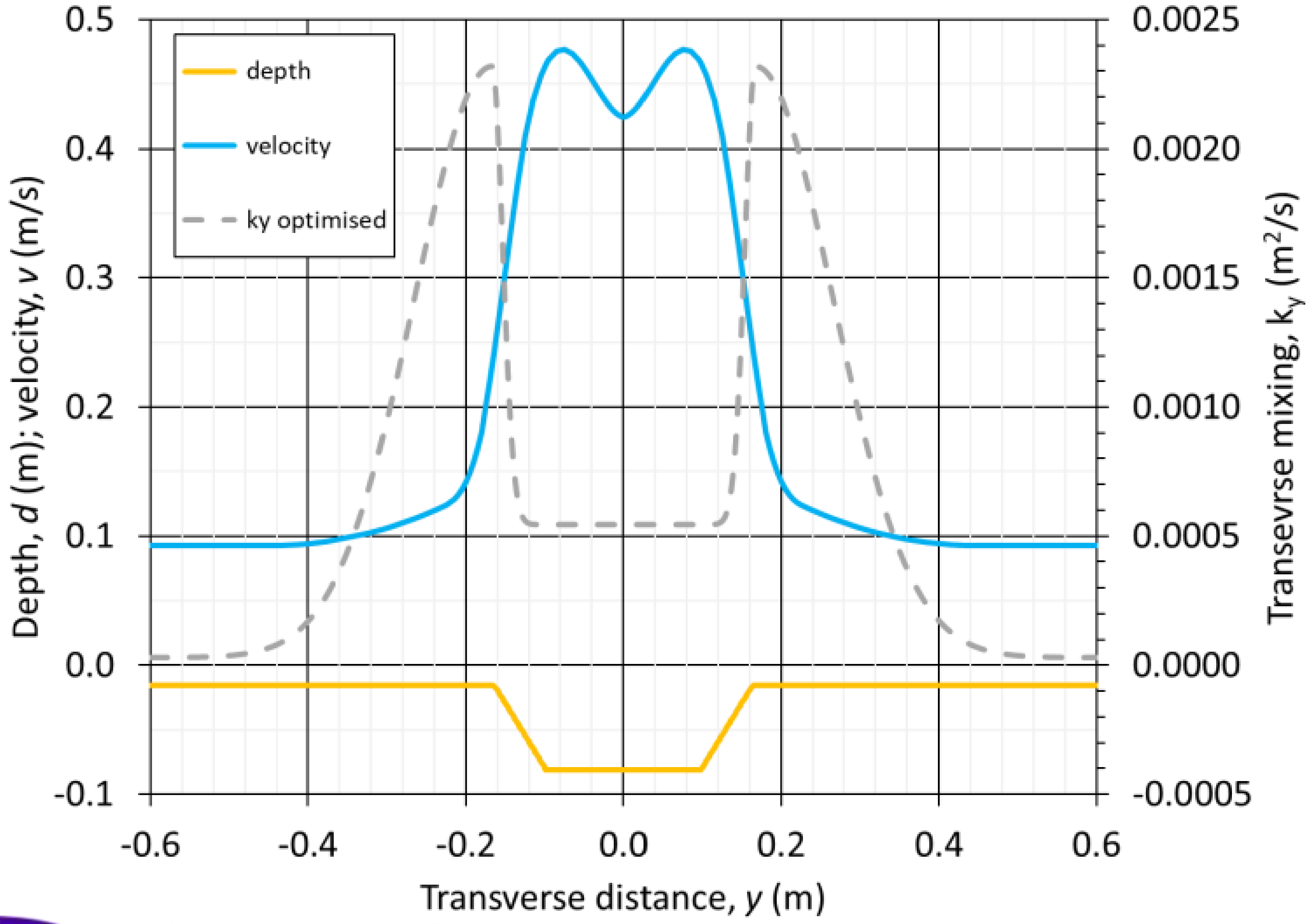
Compound Channels – transverse shear effects



- Spatial variation of transverse mixing, k_y
- Effect on longitudinal dispersion, D_x, evaluated using Chickwendu (1986)

	D_x (m^2/s)
Uniform	0.65
Step	4.30
Best fit	1.32

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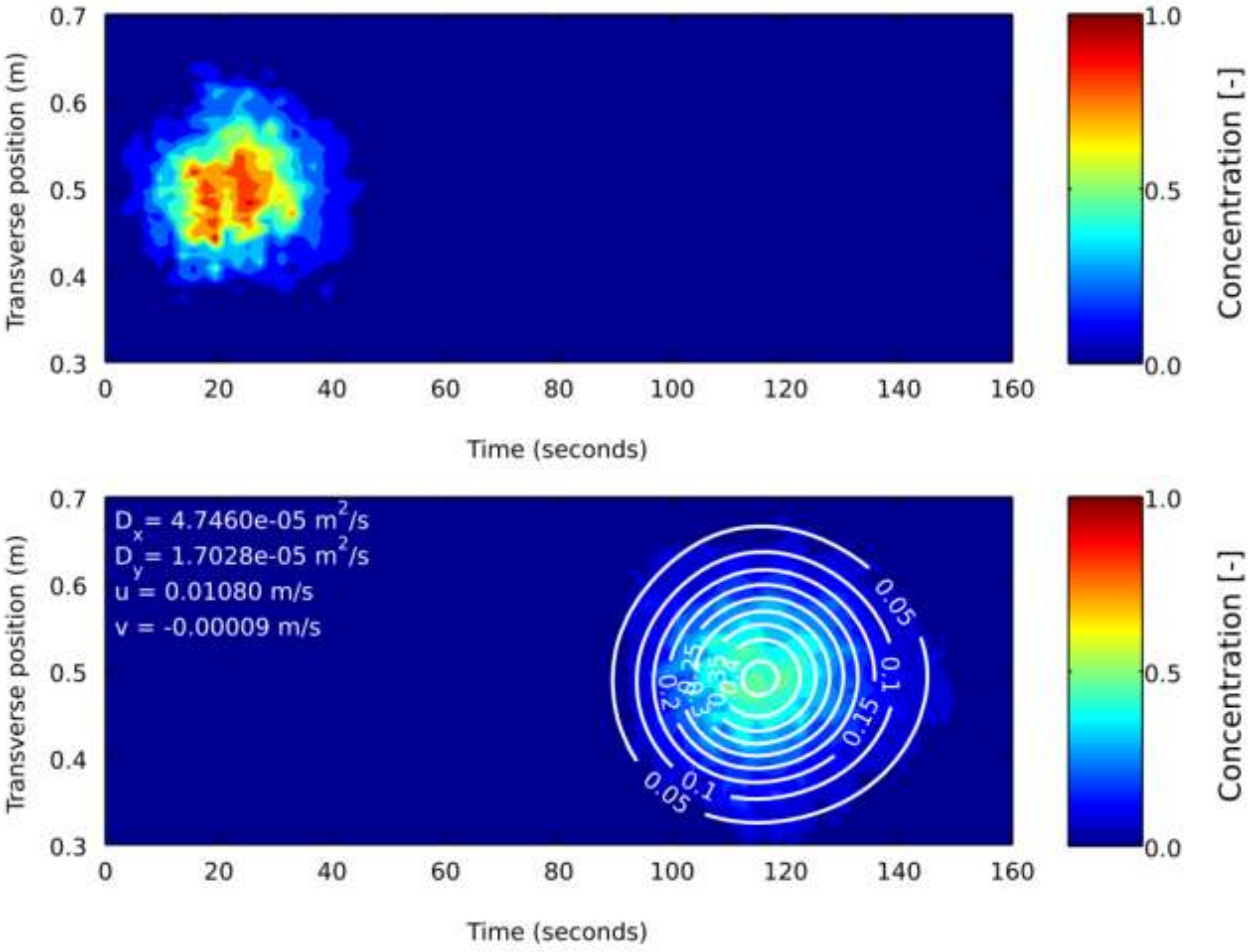
Spence, K.J., Sonnenwald, F.S. & Guymer, I. (**STILL** in preparation) “Spatial variation of transverse mixing in compound channels”

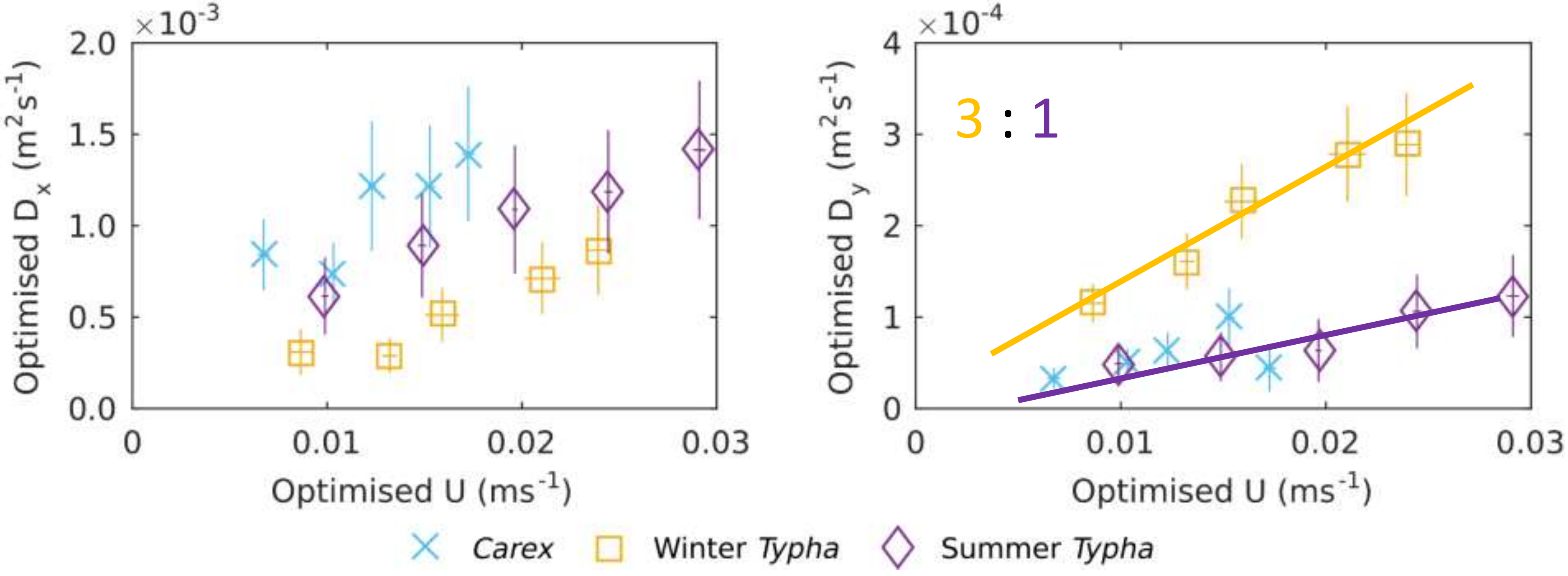
Real Vegetation - Laboratory studies



Simultaneous determination of longitudinal and transverse mixing

Sonnenwald, F., Hart, J.R., West, P., Stovin, V.R. and Guymer, I. (2017) “Transverse and longitudinal mixing in real emergent vegetation at low velocities” *Water Resources Research*

Real Vegetation - Results



- D_x similar trends, slightly different magnitudes
- Winter Typha exhibits greater transverse mixing

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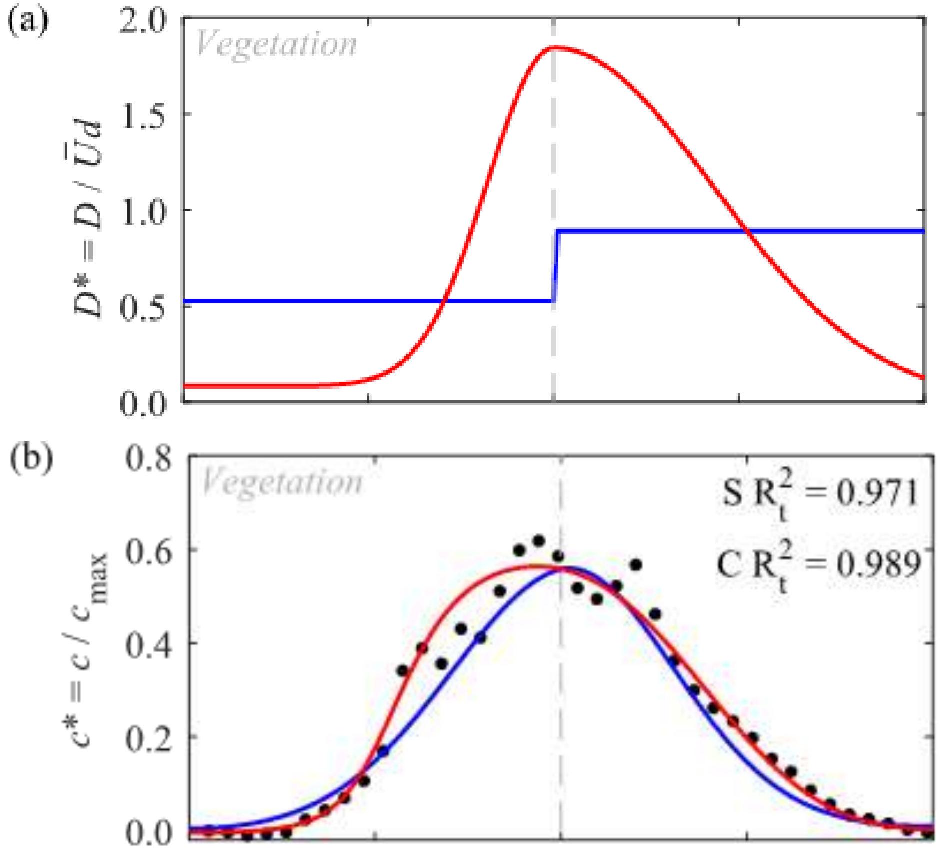
Sonnenwald, F., Hart, J.R., West, P., Stovin, V.R. and Guymer, I. (2017) “Transverse and longitudinal mixing in real emergent vegetation at low velocities” *Water Resources Research*

Partial Vegetation – transverse shear effects



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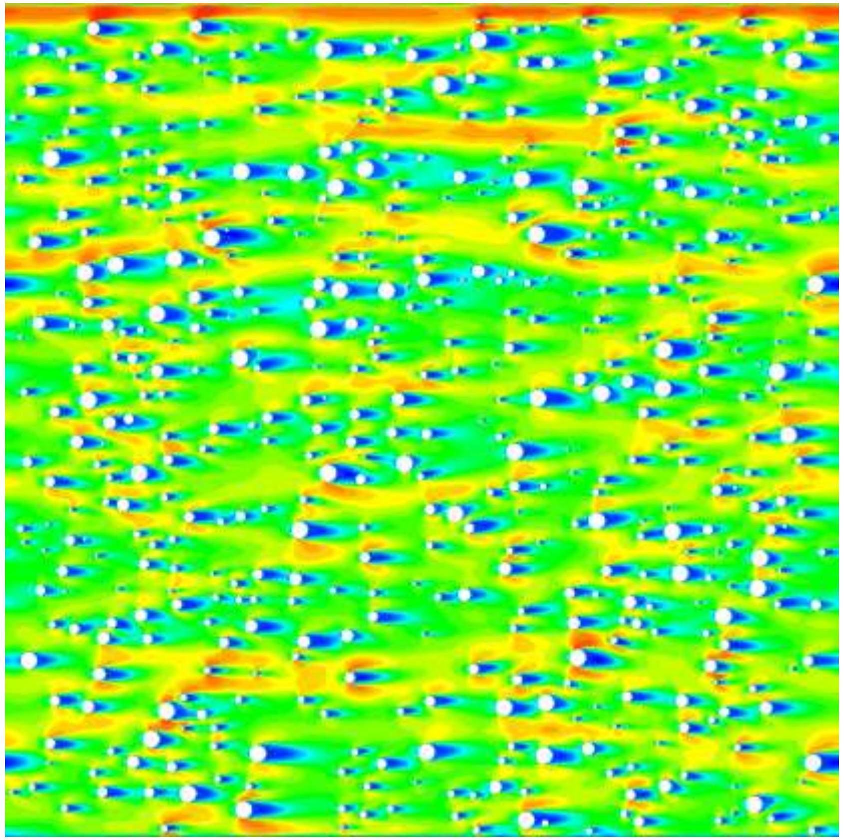
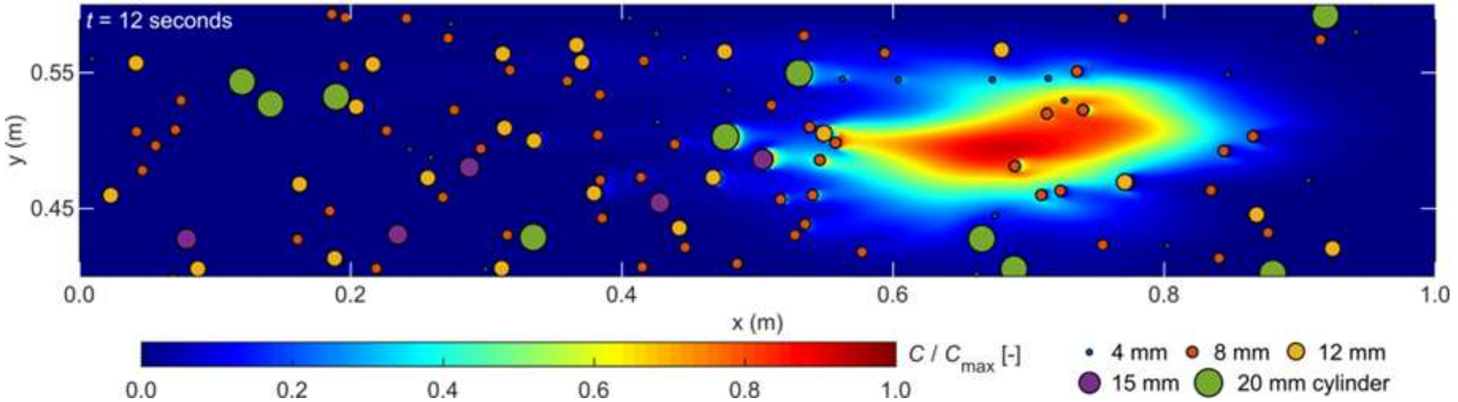
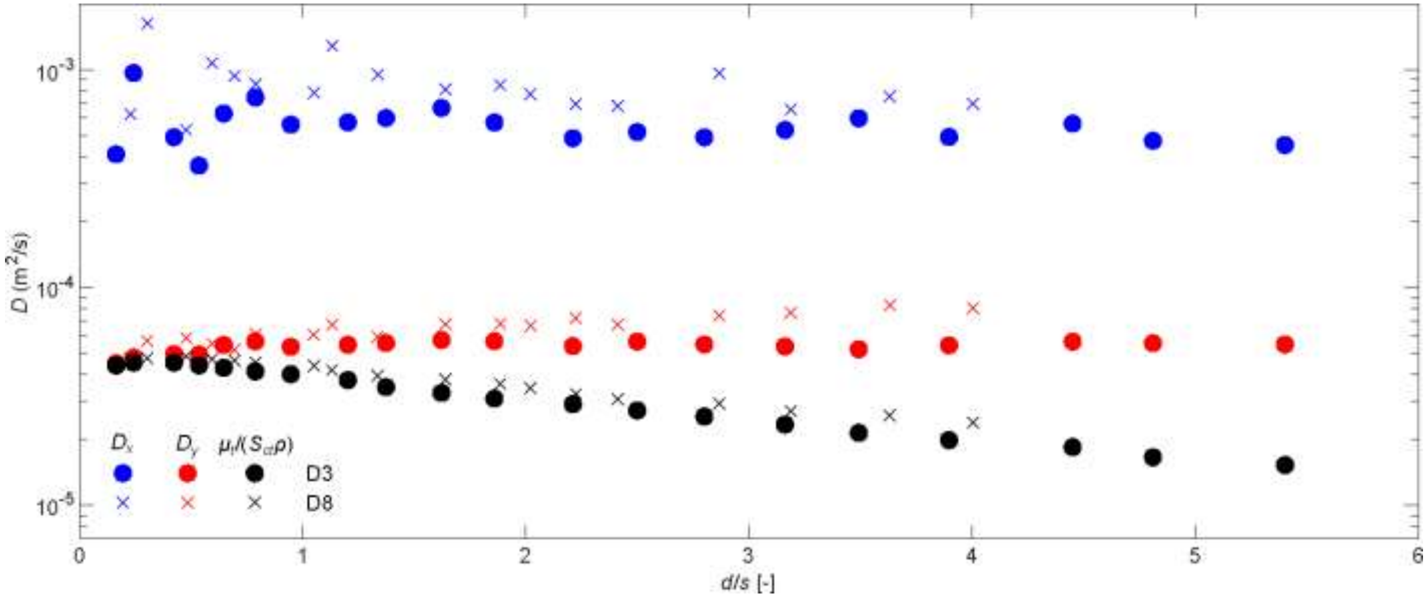
West, P.O., Wallis, S.G., Sonnenwald, F.C., Hart, J.R., Stovin, V.R., & Guymer, I. (2020). Modelling transverse solute mixing across a vegetation generated shear layer. *Journal of Hydraulic Research*

Artificial Emergent Vegetation – CFD study “RandoSticks”







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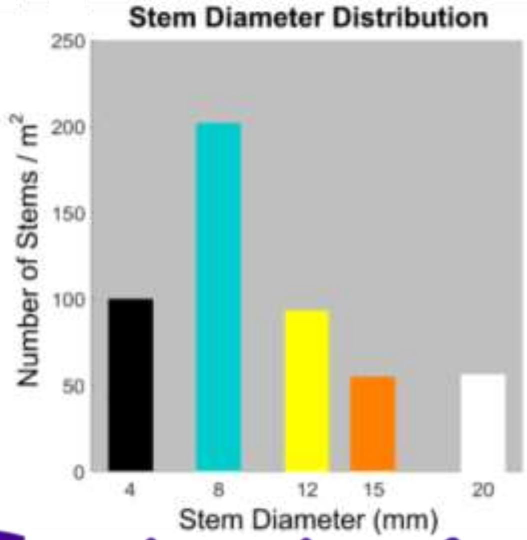
Stovin, V.R., Sonnenwald, F., Golzar, M., & Guymer, I. (2022). The impact of cylinder diameter distribution on longitudinal and transverse dispersion within random cylinder arrays. Water Resources Research, 58

RandoSticks - Laboratory System

RandoSticks morphology
Winter *Typha latifolia*



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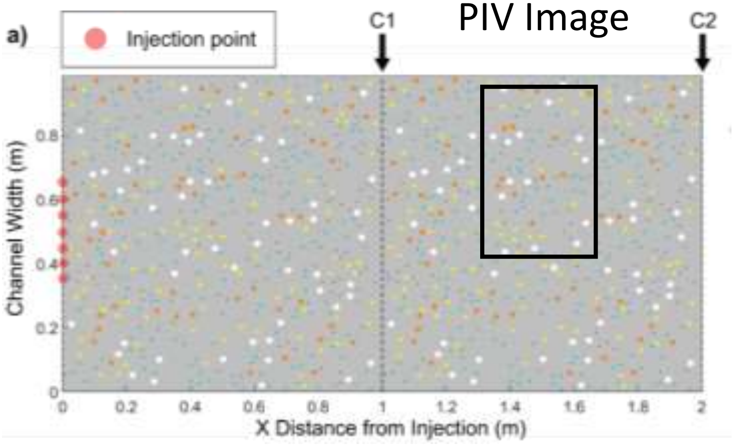
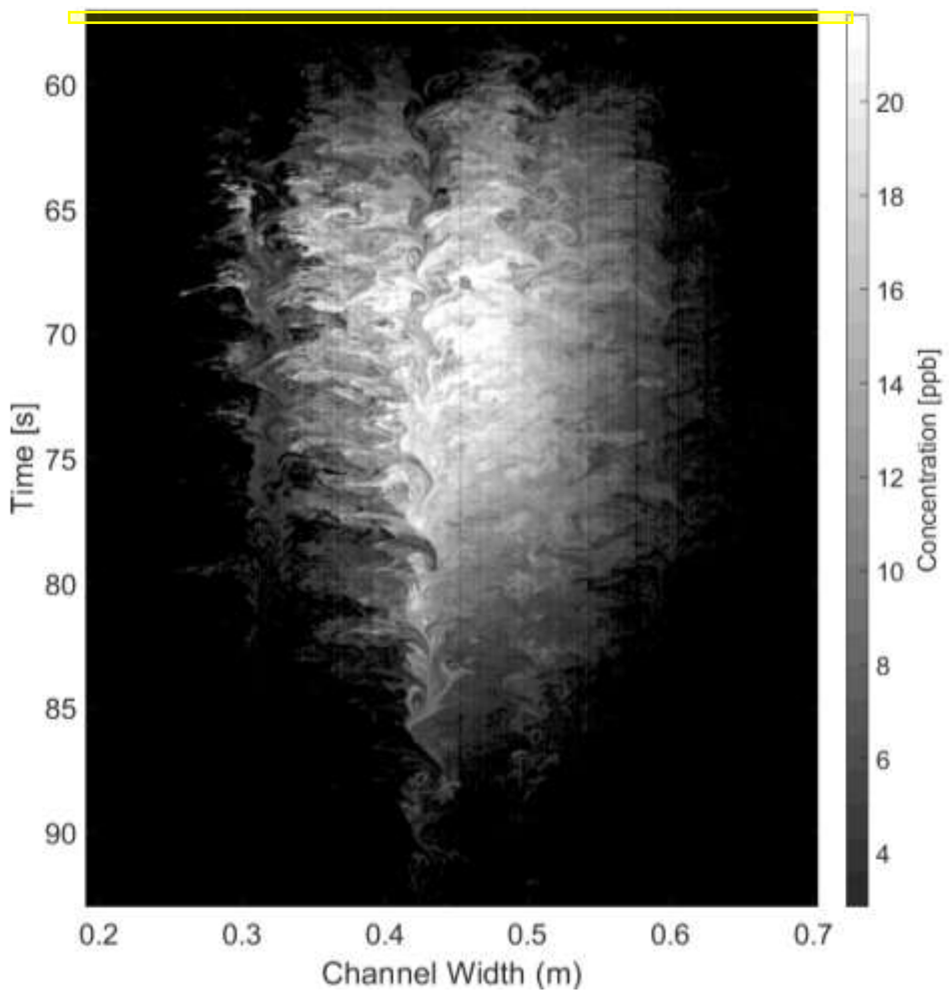
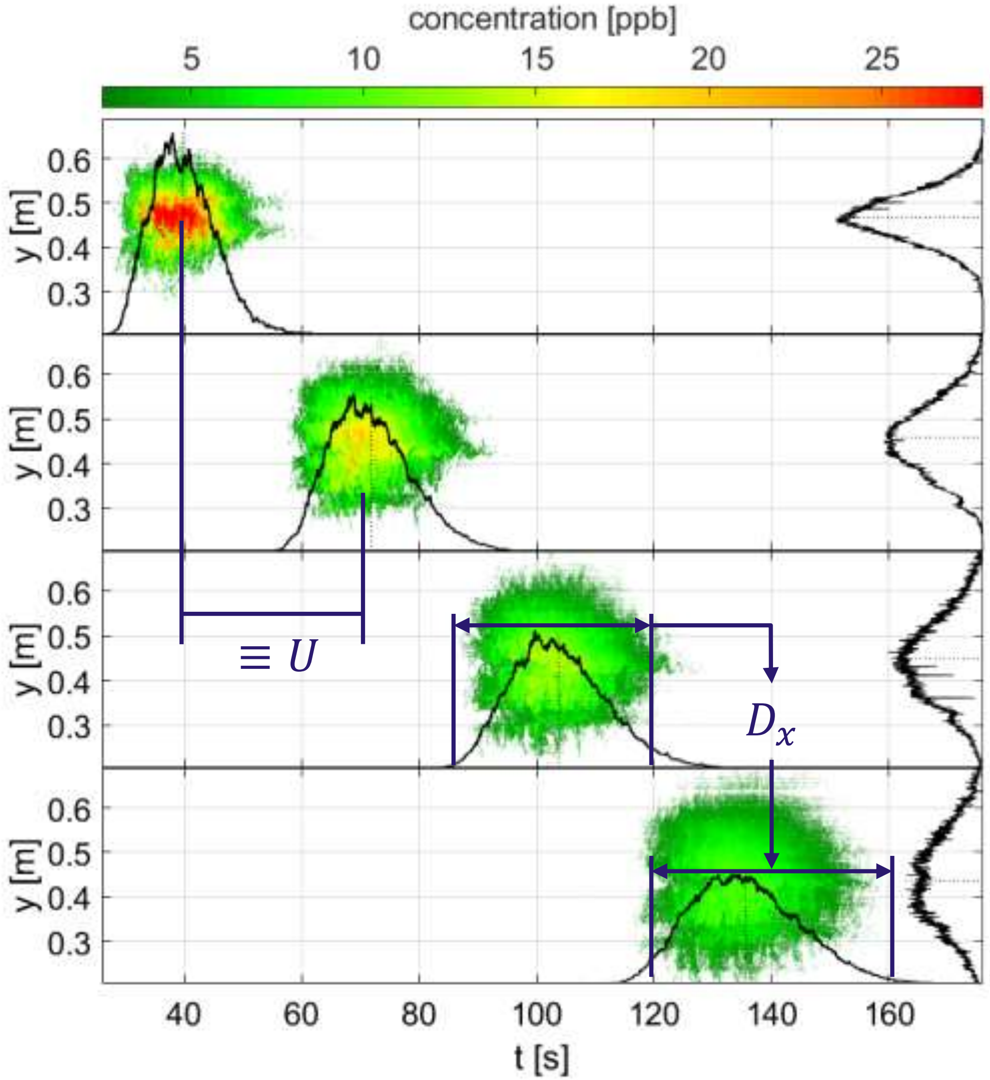
RandoSticks Layout
1.0 m x 1.0 m over 9 m



Optical System
LIF & PIV

Laser Induced Fluorescence - Experiments





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Current laboratory study Dr Jesús Leonardo Corredor García

LIF Results

- Comprehensive Re_d range for cylinder flows $40 < Re_d < 1200$
  - Laminar flow (no shedding)
  - Vortex street
  - Transition to turbulence
- Solid volume fraction $\varphi = 0.05$
- 3 reaches & 3 injection locations
- D_x and D_y proportional to Re_d
- Increases in advection, turbulence and shear contribute to mixing.

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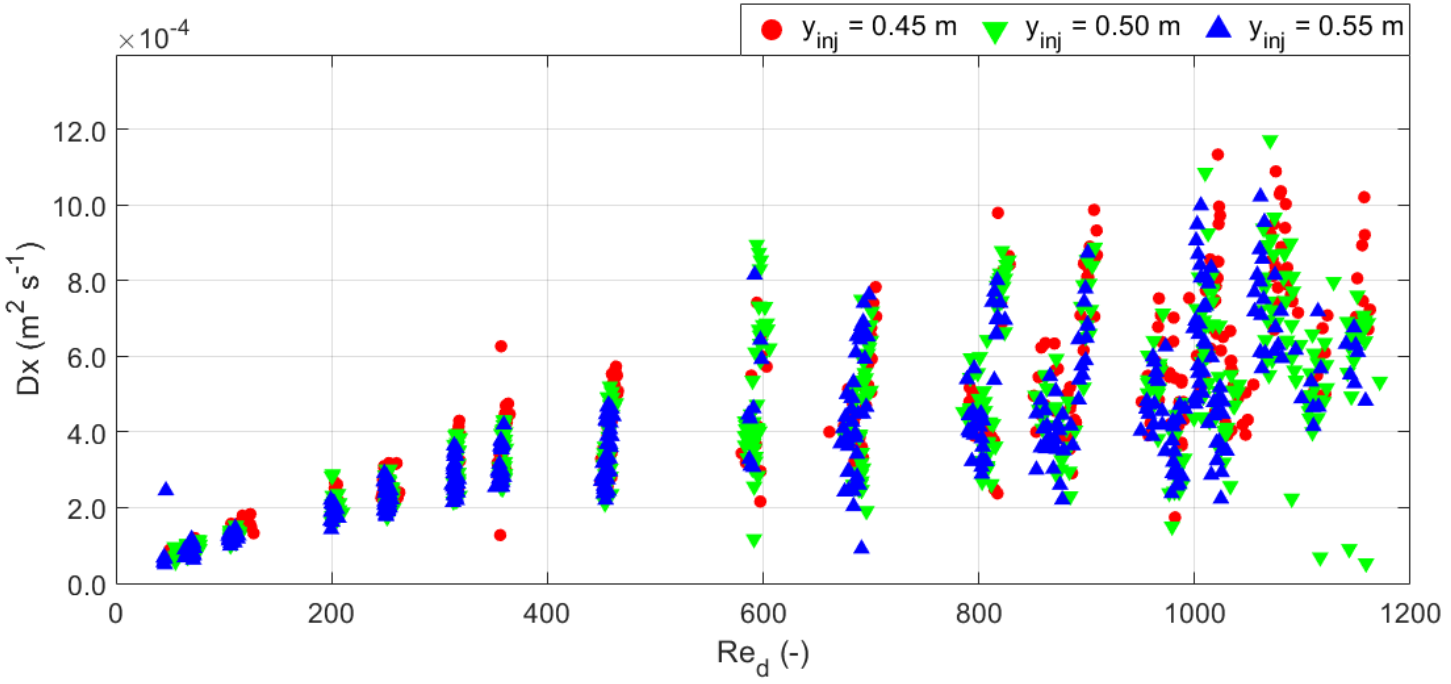
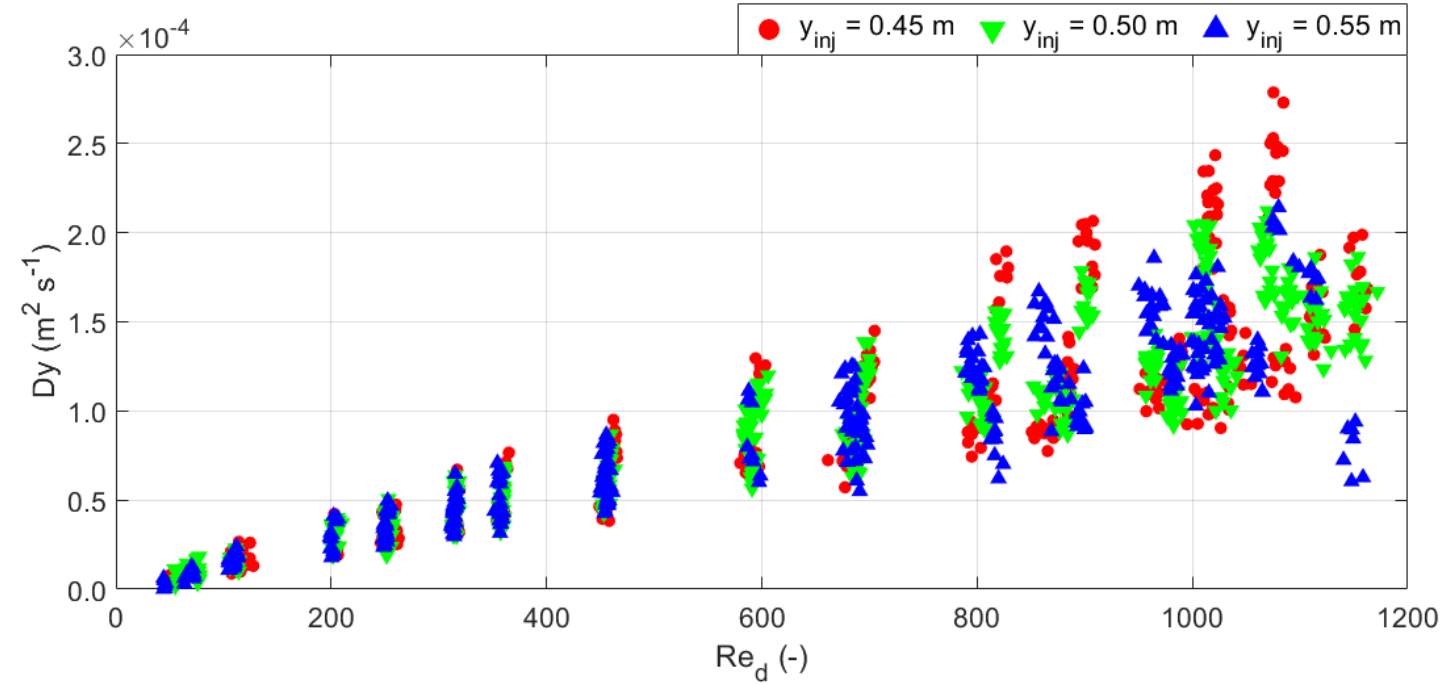
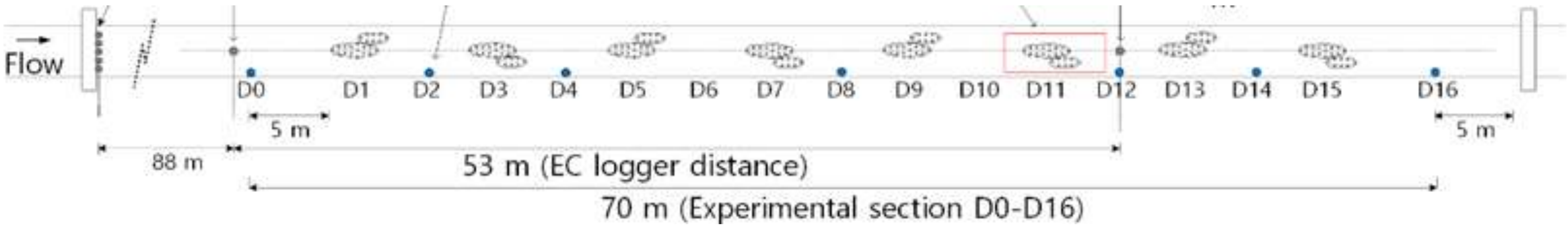




Longitudinal Dispersion with Willow Patches

@ KICT - REC (River Experiment Center)



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Västilä, K., Oh, J., Sonnenwald, F., Ji, U., Järvelä, J., Bae, I., & Guymer, I. (2022). Longitudinal dispersion affected by willow patches of low areal coverage. Hydrological Processes, 36(6), e14613. https://doi.org/10.1002/hyp.14613

Longitudinal Dispersion with Willow Patches

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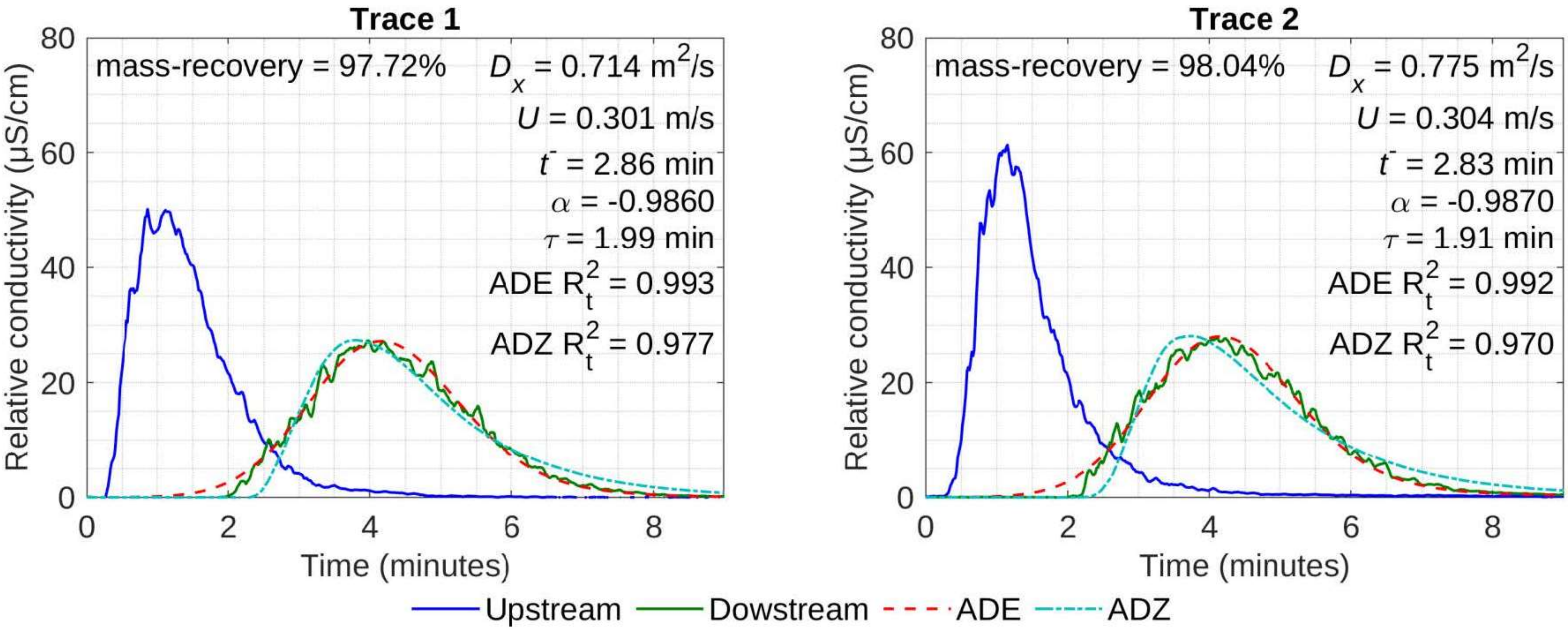

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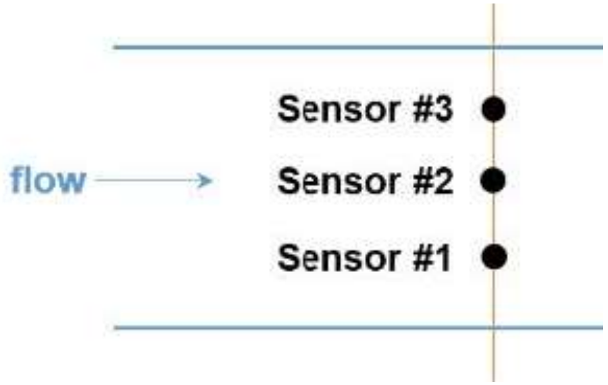
Longitudinal Dispersion with Willow Patches

@ KICT - REC (River Experiment Center)

Baseline



No vegetation

Differential advection

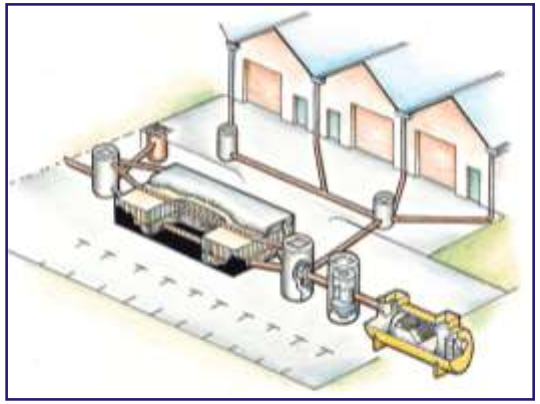
& turbulent mixing

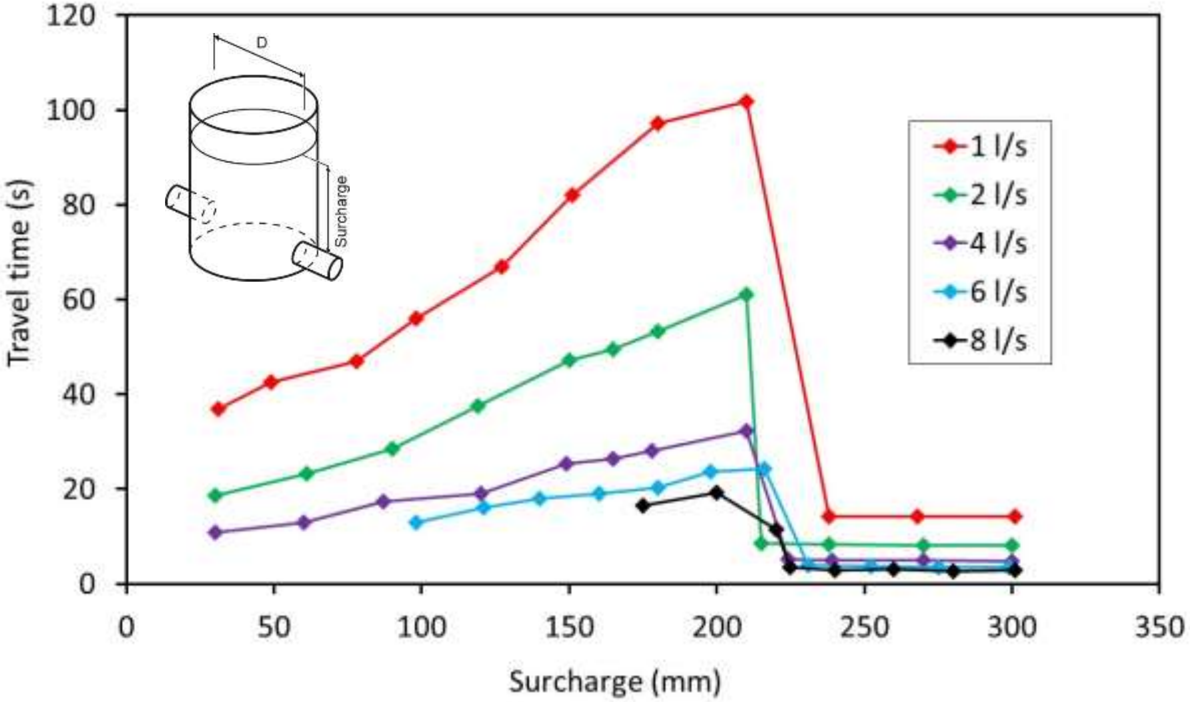
D_x

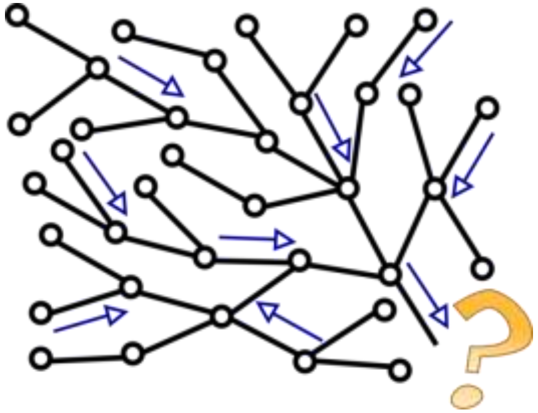
Västilä, K., Oh, J., Sonnenwald, F., Ji, U., Järvelä, J., Bae, I., & Guymer, I. (2022). Longitudinal dispersion affected by willow patches of low areal coverage. Hydrological Processes, 36(6), e14613. https://doi.org/10.1002/hyp.14613

Urban Drainage Systems

Effects of changes in shape, e.g. manholes







Commercial models employ either advection only (no mixing) or complete instantaneous mixing

Guymer, I and O'Brien, R.T. (2000) "Longitudinal Dispersion due to Surcharged Manhole", ASCE Journal Hydraulic Engineering, 126(2), 137-149.

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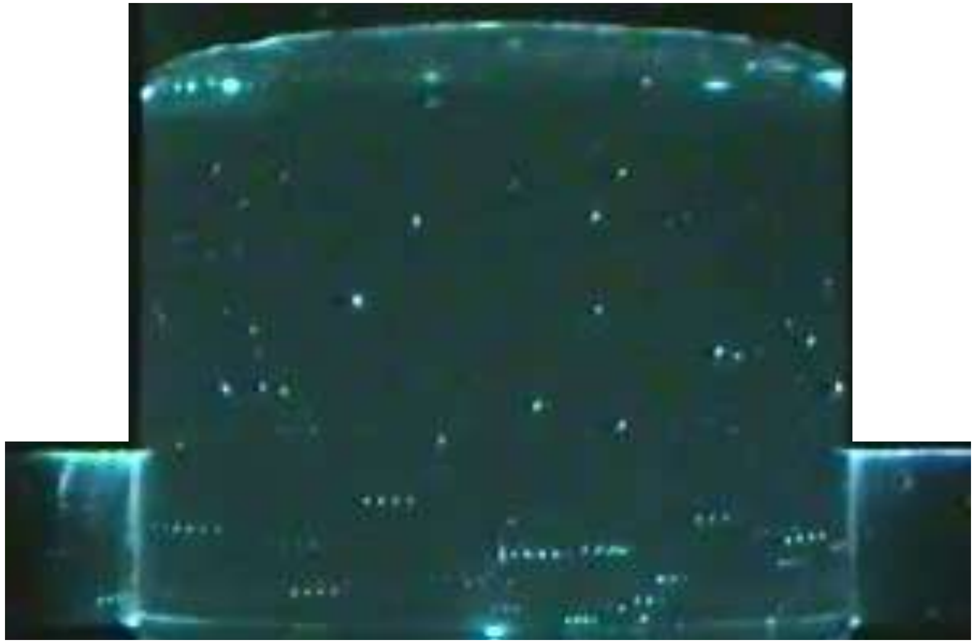
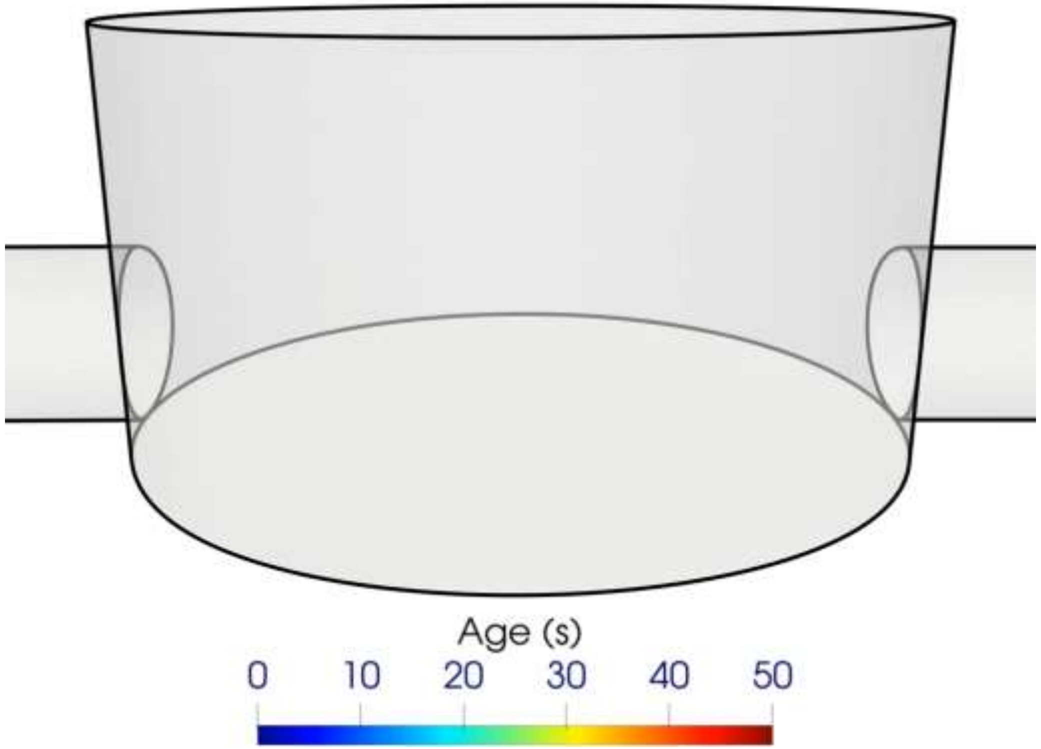
Mixing in Surcharged Manholes





Complex 3D flow paths

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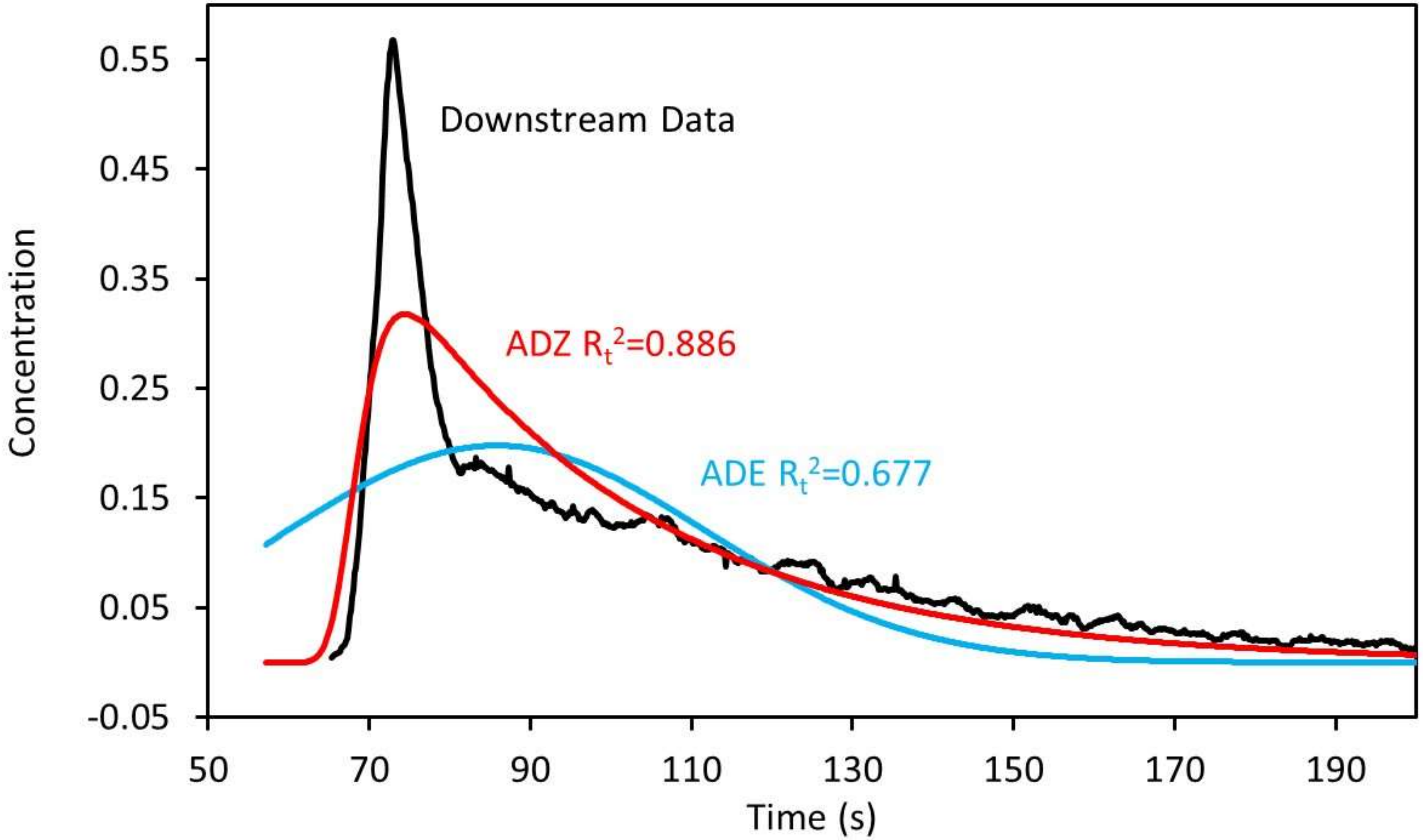
Manhole Mixing – ADE & ADZ model predictions



- Application of 2 parameter mixing models
- *That prediction is … poor !!!!*
- *What about a unit hydrograph type approach?*

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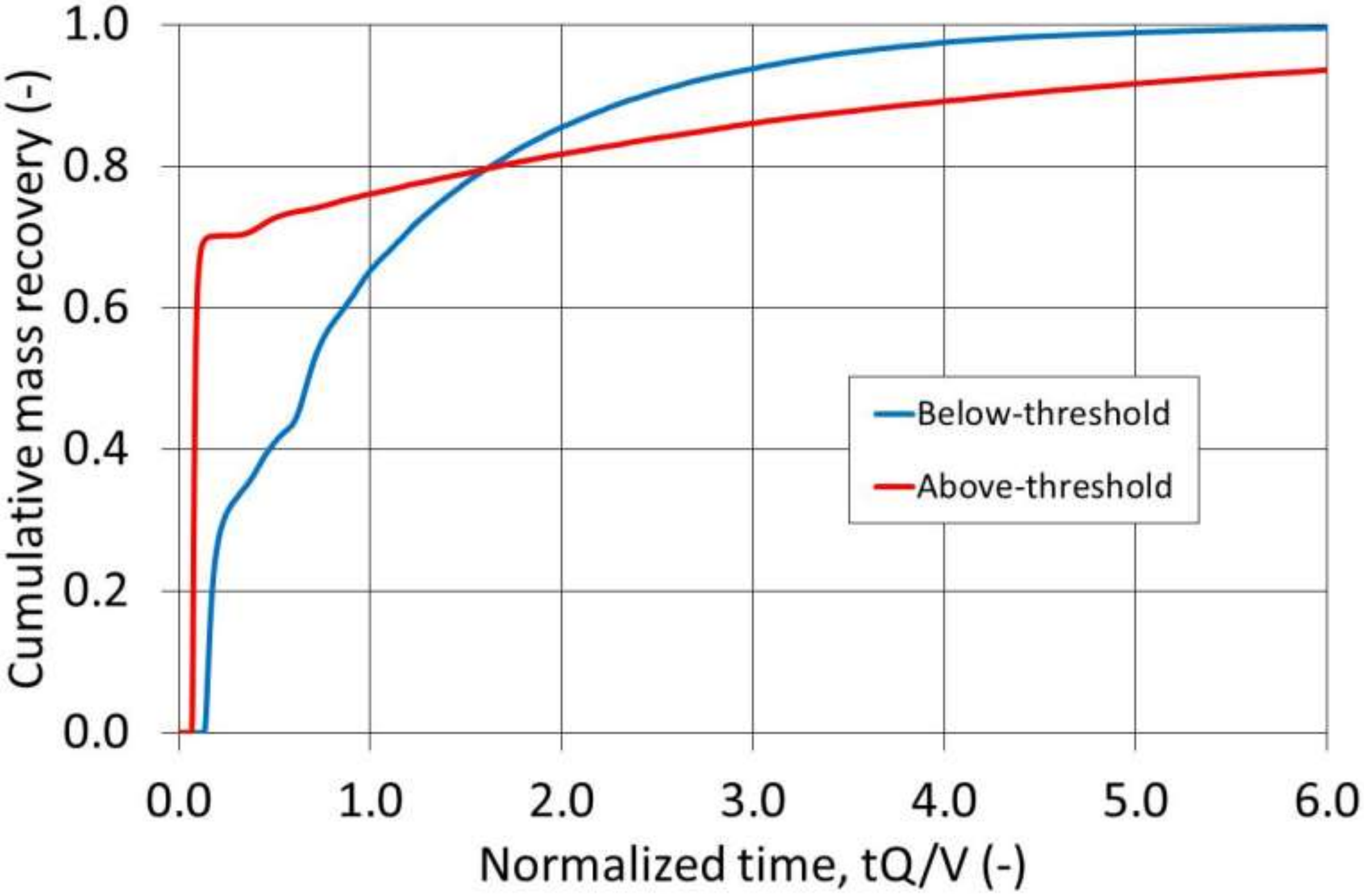
Guymer, I and O'Brien, R.T. (2000) "Longitudinal Dispersion due to Surcharged Manhole", ASCE Journal Hydraulic Engineering, 126(2), 137-149.

Manholes – Non-dimensional CRTD



- for large $Ø_m$:$Ø_p$ ratio surcharged circular manholes
- deconvolution of laboratory trace data
- mixing can be characterised by just two dimensionless CRTDs

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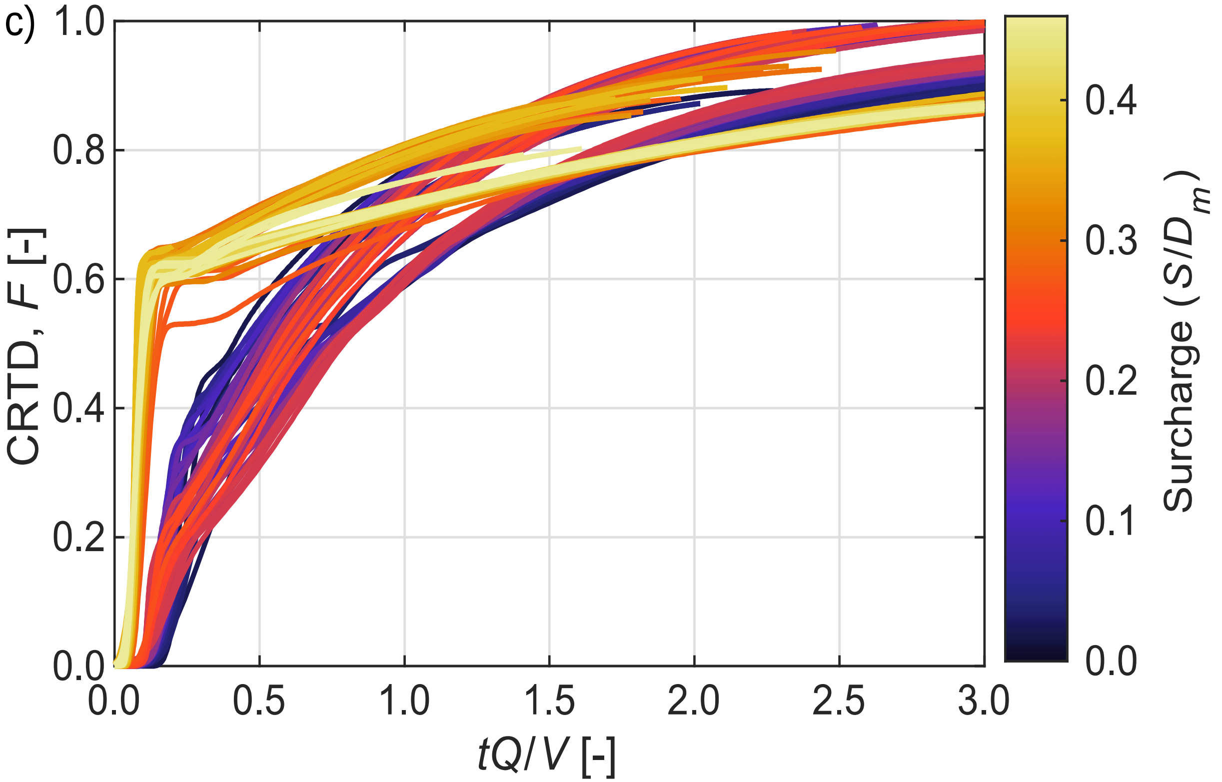
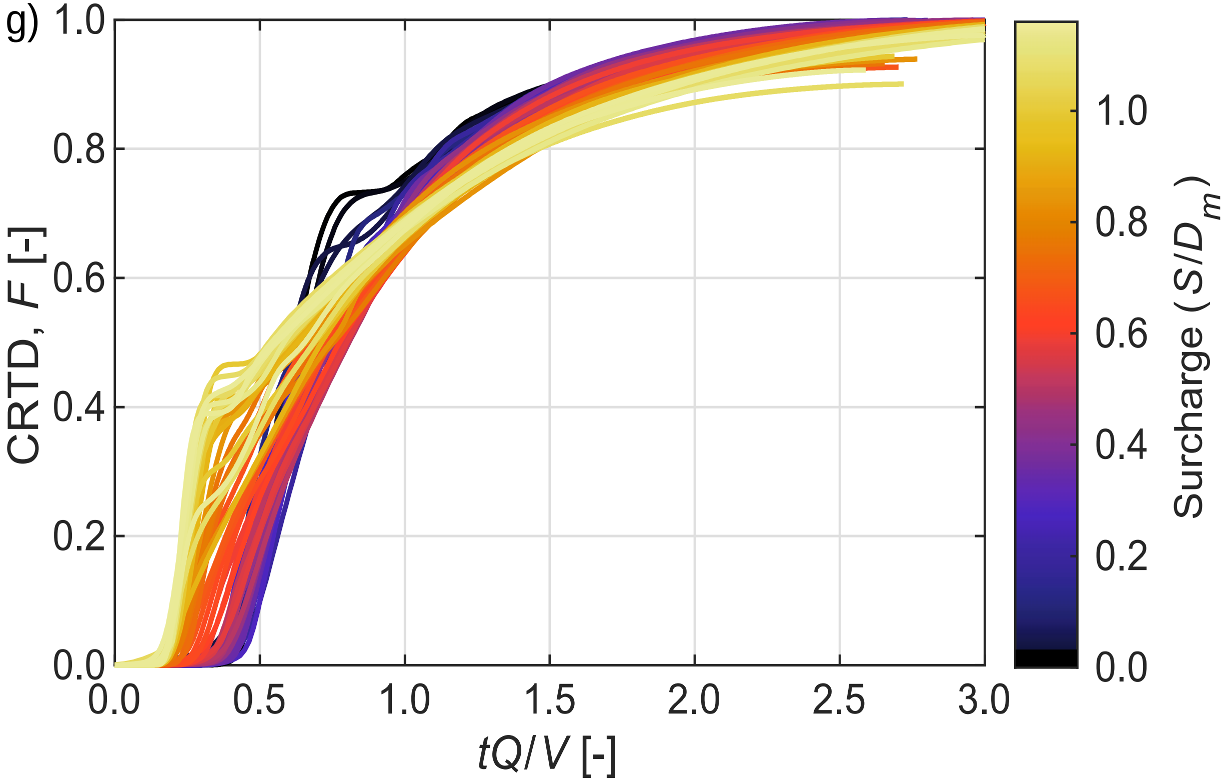
Guymer, I. & Stovin, V.R. (2011) "A 1D mixing model for surcharged manholes" ASCE, J. Hydraulic Engineering, 137(10), 1160-1172.

Experimental Deconvolved CRTDs



c) straight-through Dm/Dp = 9.1



g) 90° angled outlet manholes

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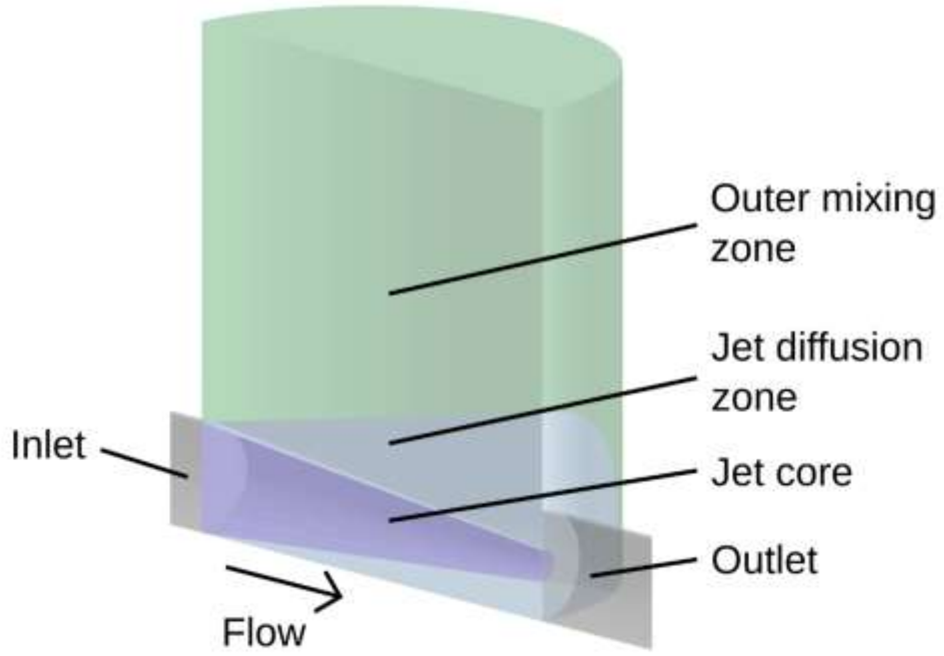
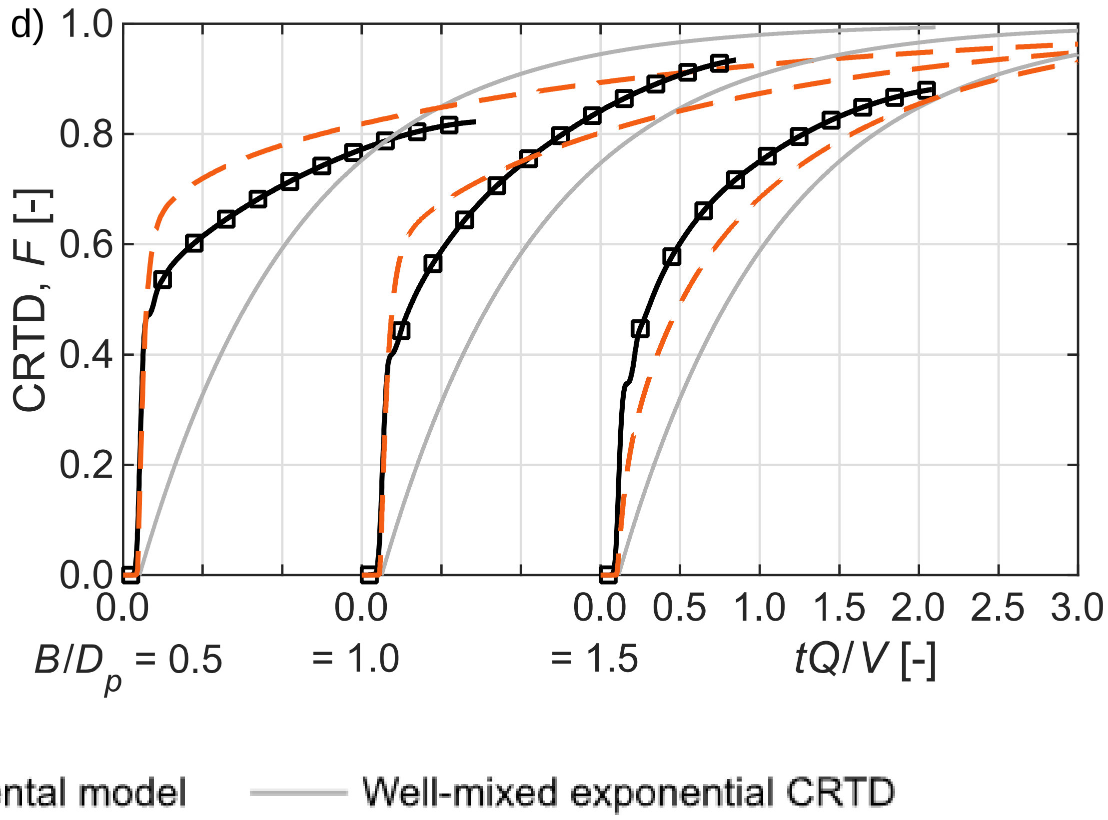
Comprehensive data set for different manhole:pipe diameters; flow rates; surcharge depths; outlet angles and step heights

Compartmental “Jet Mixing” Model





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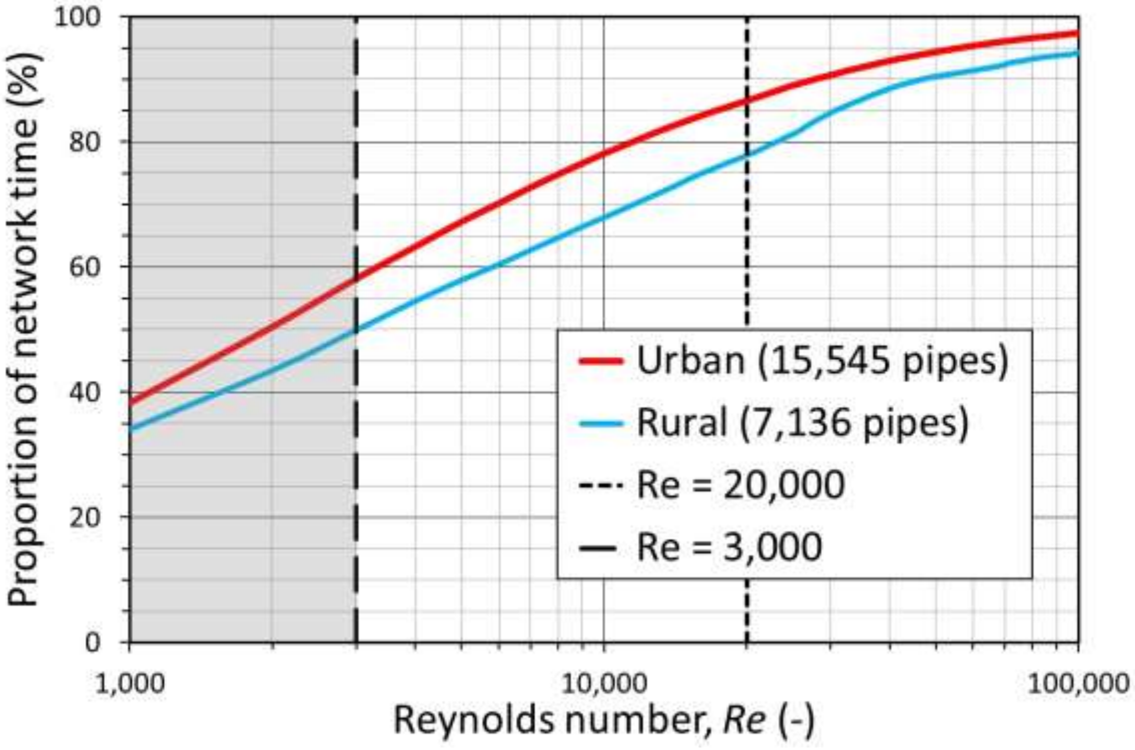
Sonnenwald, F., Mark, O., Stovin, V., & Guymer, I. (2021). Predicting manhole mixing using a compartmental model. Journal of Hydraulic Engineering, 147(12), 04021046.

Pipe flows - challenge and context

- In drinking water distribution systems, numerous lengths have laminar flow for long durations
- In buildings flows are mainly stationary or laminar
- Do we have the tools to model laminar and unsteady flows?
- In laminar flow *"Given sufficient time"*

  $t > 0.5a^2/D_m$ for 15 mm diameter pipe $t > 8$ hrs



- How do we know "the time in the flow"?
- If Taylor/Gaussian RTD is not applicable, then what?
- Challenges of unsteady flows

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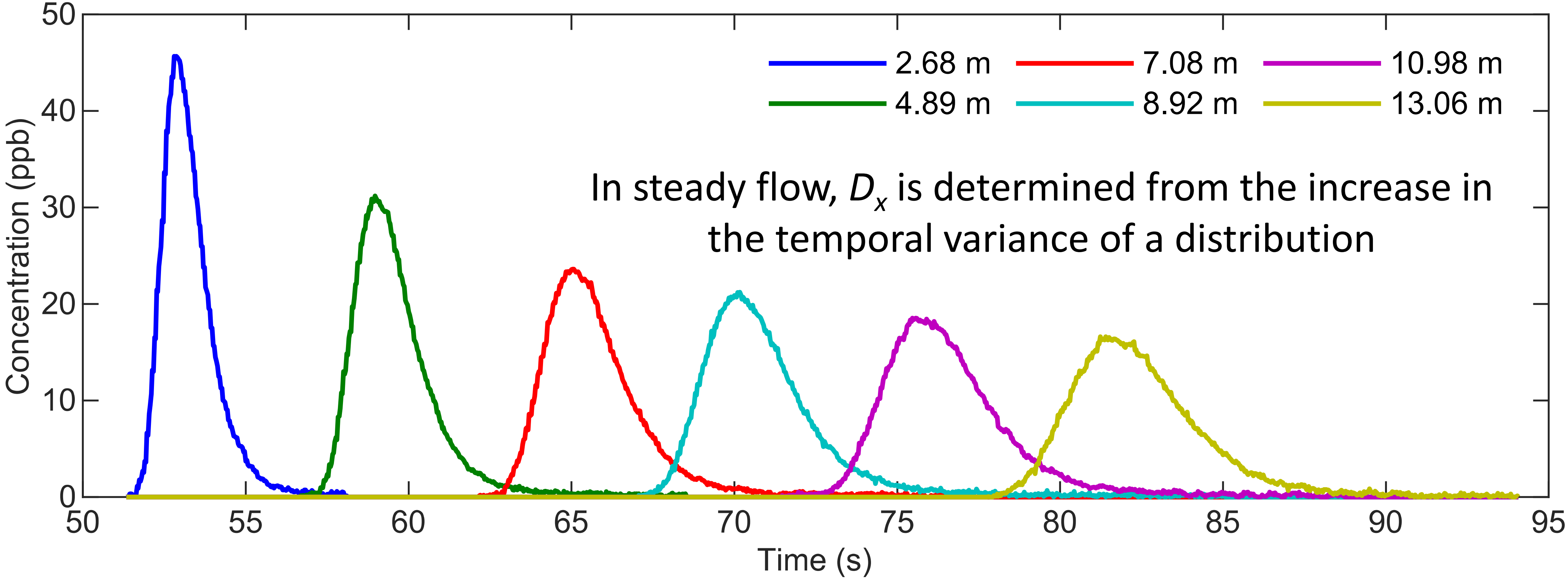
Longitudinal Dispersion in Pipes



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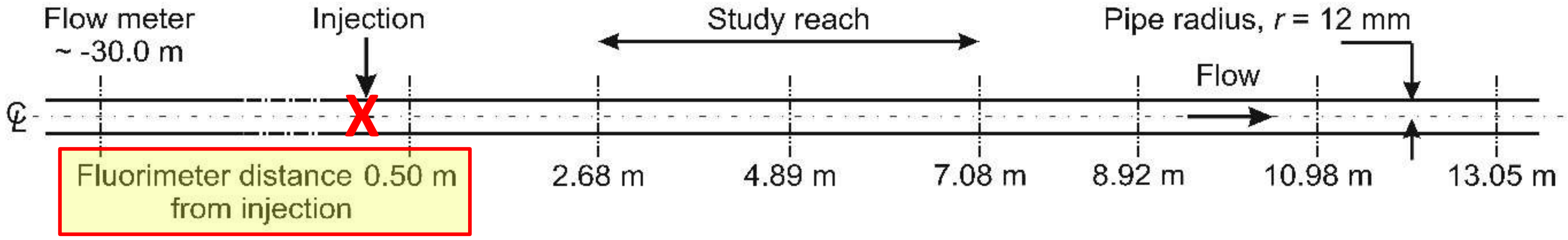
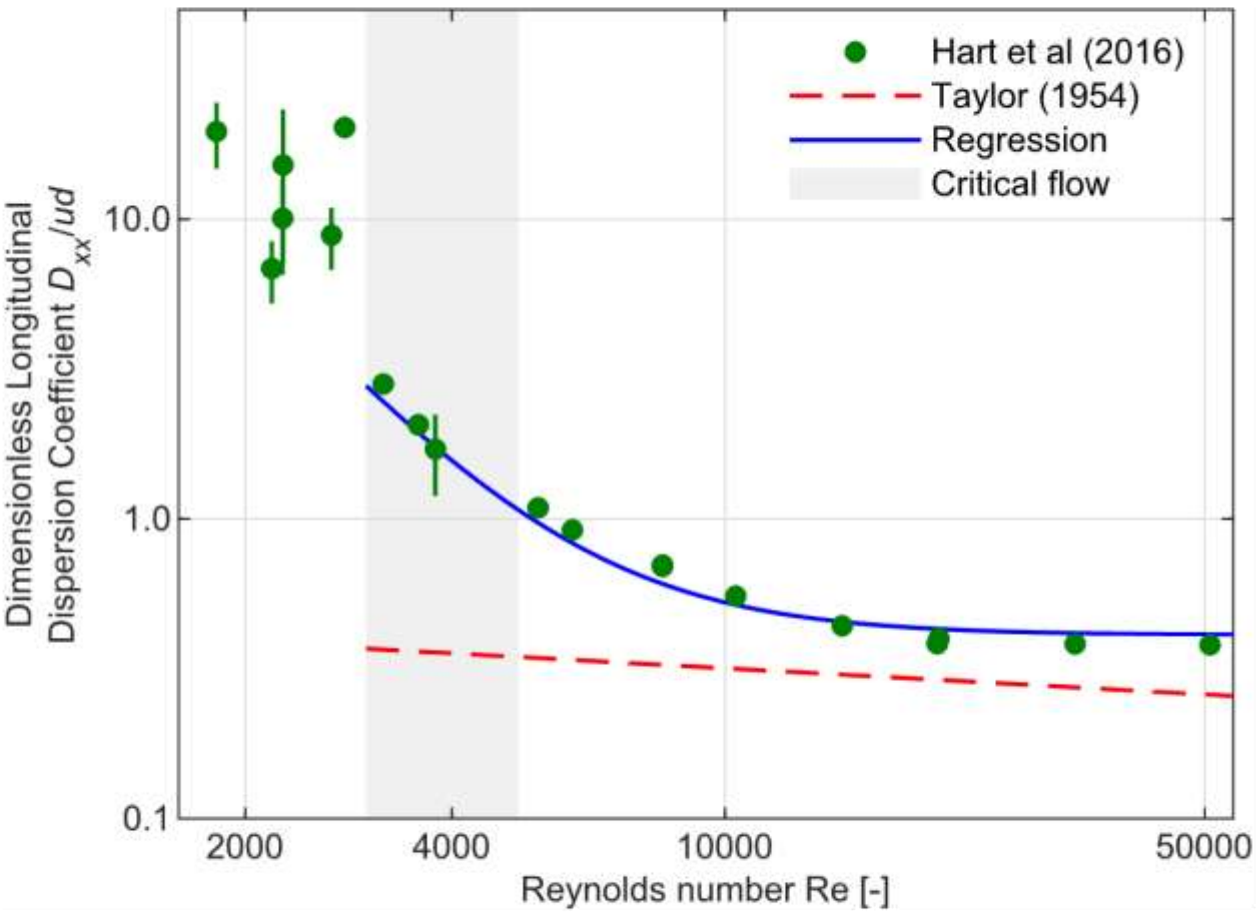


Longitudinal Dispersion in pipes – steady flow



- Longitudinal dispersion coefficient deviates from Taylor prediction for Re < 10,000, due to boundary shear effect
- For transitional and turbulent flow the RTD is Gaussian shape
- In laminar flow, Gaussian if

  $t > 0.5a^2/D_m$

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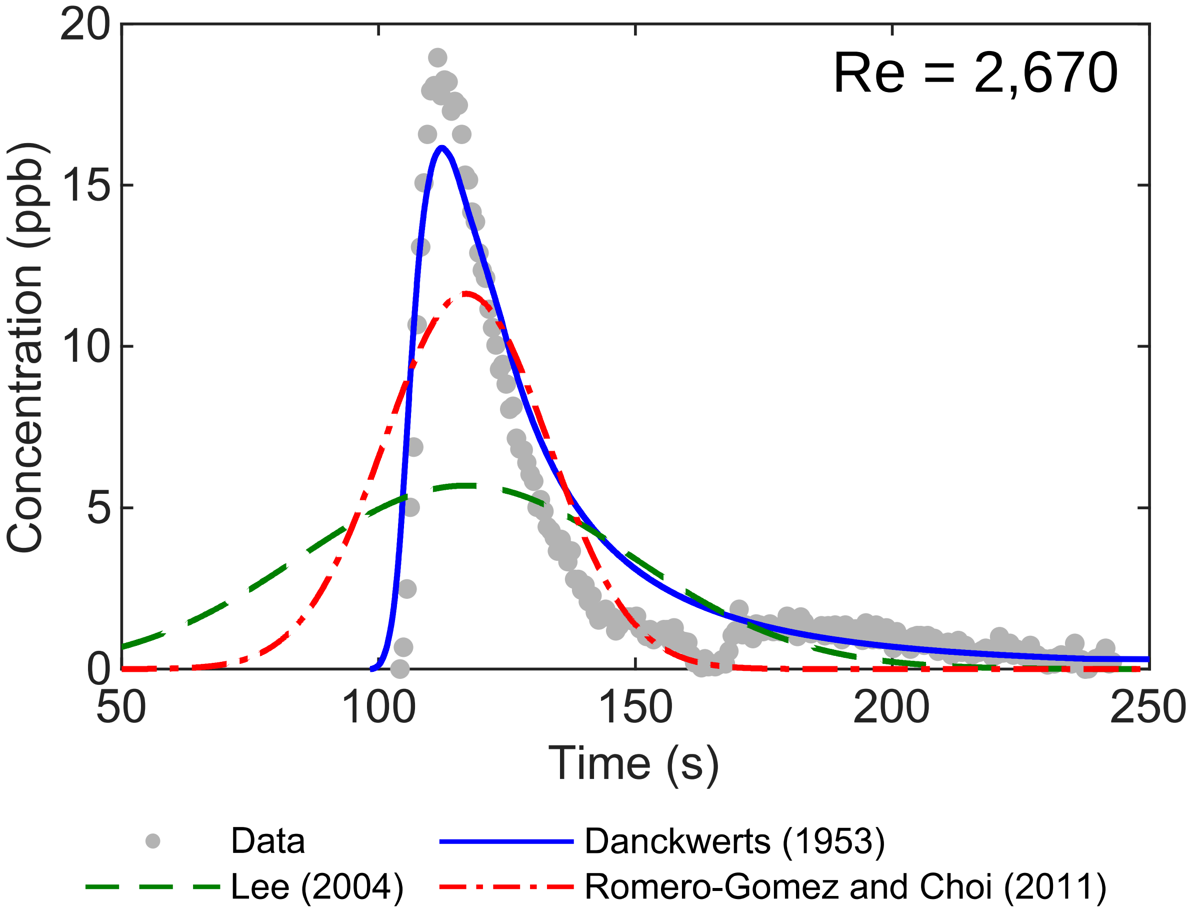
Hart, J.R., Guymer, I., Sonnenwald, F. and Stovin, V.R. (2016) "Residence Time Distributions for Turbulent, Critical and Laminar Pipe Flow" ASCE J. of Hydraulic Eng.

Application to Laminar Flow



- Predictions made from upstream data recorded 4.89 m from injection
- Compared to data 8.17 m further downstream

Predictions using:

i) Modified Gaussian

Lee (2004)

Romero-Gomez and Choi (2011)

ii) Laminar velocity profile RTD

Danckwerts (1953)

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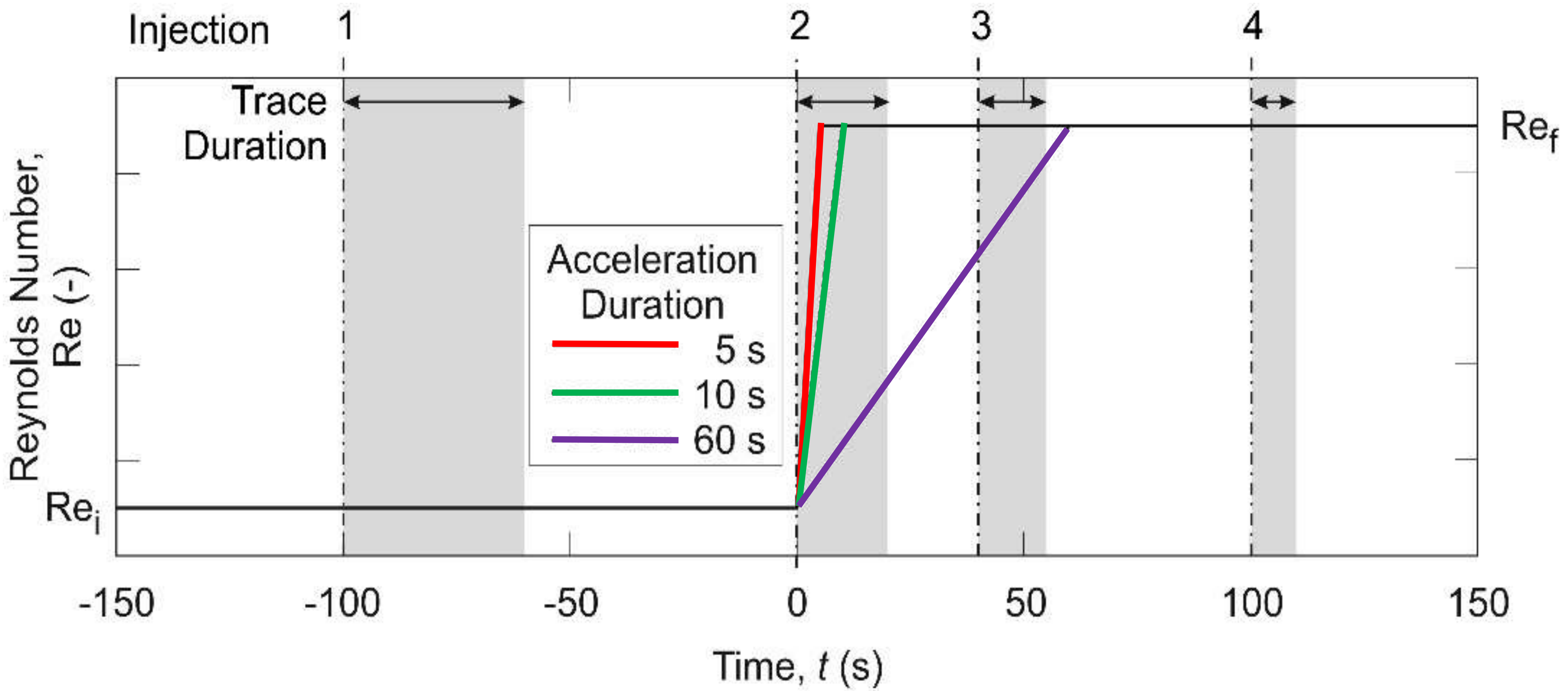
Hart, J.R., Guymer, I., Sonnenwald, F. and Stovin, V.R. (2016) “Residence Time Distributions for Turbulent, Critical and Laminar Pipe Flow” ASCE J. of Hydraulic Eng.

Longitudinal Dispersion in Pipes for Unsteady Flow



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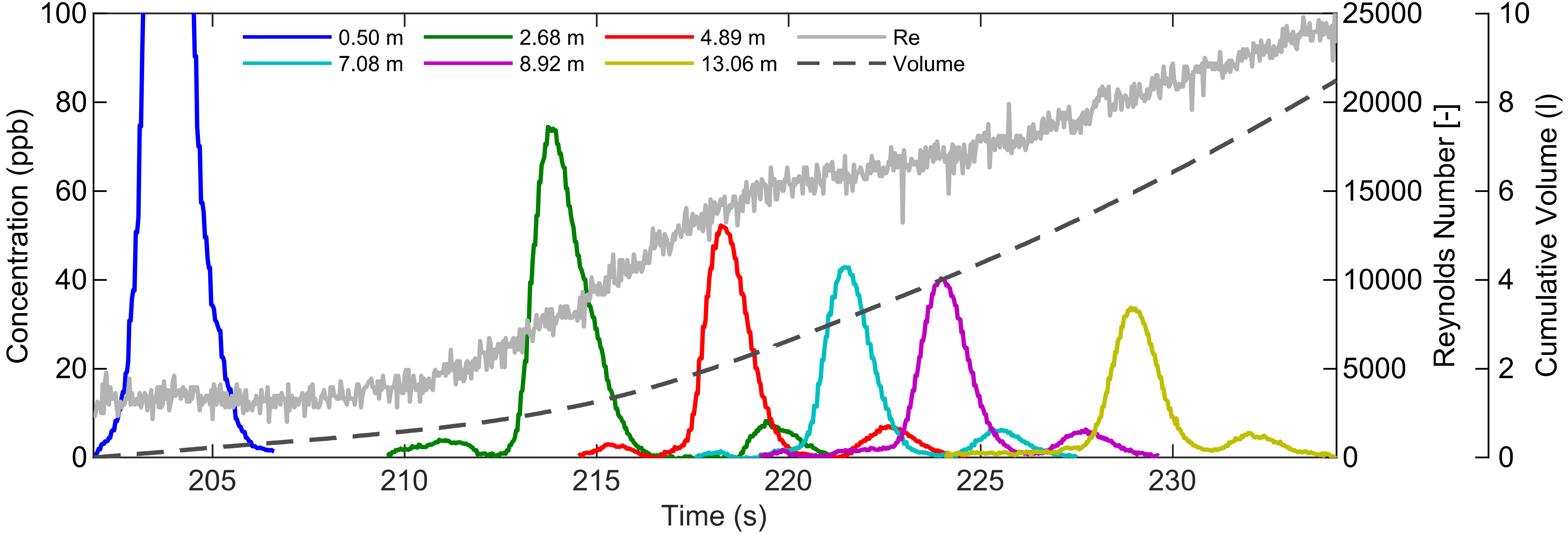
Hart, J., Sonnenwald, F., Stovin, V.R. & Guymer, I. (2021) Longitudinal Dispersion in Unsteady Pipe Flows. ASCE J. Hydraulic Engineering, 147(9)

Laminar to Turbulent Accelerating Flow



- Note the disaggregation of the tracer between 0.5 m and 2.68 m

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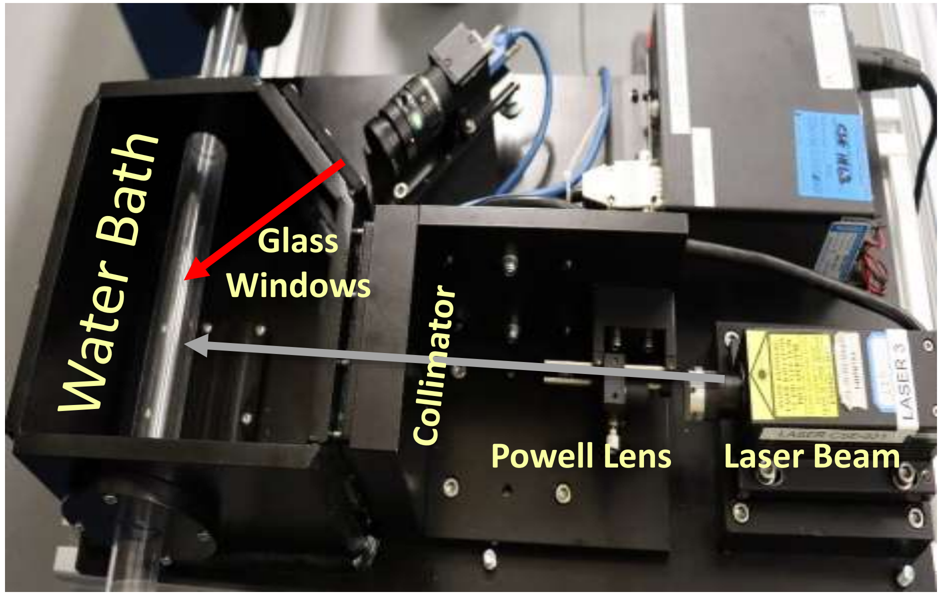
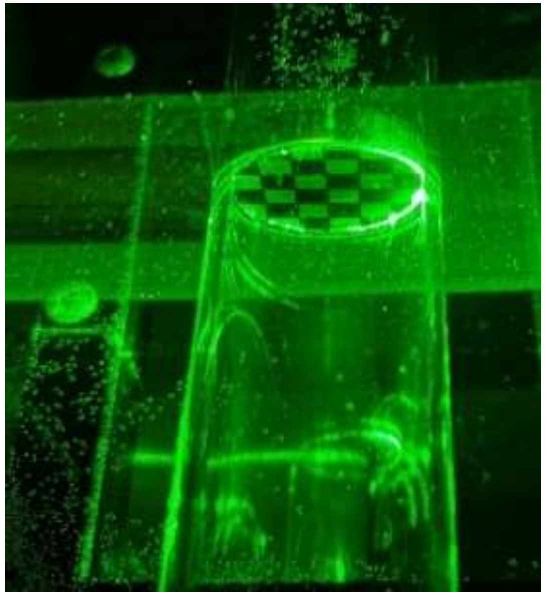
Hart, J., Sonnenwald, F., Stovin, V.R. & Guymer, I. (2021) Longitudinal Dispersion in Unsteady Pipe Flows. ASCE J. Hydraulic Engineering, 147(9)

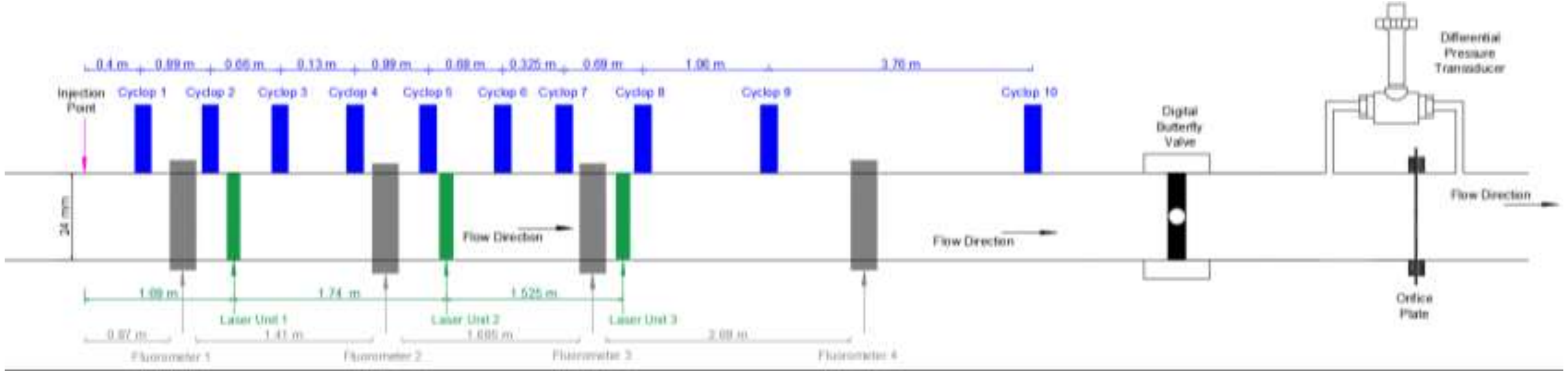
Exploring cross-sectional mixing in pipes

- 24 mm diameter
- 13 m long pipe
- Accelerating flows
- Re = 1,000 to 11,000
- 4x LIF systems





Current laboratory study
Dr Zhangjie Peng



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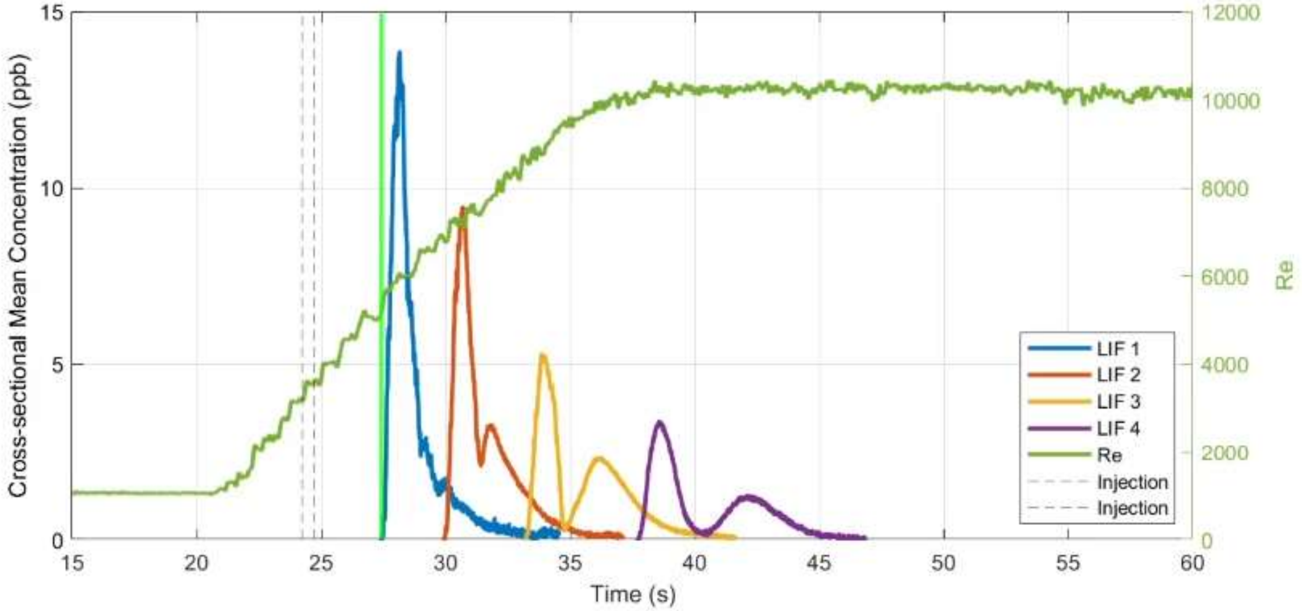
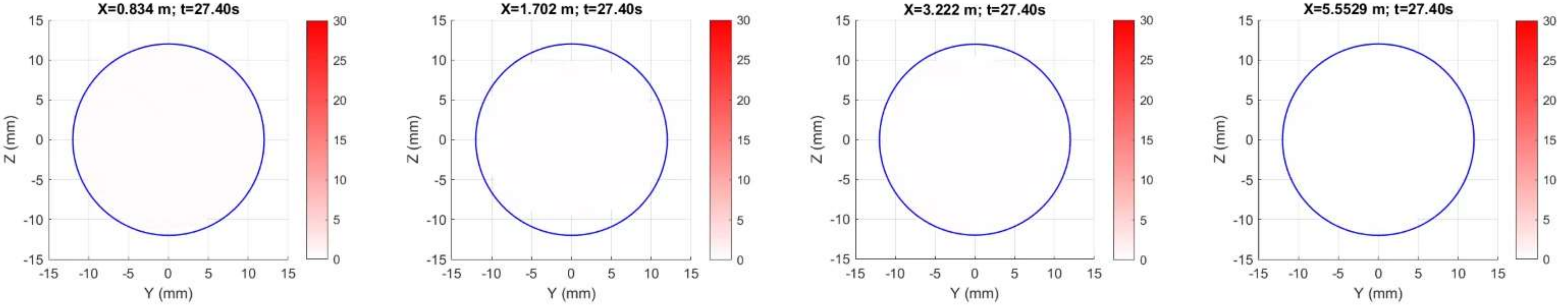
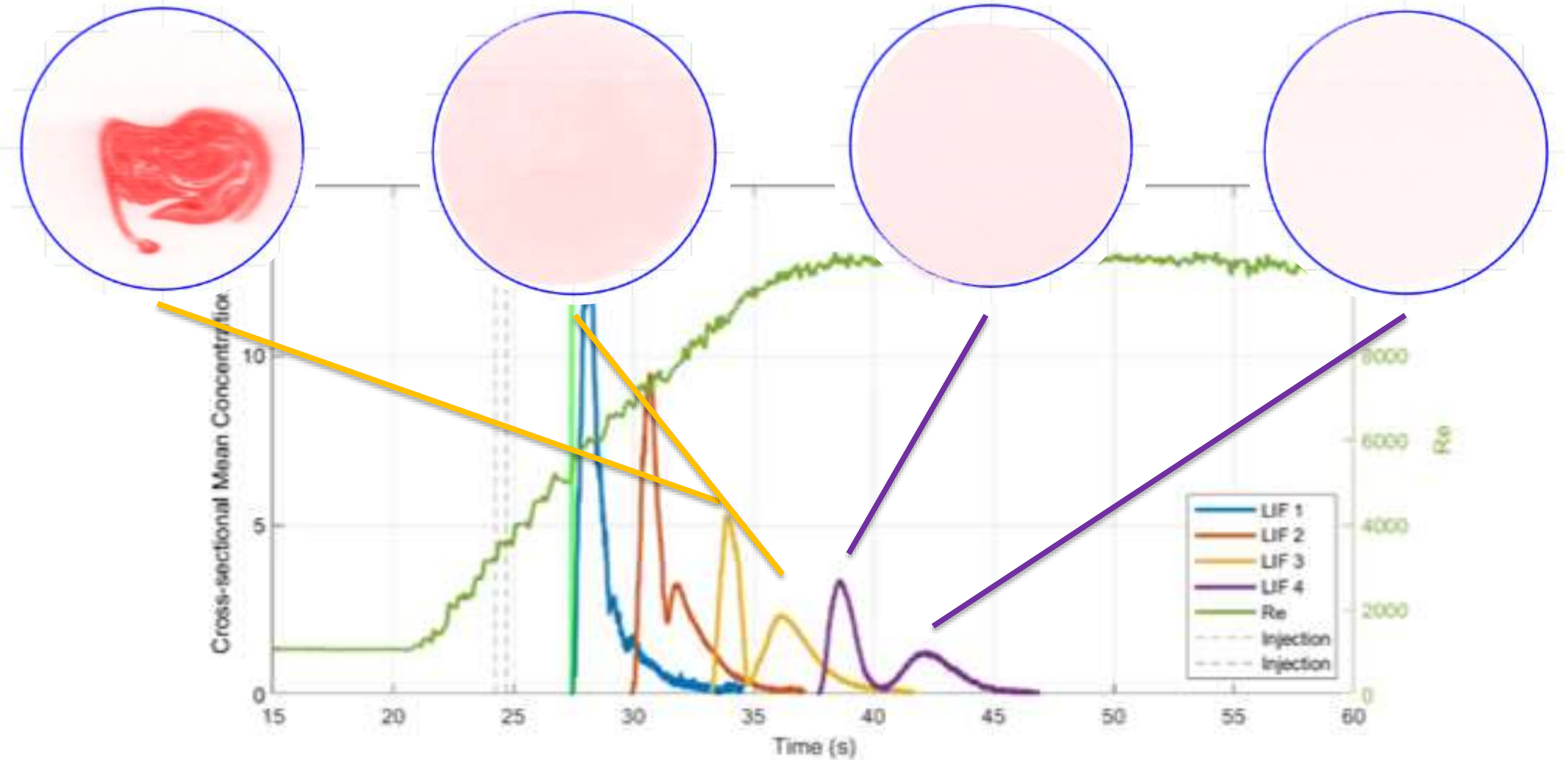
Pipe LIF Study



Unsteady flow Injection @ 4s





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- Disaggregation caused by non-uniform acceleration
- Cross-sectionally well-mixed for turbulent conditions

Comments

- Longitudinal dispersion coefficients, D_x, integrate spatial and temporal flow variations to describe "mixing"
- Knowledge of the major flow processes helps to estimate magnitudes of D_x
- Velocity measurements, in combination with dye tracing, can be used to quantify D_x

Acknowledgements

- ISH Organising Committee for the invitation to present
- Funders/supporters

UKRI Engineering and Physical Sciences Research Council

NERC SCIENCE OF THE ENVIRONMENT

Environment Agency

Unilever

highways england

dwi

RPS

SEVERN TRENT WATER

- Numerous researchers & technicians
- Colleagues, in many locations, who question my ideas,

  and especially friends who tell me when I'm being stupid!

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Many thanks!