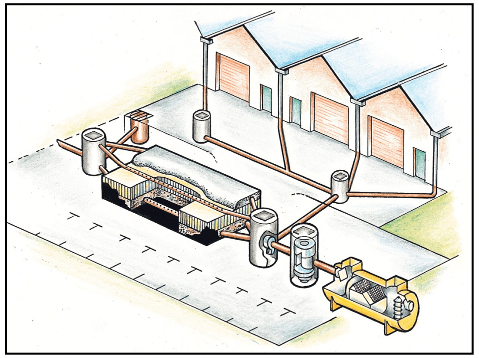
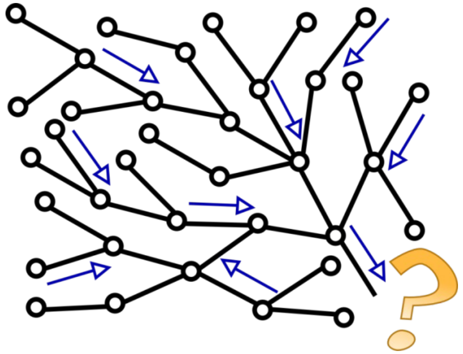
Manhole Mixing and Modelling



Dr Fred Sonnenwald



Mixing processes in pipes, sewers and the natural environment from theory to practice - Day 1

April 18th, 2023

Why mixing in manholes?

- CSO overflows in the news
- Water Framework Directive
- Sewer network water quality models are known to be poor - are we modelling them as well as we can?
    - Commercial models assume complete instantaneous mixing (well mixed) in manholes!

Eastern Daily Press > News > Health

Where raw sewage was discharged into Norfolk rivers

s Bishop

4:02 PM April 13, 2022 **Updated:** 6:36 PM April 13, 2022

vas discharged into Norfolk's rivers for the equivalent of more than 1,000 days last year,

Environment ▶ Climate crisis Wildlife Energy **Pollution**

Pollution

Raw sewage 'pumped into English bathing waters 25,000 times in 2021'

Liberal Democrats condemn 'environment scandal' as party releases figures compiled from Environment Agency data

Sandra Laville
Environment correspondent

Mon 2 May 2022 06.00 BST

The publication of the figures follows the opening of the official sea-swimming season on Sunday. Photograph: Matt Cardy/Getty

Untreated sewage was discharged into England's coastal bathing waters for more than 160,000 hours last year, according to figures collated by the Liberal Democrats to mark the start of the summer sea-swimming season.

The Guardian

You are here: Database Items | Runs | Simulations | Water Quality Simulations | Network Model

Network Model

WATER QUALITY

The network model is used to generate the concentration of dissolved pollutants and suspended sediment at the nodes.

In InfoWorks ICM, the urban drainage network is made up of nodes and links. Nodes are used to model storage volume in the network and may be points at which conduits meet. Nodes may, for example, represent:

- manholes
- outfalls
- tanks
- pump wet-wells
- ponds

InfoWorks ICM

The governing equation at a node is given by conservation of mass. Pollutant inflows come from external sources such as the surface pollutant model, trade and wastewater events, point inputs defined in a pollutant graph, and also from incoming conduits. The equation is:

$$\frac{dM_j}{dt} = \sum_i Q_i c_i + \frac{dM_{sJ}}{dt} - \sum_o Q_o c_o \quad (1)$$

where:

- M_J is the mass of suspended sediment or dissolved pollutant in node J (kg)
- Q_i is the flow into node J from link i (m³/s)
- c_i is the concentration in the flow into node J from link i (kg/m³)
- M_{sJ} is the additional mass entering node J from external sources (kg)
- Q_o is the flow from node J to link o (m³/s)
- c_o is the concentration in the flow from node J to link o (kg/m³)

It is assumed that there is no deposition on the floor of the node, and that suspended sediment and dissolved pollutant inflows are well mixed in the node due to turbulence in the flow. In other words:

DHI MIKE

22.4.1 Manholes and Structures - General Solution

At manholes a local continuity equation is applied. It is assumed that the substance in the nodal point is fully mixed over the volume. This assumption might not always be fulfilled, e.g. when flooding occurs. The continuity equation for a manhole reads:

US EPA SWMM

3.4.7 Water Quality Routing

Water quality routing within conduit links assumes that the conduit behaves as a continuously stirred tank reactor (CSTR). Although a plug flow reactor assumption might be more realistic, the

A brief history

Early 90s

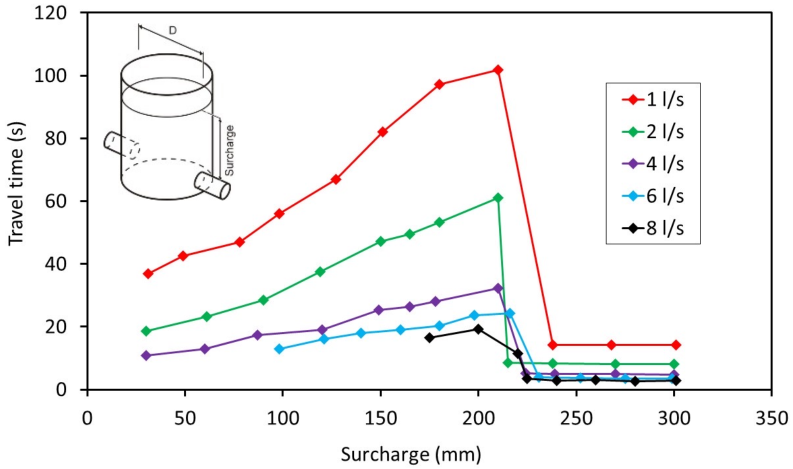
Manholes become surcharged in combined sewer networks – how do they behave?

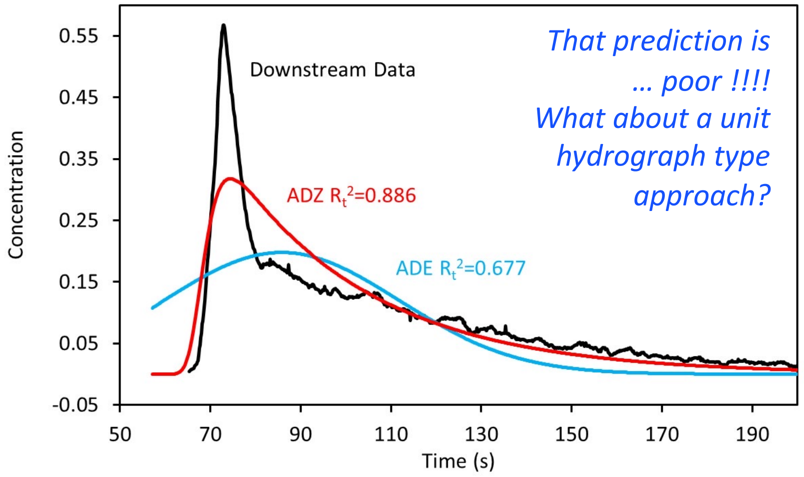
1992-2008

Dye tracing reveals odd behaviour with surcharge depth, a “threshold”

2005-2011

ADE and ADZ models don’t describe observations, a dimensionless RTD does

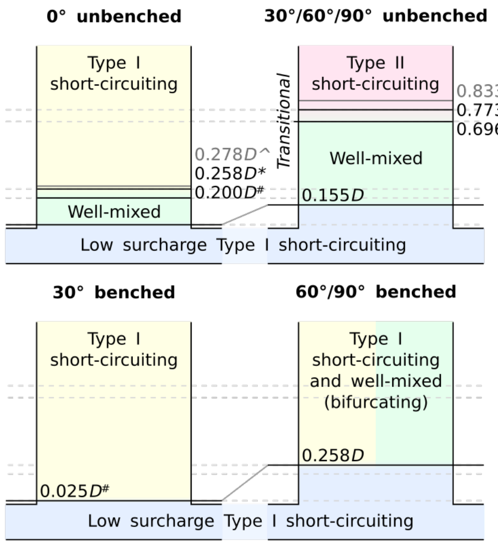




A brief history continued

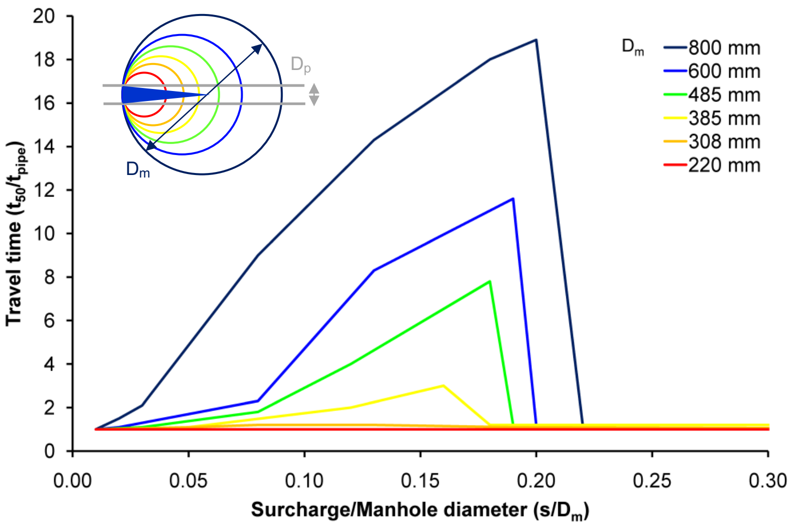
2010-2014

How can we best find the RTD? CRTD shapes linked to manhole characteristics



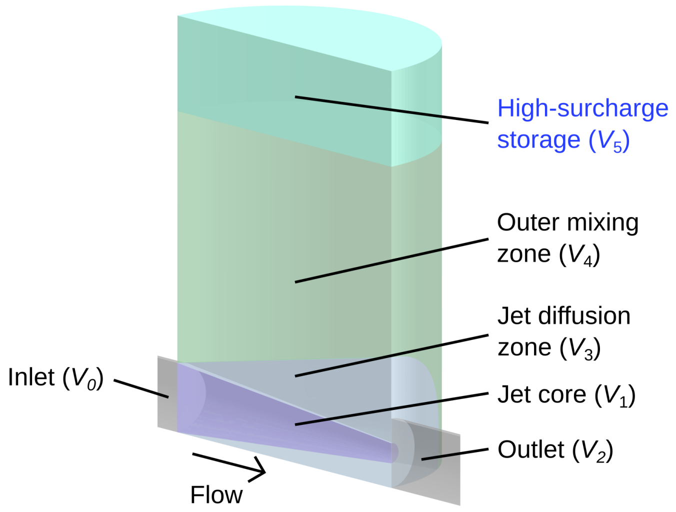
2008-2017

Narrow diameter manholes don't mix, jet theory suggested to explain this behaviour



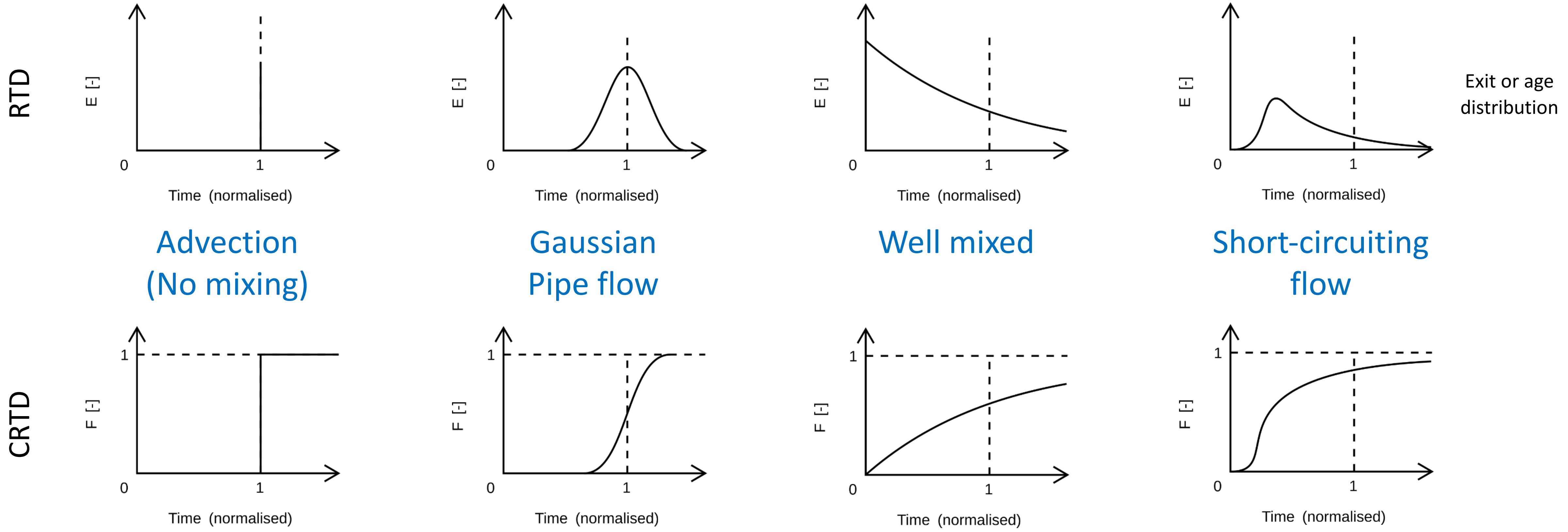
2020-2022

Compartmental modelling predicts RTDs and mixing in arbitrary manhole geometries

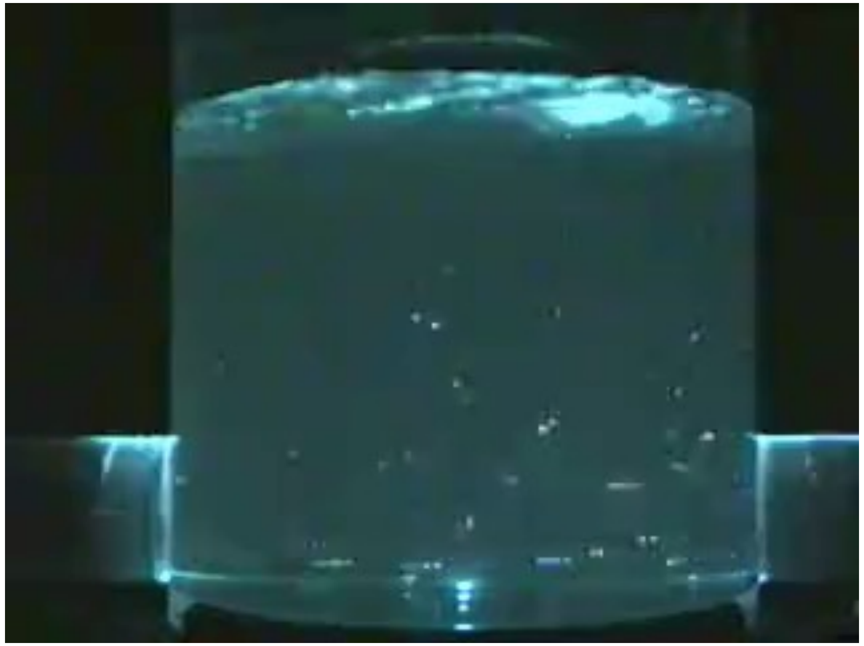


RTDs and CRTDs

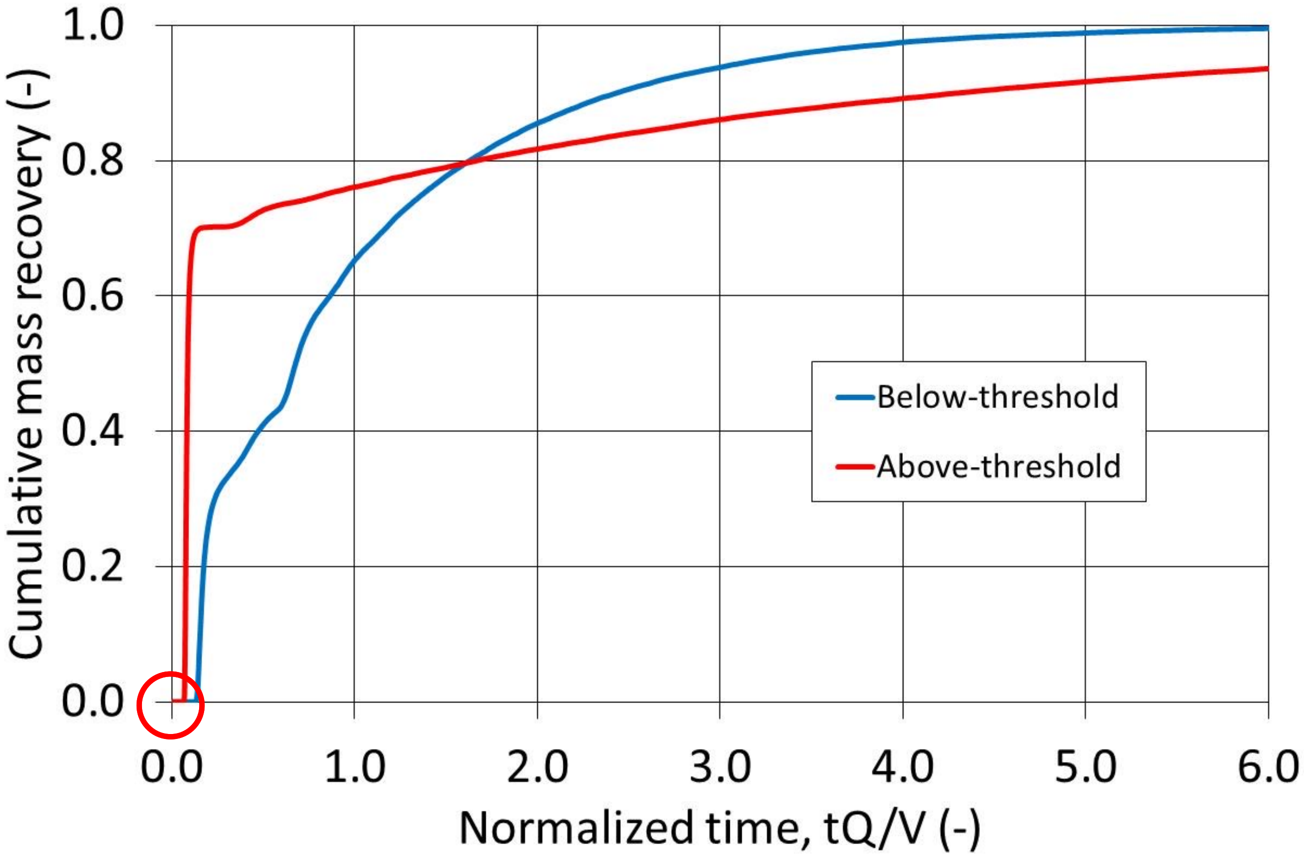
- The Residence Time Distribution (RTD) is a highly flexible model that describes the travel time and mixing characteristics of a system, predicting downstream concentrations, and can be obtained experimentally using deconvolution
- The Cumulative Residence Time Distribution (CRTD) can be easily visually interpreted



Mixing in a high-surcharge manhole



Flow ⟶



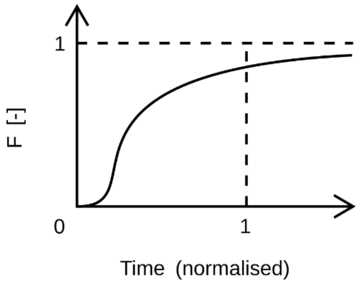
Short-circuiting behaviour is observed where most of the material passes directly through the manhole

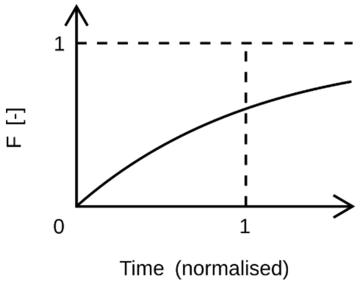
Not well mixed!!!

University of Sheffield

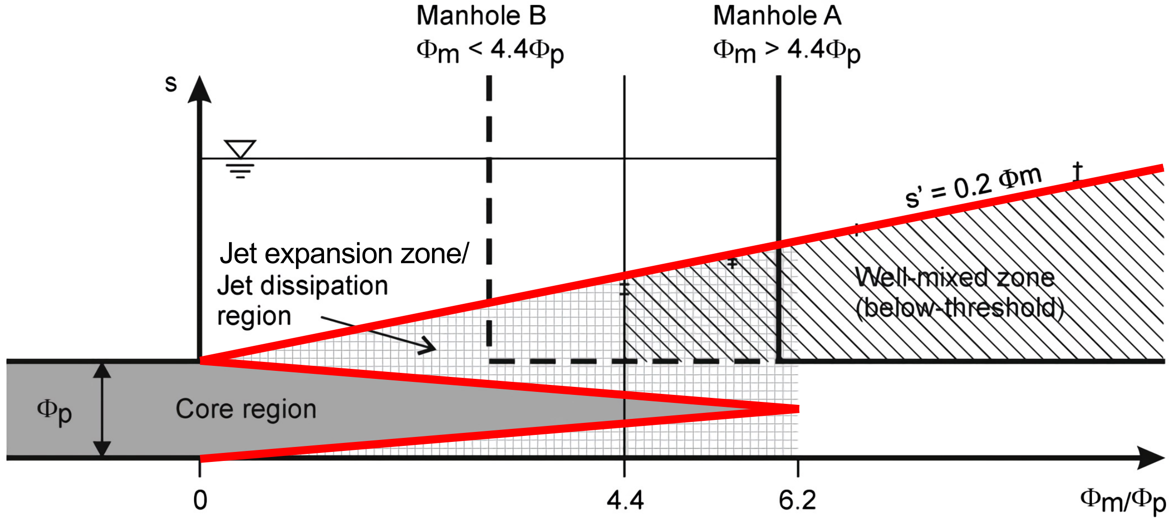
Mixing in surcharged manholes

- Threshold concept
  - Short-circuiting vs well-mixed

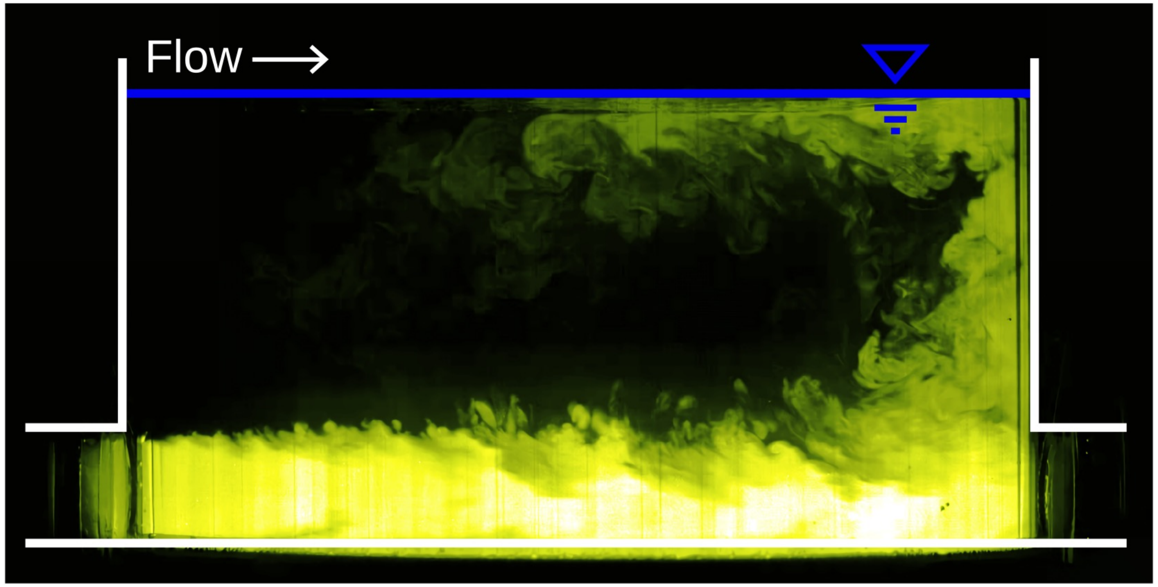




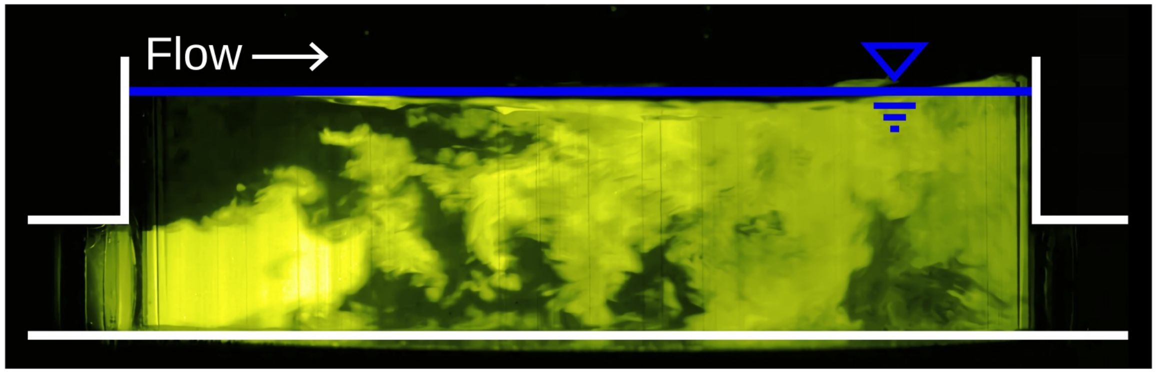
- Explained (mostly) by jet theory



Above-threshold

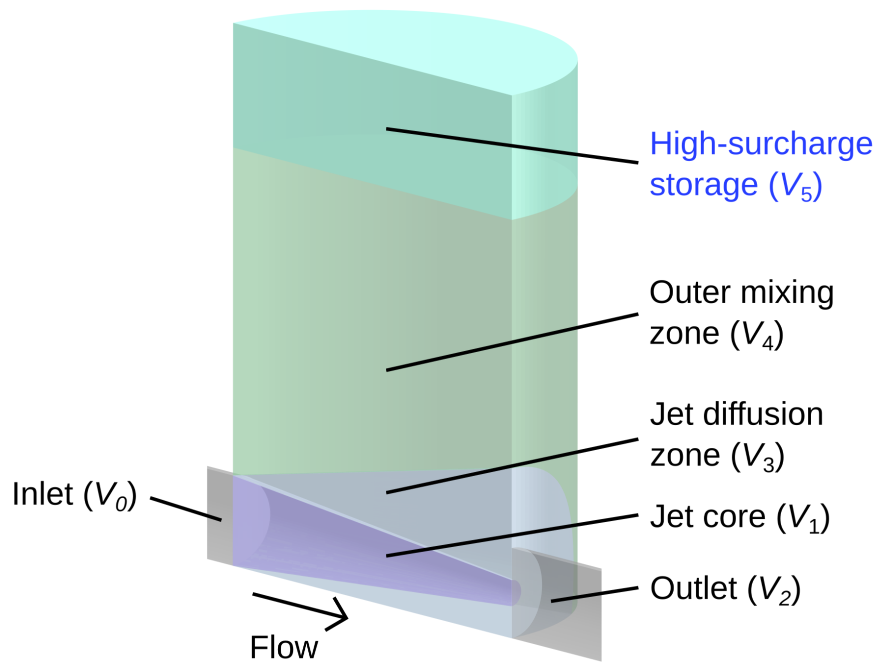


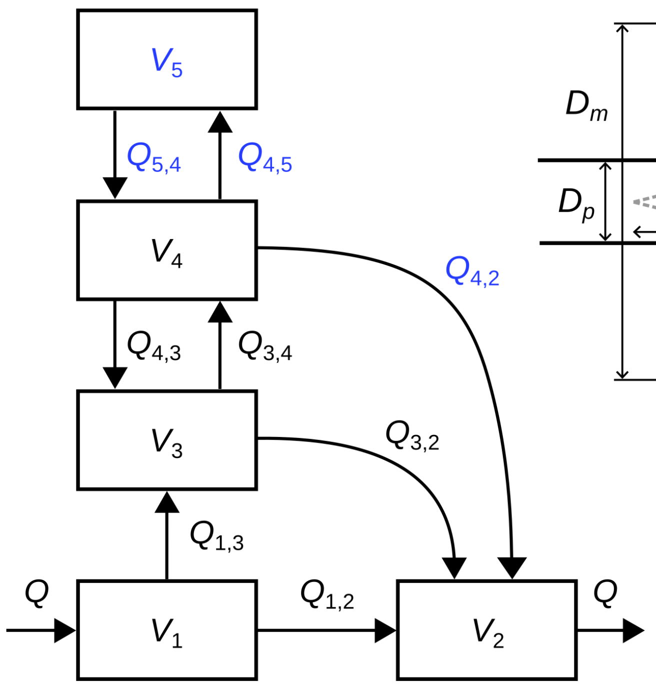
Below-threshold

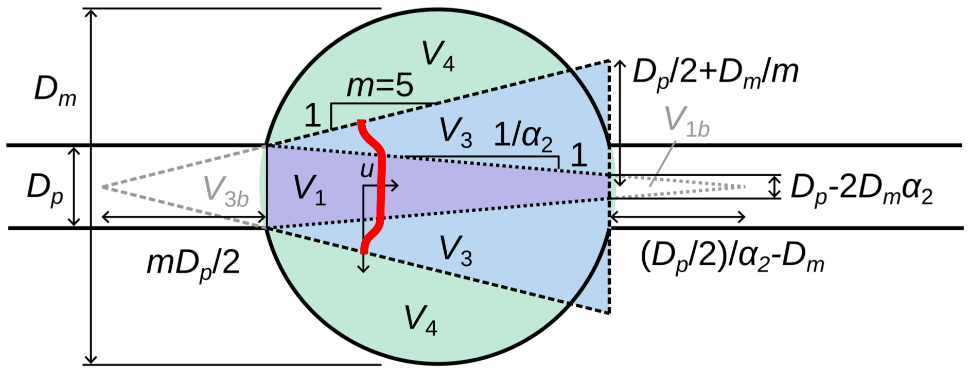


Compartmental "jet mixing" model

- Divide manhole volume up into zones according to jet theory
  - Zone volumes from basic geometry - cones, cylinders, etc.
- Exchange between zones is calculated from jet theory and continuity

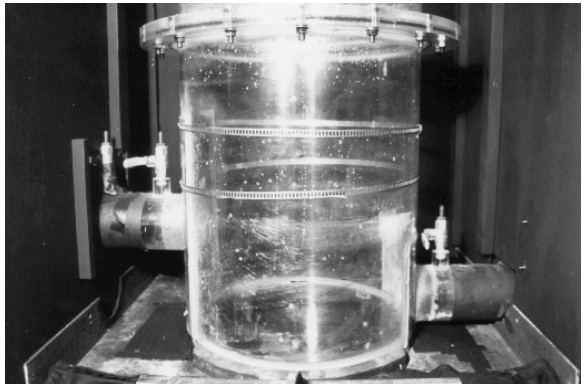


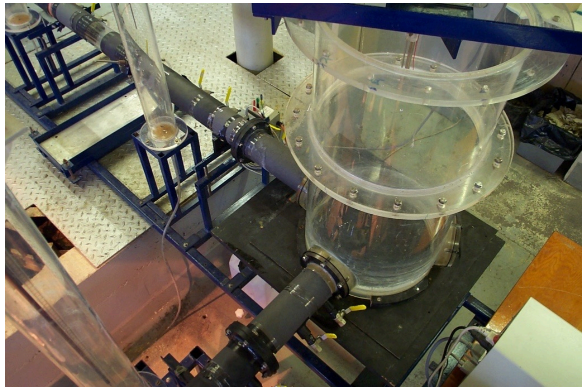


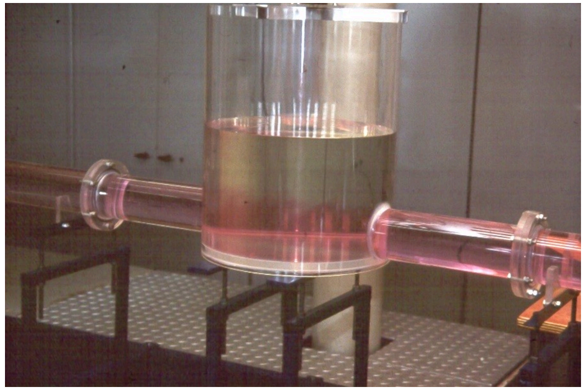


Experimental data for validation

- 5,000 rhodamine dye traces in model manholes carried out across 4 PhDs in the labs
  - Turner Series 10 fluorometers
- Unbenched
  - 218, 388, 500, 600, 800 mm diameter manholes
  - D_m/D_p = 4.4, 5.7, 6.8, 9.1
  - Stepped outlet 0.5, 1.0, 1.5, 2.0D_p
  - 30, 60, 90° outlet angles
- Dataset available online, including deconvolved RTDs/CRTDs

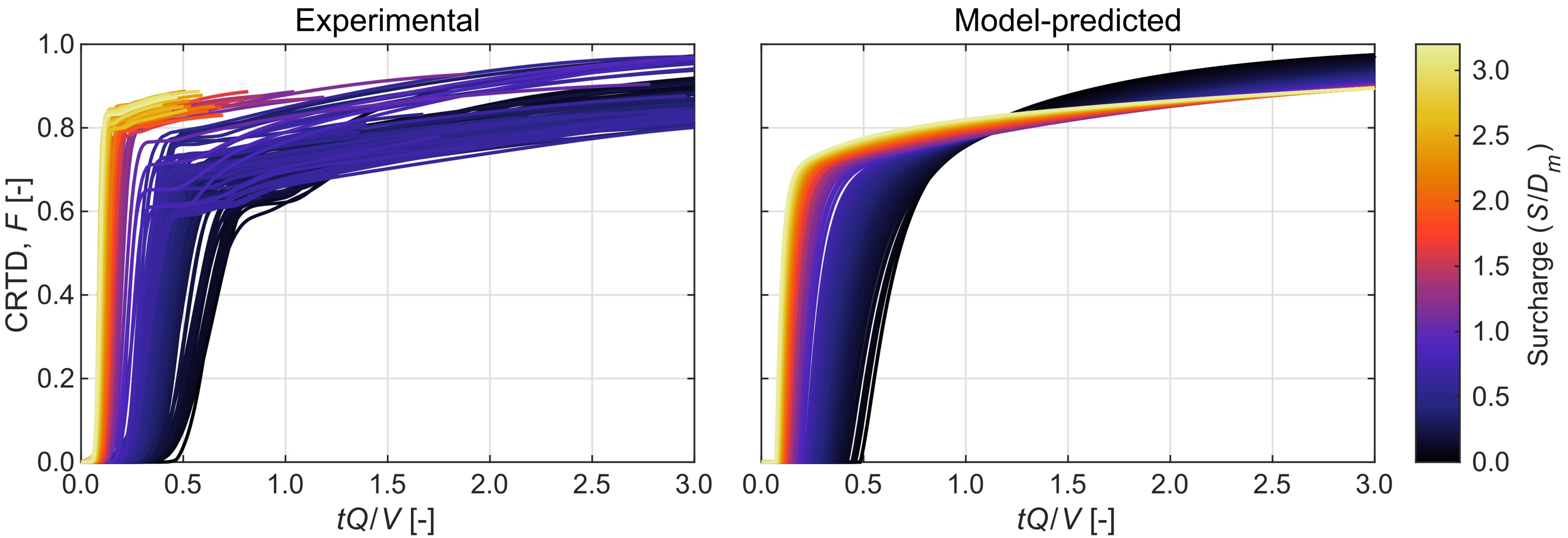






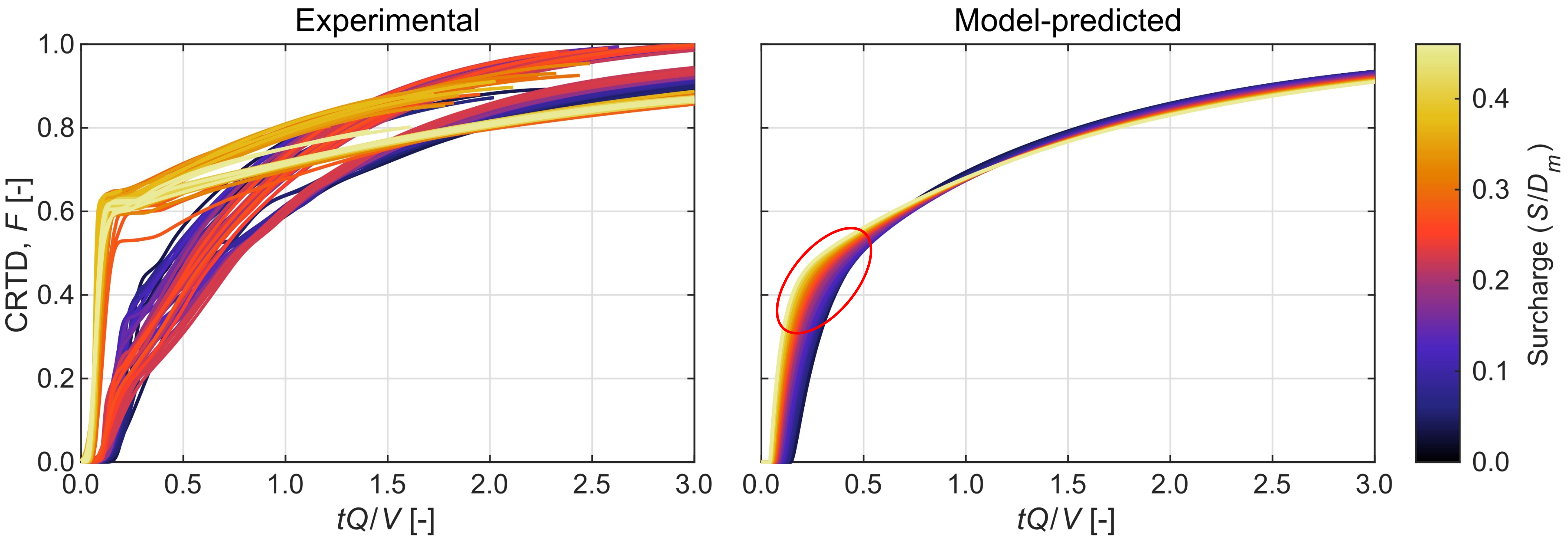
Experimental vs model-predicted CRTDs

Straight-through D_m/D_p = 4.4



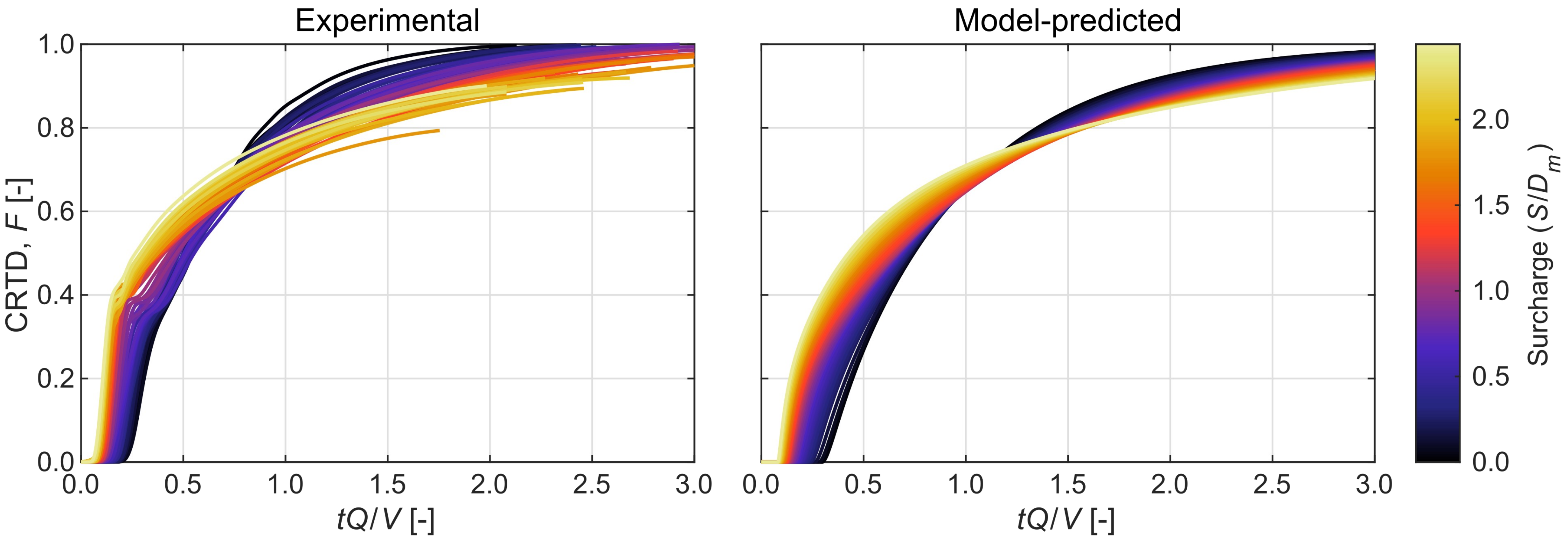
Experimental vs model-predicted CRTDs

Straight-through D_m/D_p = 9.1



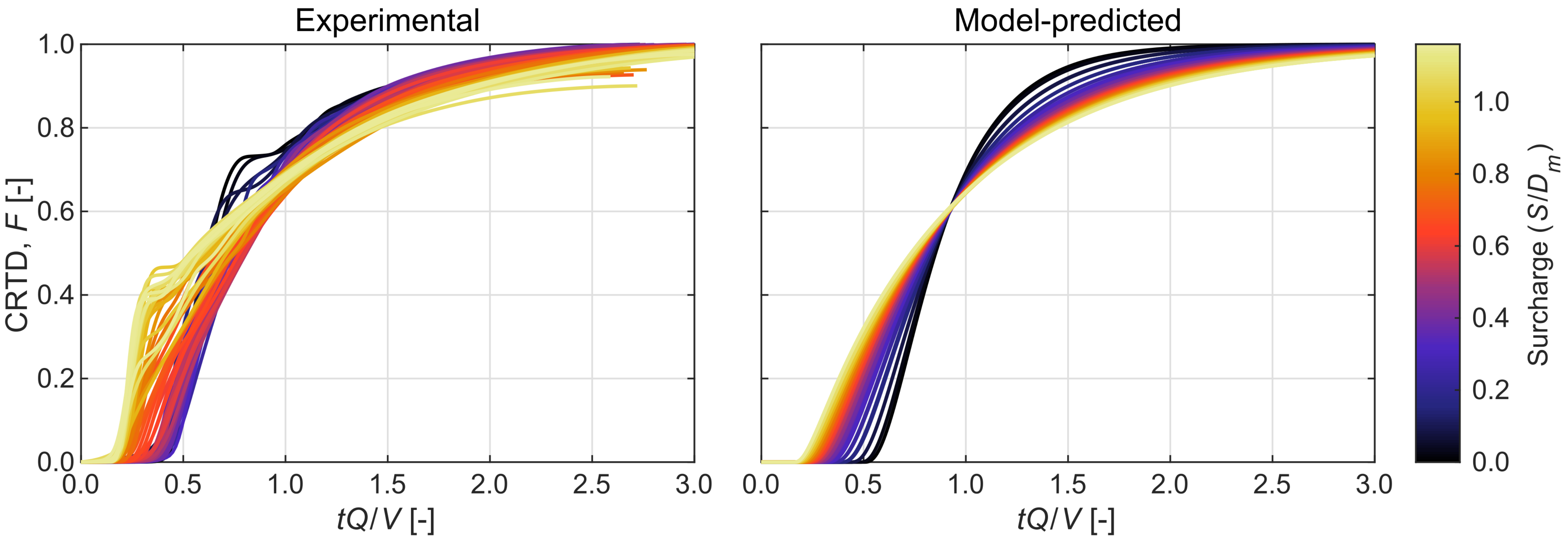
Experimental vs model-predicted CRTDs

Stepped B/D_p = 1.5

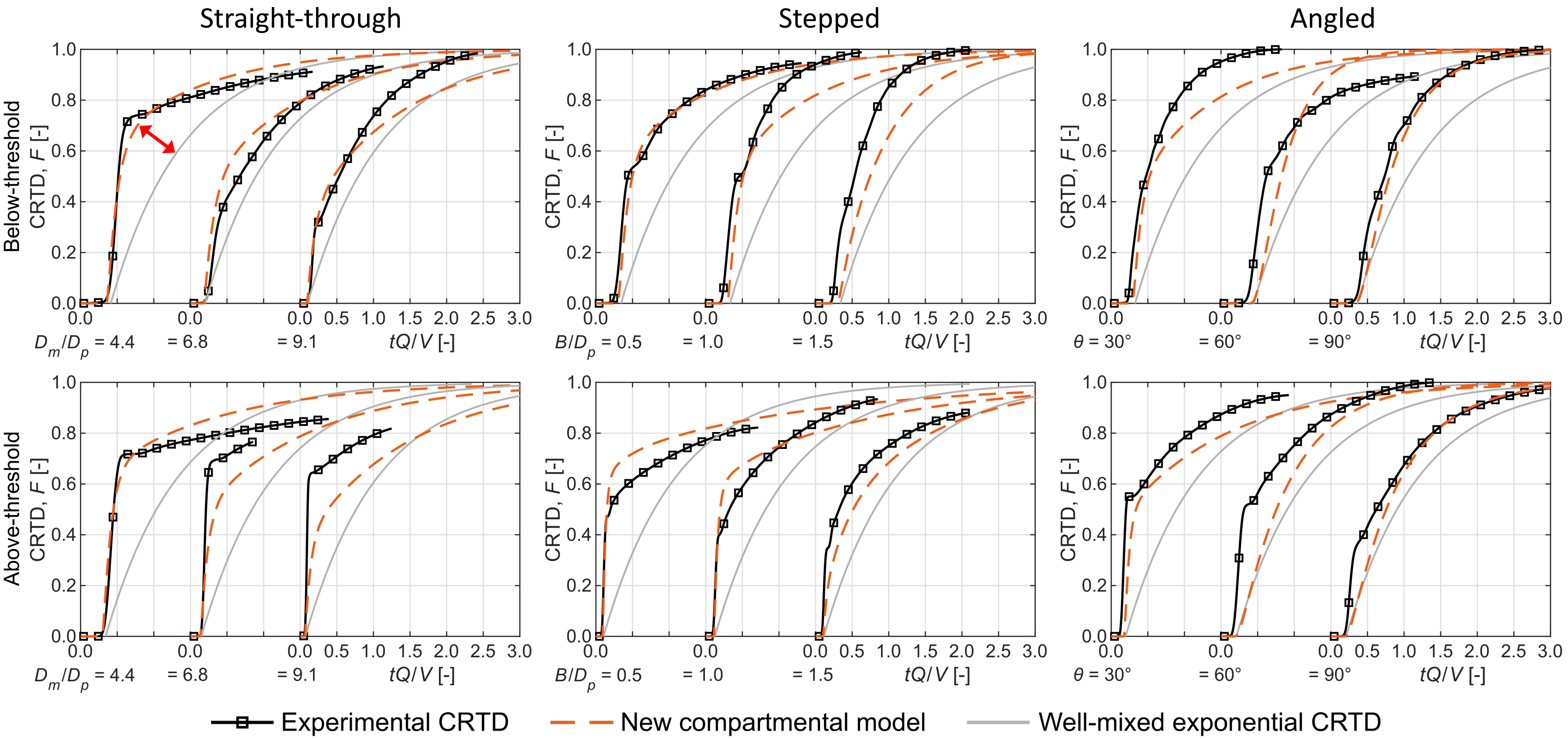


Experimental vs model-predicted CRTDs

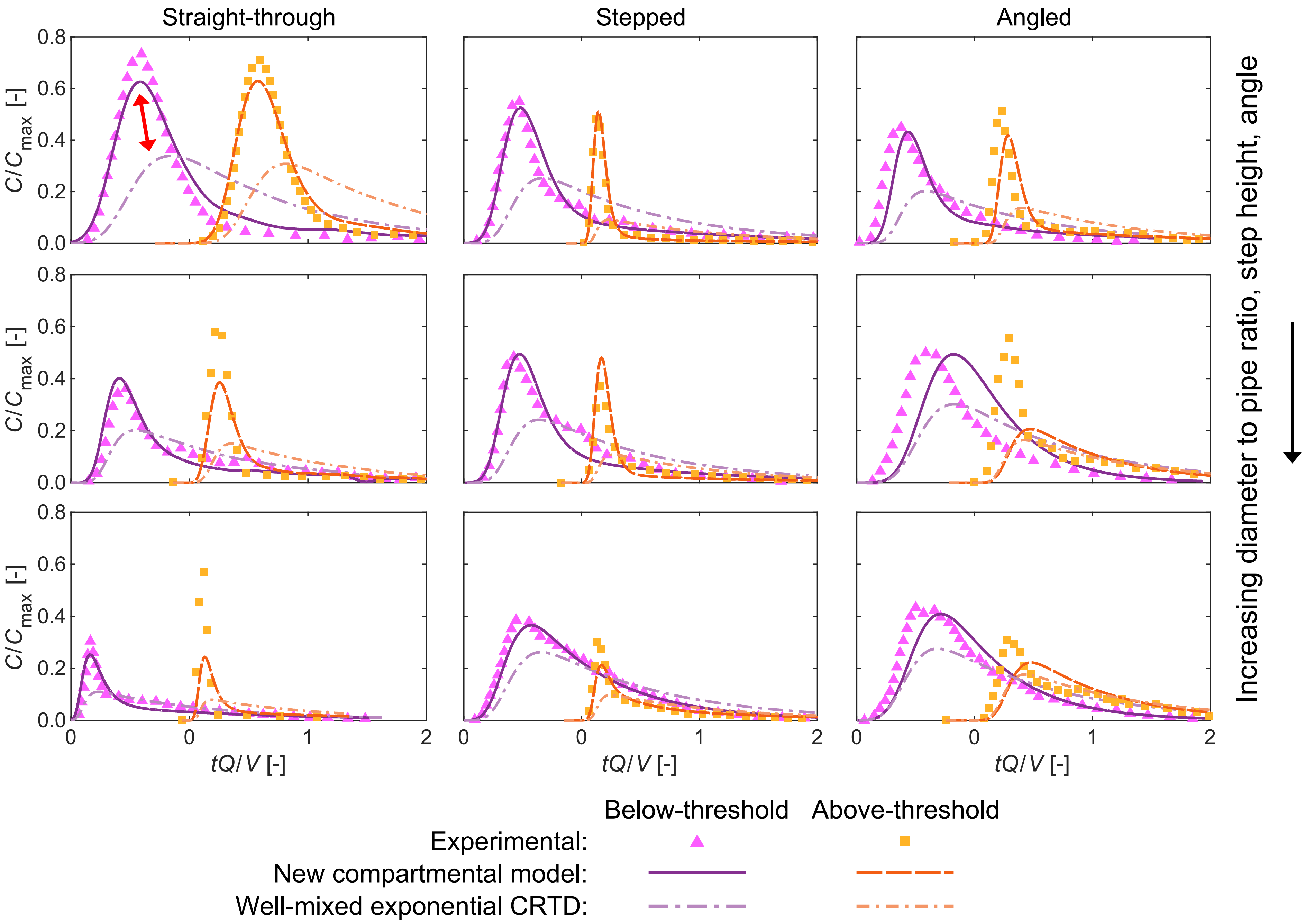
90° angled



Comparison with well-mixed model



Jet mixing model predictions

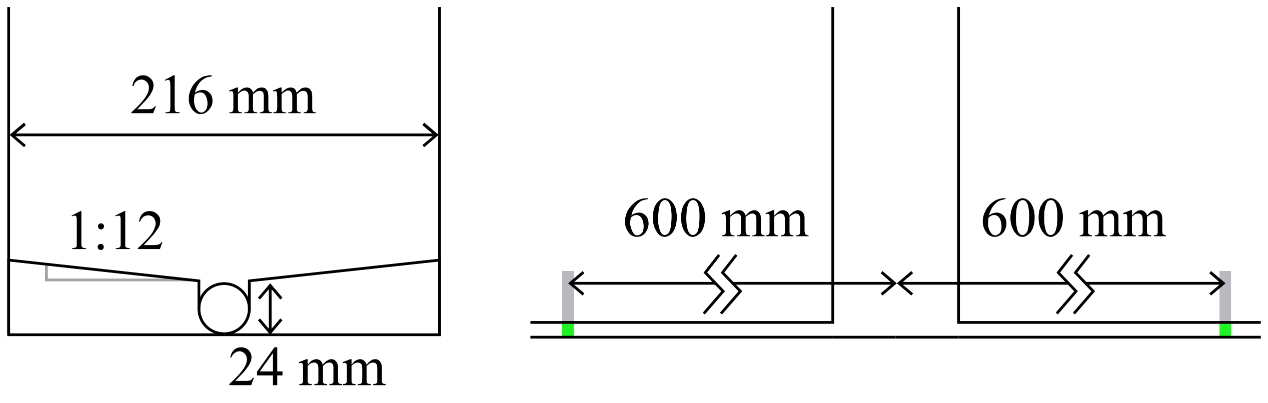


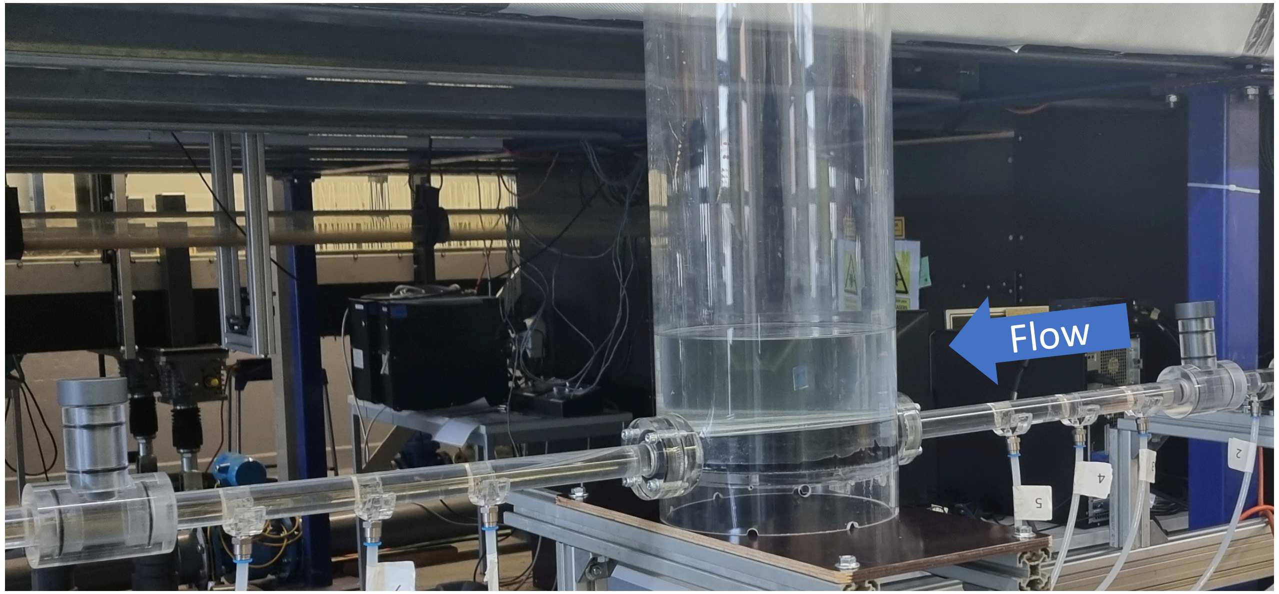
Mean R_t^2

Well-mixed exponential CRTD	
BT	AT
0.806	0.714
New compartmental model	
BT	AT
0.927	**0.925**

What about benched manholes?

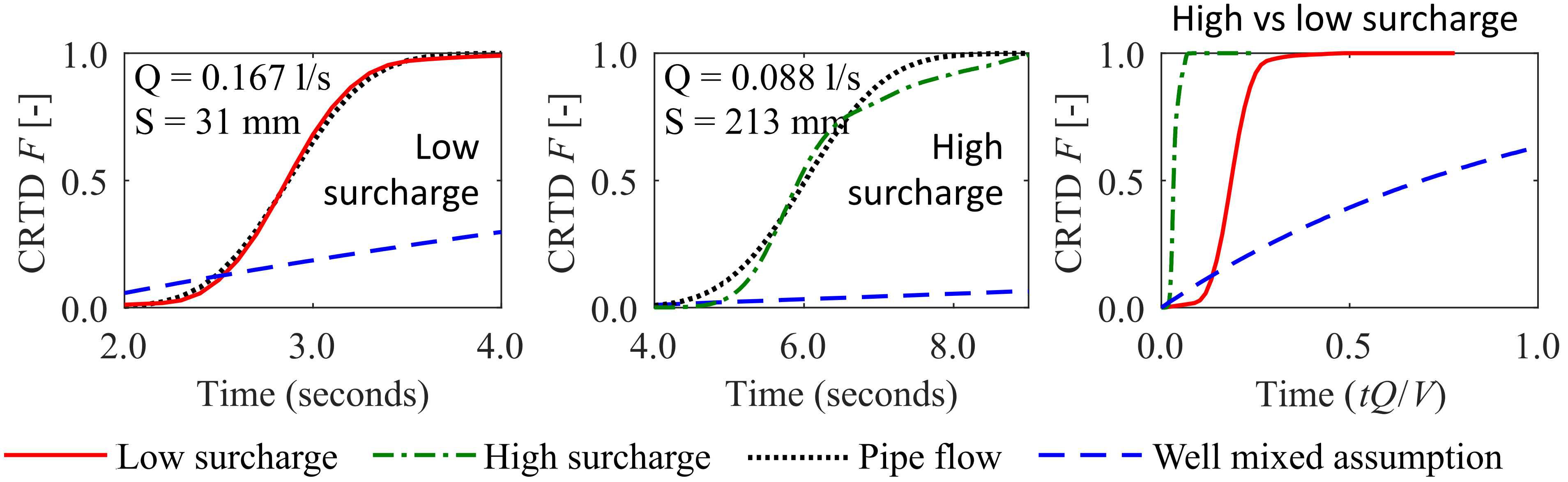
- Master's project collected concentration data from a model benched manhole
  - Varying flow rate & surcharge
  - Rhodamine WT dye injections recorded with Cyclops-7 fluorometers
- Modelled with the compartmental jet mixing model, taking into account benching

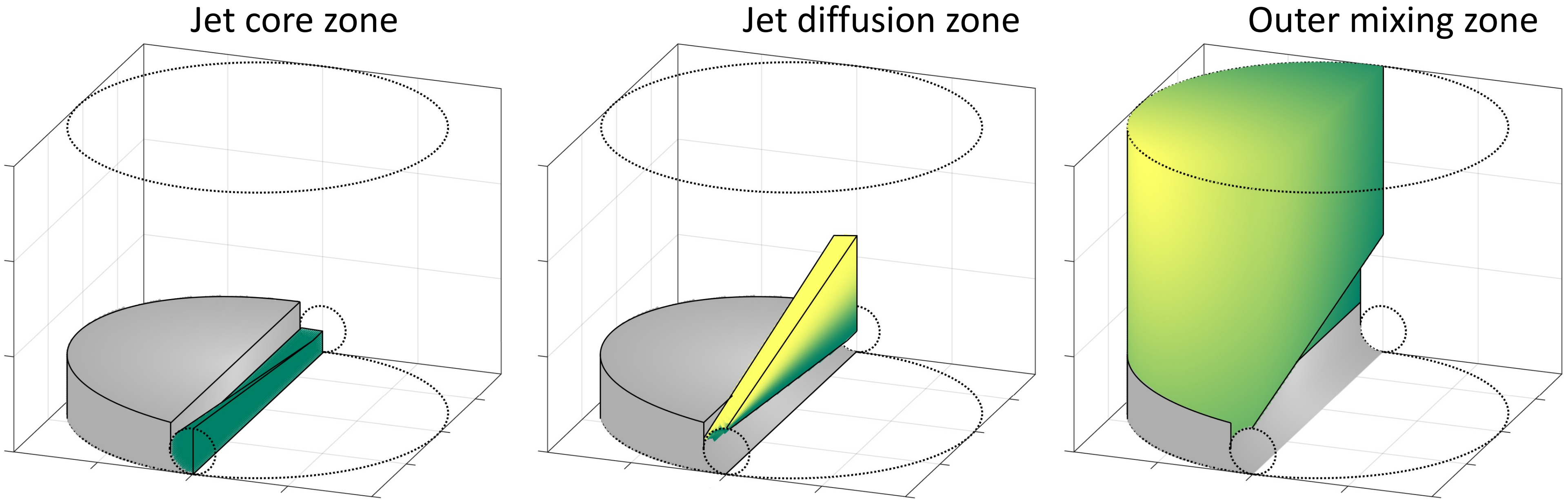




Deconvolved CRTDs

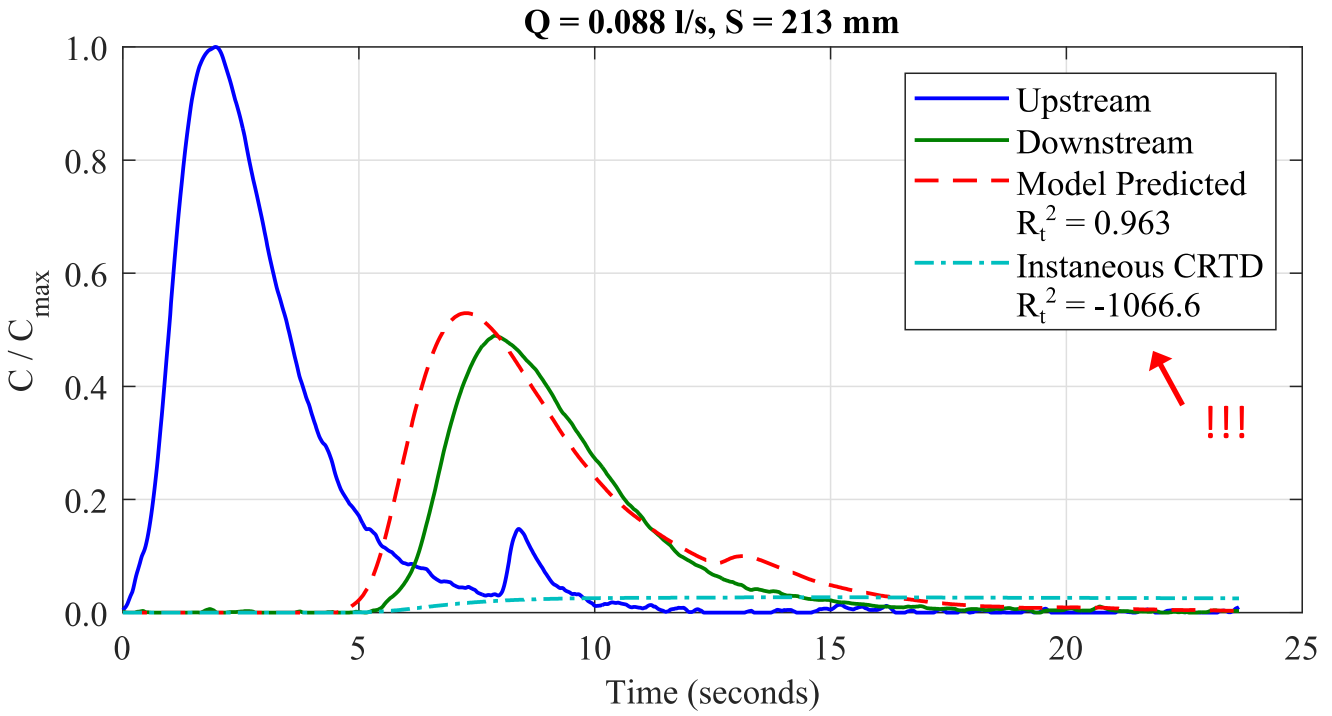
- Observed mixing in benched manholes is not instantaneous
- More Gaussian, suggesting jet core zone is pipe like?
- Clear need for improved modelling
- Jet zones appear to be constrained by benching
- Half of jet core acts as a pipe





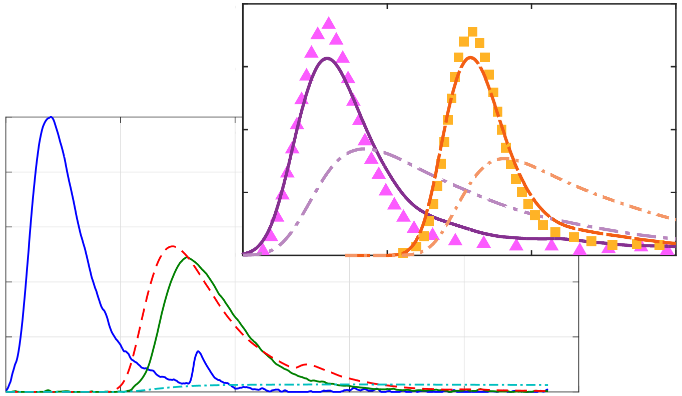
Compartmental model predictions

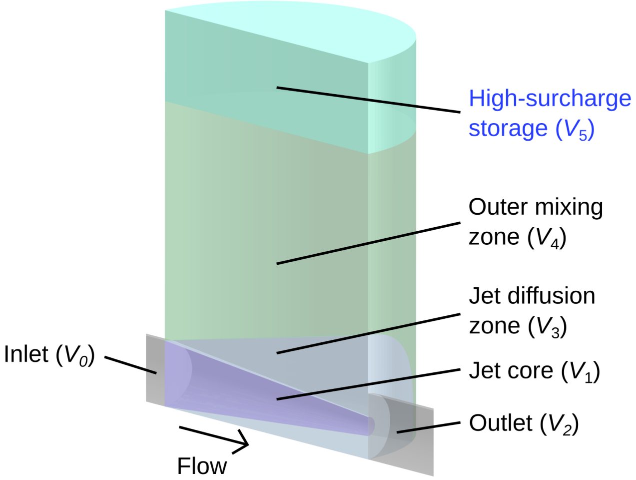
- Very good predictions for all 66 traces:
  - Mean $R_t^2 = 0.965$
  - Standard deviation $R_t^2 = 0.034$
  - R_t^2 peak aligned, some small issue with estimating first arrival time
- All instantaneous mixing predictions had $R_t^2 < 0$, completely under-estimating peak concentrations

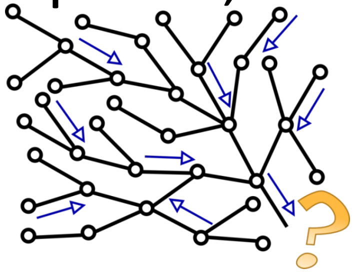


Summary

- Instantaneous complete mixing throughout the manhole volume is a poor description of benched and high-surcharge manholes
- The jet mixing compartmental model predicts CRTDs consistent with experimental results
  - Under-estimates short-circuiting in some conditions, likely due to not accounting for more complex hydrodynamics
- Successfully predicts downstream concentrations, higher and more realistically than the well-mixed model, particularly for the common $D_m/D_p < 4.4$ manholes and benched manholes
- Completely analytical, requires no assumptions, and is suitable for practical applications
- What about pipes?







Thank you for listening!

…and thanks to

Prof Ian Guymer, Prof Virginia Stovin, Dr Ole Mark

Dr Robert O'Brien, Dr Peter Dennis, Dr Chanwit Saiyudthong, Dr Shing-Tak Douglas Lau, Mr Angus C L Wong

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