

# Fluorescent Dye Traces in Four UK Sewer Networks

## Read Me

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## 1 Introduction

This dataset describes experimental fluorescent dye traces (temporal concentration profiles) recorded in manholes within combined sewer networks located in four different cities across the United Kingdom. It accompanies the journal article entitled "Quantifying mixing in sewer networks for source localisation" (Sonnenwald *et al.*, submitted). This dataset was collected by Professor Ian Guymer and colleagues. This archive was funded by EPSRC grant EP/P012027/1 and the UK Health Security Agency.

Please visit <https://www.sheffield.ac.uk/mixing-studies> for more information.

## 2 File naming and data format

This dataset consists of this PDF read me document and a ZIP archive containing four sub-folders, which in turn each contain three XLSX spreadsheets. These spreadsheets detail network geometry, a database of trace characteristics, and then the traces themselves. Each sub-folder, containing data for one city, is named CITYX where X is 1 through 4. Details of network geometry are provided in CITYX GEOMETRY.XLSX, the database of trace characteristics is provided in CITYX OVERVIEW.XLSX, and the traces themselves are provided in CITYX TRACES.XLSX.

### 2.1 City geometry

The geometry XLSX files provide descriptions of the conduits between the instrumented manholes. Columns A-J describe the conduit number, upstream manhole ID, downstream manhole ID, conduit length, shape, width, height, roughness, slope, and nominal day time flow rate from modelling. Manhole ID is in the format of CXMYSZ where X is city number, Y is the instrumented manhole it is upstream of, and Z is the number of conduits upstream. The conduit shapes correspond to those given by Innovyze, Inc. (2022).

### 2.2 City overview

The overview XLSX files describe the recorded concentration profiles in two sheets. The first sheet provides details of the individual traces, while the second sheet describes upstream/downstream temporal concentration profile pairs suitable for determining dispersion coefficient.

### 2.2.1 Traces

Columns A-Q of the “Traces” sheet describe the trace number, manhole it was recorded at, which injection it was recorded from, the injection dose of Rhodamine WT dye, the instrument order (with 1 being most upstream), trace quality, if moments analysis was suitable to run, the 0th moment (mass), the 1st moment, the centroid of the recorded concentration profile in minutes since injection, the 2nd moment, the variance of the recorded profile, the 3rd moment, the skew of the profile, the calculated discharge, the distance between the monitored manhole and the injection location, and the mean temperature over the duration of the trace. Units are given in the column headings.

### 2.2.2 Trace pairs

Columns A-E of the “Trace pairs for analysis” sheet describe the reach number, the number of the upstream trace, the number of the downstream trace, the distance between them, and whether or not the traces are suitable for dispersion analysis.

Columns F-I are the results of optimising the routing solution to the advection-dispersion equation (ADE), Eq. 1, to find the longitudinal velocity, the travel time, the longitudinal dispersion coefficient, and then the goodness-of-fit between the optimised ADE prediction and measured downstream concentration profile, expressed as  $R_t^2$  where 1.0 indicates a perfect fit (Young *et al.*, 1980). The ADE routing solution is given by:

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

where  $c(x, t)$  is the concentration profile at location  $x$  and time  $t$ ,  $x_1$  is the upstream measurement location,  $x_2$  is the downstream measurement location,  $U$  is longitudinal velocity,  $D_x$  is the longitudinal dispersion coefficient,  $\bar{t}$  is travel time, and  $\gamma$  is a dummy variable of integration (Rutherford, 1994). For more details on optimising dispersion coefficient, see Guymer & O’Brien (2000).

Columns J-O are the results of optimising the aggregated dead zone model (ADZM), Eq. 2, to find velocity, travel time, cell residence time, cell time delay, dispersive fraction, and then the goodness-of-fit between the optimised ADZM prediction and measured downstream. The ADZM is given by:

$$c(x_2, m) = \exp(-\alpha \Delta t) c(x_2, m-1) + (1 - \exp(-\alpha \Delta t)) c(x_1, m - \delta - 1) \quad (2)$$

where  $m$  is any given time-step,  $\alpha$  is the cell time constant,  $\Delta t$  is the time step,  $\delta = \text{floor}(\tau/\Delta t)$ , and  $\tau$  is cell time delay (Rutherford, 1994). Travel time  $\bar{t}$  can be found as  $\tau + T$ , cell residence time  $T$  as  $1/\alpha$ , and dispersive fraction  $D_f$  as  $T/\tau$ .

Column P indicates the minimum trace quality of the upstream and downstream traces.

## 2.3 City traces

The traces XLSX files provide the recorded calibrated temporal concentration profiles. Each file contains several sheets, one for each trace number given in the overview spreadsheet, titled, CITYXTYYY, where YYY is trace number, There are two columns, the first is the time in minutes since injection and the second is calibrated concentration in ppb.

## 2.4 Pre-processing

All the recorded solute traces have been processed consistently. Times were corrected as the linear interpolation between 0 at the previous clock sync and the reported clock offset at the next sync. The concentration data were temperature corrected. Based on the injection time, an approximate start and end of the trace was identified. A calibration was then applied. Visual inspection was used to identify background concentrations before and after the trace, and a linear background concentration between the two subtracted. In cases where the trace did not show steady background concentrations both before and after the trace, the background subtraction was carried out assuming steady background as otherwise observed.

To determine the start and end of the data, a moving average was temporarily applied to reduce the impact of noise and then the 1% of peak times of the smoothed data was used to cut-off the data record. In some instances, the start or end of the trace was manually defined due to poor quality data or traces overlapping due to injections too close together in time.

As trace quality was not consistent across all measurements, definitions of trace quality were created (Table 1) and used to evaluate the traces. The trace quality definitions were used in context with other traces from the same injection. It is recommended to only analyse traces of Good quality or better.

Discharge was calculated by equating the mass passing the monitoring instrument (the first moment) with the known mass of injected dye as  $Q = v_0/M_0$ , where  $Q$  is discharge,  $v_0$  is injected dye volume in  $\mu\text{l}$ , and  $M_0$  is the 0th moment in ppb.s.

Quality Level	Description	Definition
0	Unusable	Concentrations measured exceed the scale of the instrument.
1	Poor	Traces have a very odd profile shape, unrealistic sudden fluctuations in concentration, or unrealistic profile duration.
2	Not Ideal	Traces are very noisy (~50%), cut off early, or have an odd shape.
3	Acceptable	Traces generally have a good signal, but noise levels are moderate (~20%) and/or shape/peak concentration is inconsistent.
4	Good	Traces have a good signal, but there is some noise (~5%) and minor doubt about profile shape or peak concentrations compared to other traces.
5	Best	Traces have a good concentration signal, low noise, and descend in peak concentration between measurement locations.

Table 1: Trace quality definitions

## 3 Experimental setup

To collect this data, fluorescent dye tracing was conducted in four UK combined sewer networks. Up to ten Turner Designs Cyclops-7F submersible fluorometers were used, attached to Precision Measurement Engineering submersible Cyclops-7 loggers configured to log at 5-second intervals.

Between 1 and 50 ml of dye diluted into 1 litre of distilled water was poured into the dry weather channel of an upstream manhole as a pulse injection. Dye volume was increased with increased distance and dilution to the furthest monitoring location. The dye used was Rhodamine WT in a 20% solution obtained from Town End (Leeds) plc.

A combined concentration temperature calibration was carried out for the instruments at the end of the experiments. The instruments and calibration solutions of 0, 250, 500, 750, and 1000 ppb (made using distilled water) were placed in a climate-controlled chamber at the Arthur Willis Environment Centre programmed to remain at 5, 10, 15, and 20 °C each for 24 hours. After at least 16 hours to allow temperatures to reach steady-state, each instrument was placed in each calibration solution for five to ten minutes. The standard logarithmic fluorescence temperature correction formula is  $c_s = c \exp(n_t(T_s - T))$ , where  $c_s$  is the concentration at a standard temperature,  $c$  is the measured concentration,  $n_t$  is a temperature exponent,  $T_s$  is a standard temperature, and  $T$  is the measured temperature (Smart & Laidlaw, 1977). The concentration readings and readings from the logger’s built-in temperature sensor were fit with least-squares optimisation to the correction formula to find a temperature exponent of -0.0227 for the measurement system. After correction to a standard temperature of 20 °C, a linear calibration equation was obtained for each instrument.

Instruments were installed into safely accessible manholes. Initial fixing of the fluorometers to the side wall of the sewer often resulted in excessive ragging or the probe not being fully submerged. Upon switching to securing the probes by chain and laying them in the main channel to allow more freedom of movement, ragging almost completely ceased. In instances where the water depth was insufficient, a small temporary weir was installed to submerge the probe further. More detailed guidance on conducting dye tracing in sewers is provided by Turner Designs Inc. (2022).

The dye tracing campaign was carried out throughout 2021 and 2022 over a total of 23 days in four UK cities. Cities 1 to 3 were linear networks with injections at the top of the network. While City 4 had measurements along a linear path, it also had the most complex set of experiments with injections on four different branches of the network. An overview of the cities is given in Table 2 and long sections are shown in Fig. 1. Network geometry was taken from validated InfoWorks sewer models.

## Acknowledgements

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City	Number of monitoring locations	Length (km)	Primary conduit shape	Pipe diameter (mm)			Slope (1 in X)		
				min	median	max	min	median	max
1	8	3.6	Circular	300	825	1200	826	69	7
2	3	6.2	Egg	225	1000	2450	3000	311	11
3	3	6.3	Circular	225	525	1400	2700	148	11
4	4	3.1	Circular	225	885	1650	2500	112	5

Table 2: Overview of study sewer networks

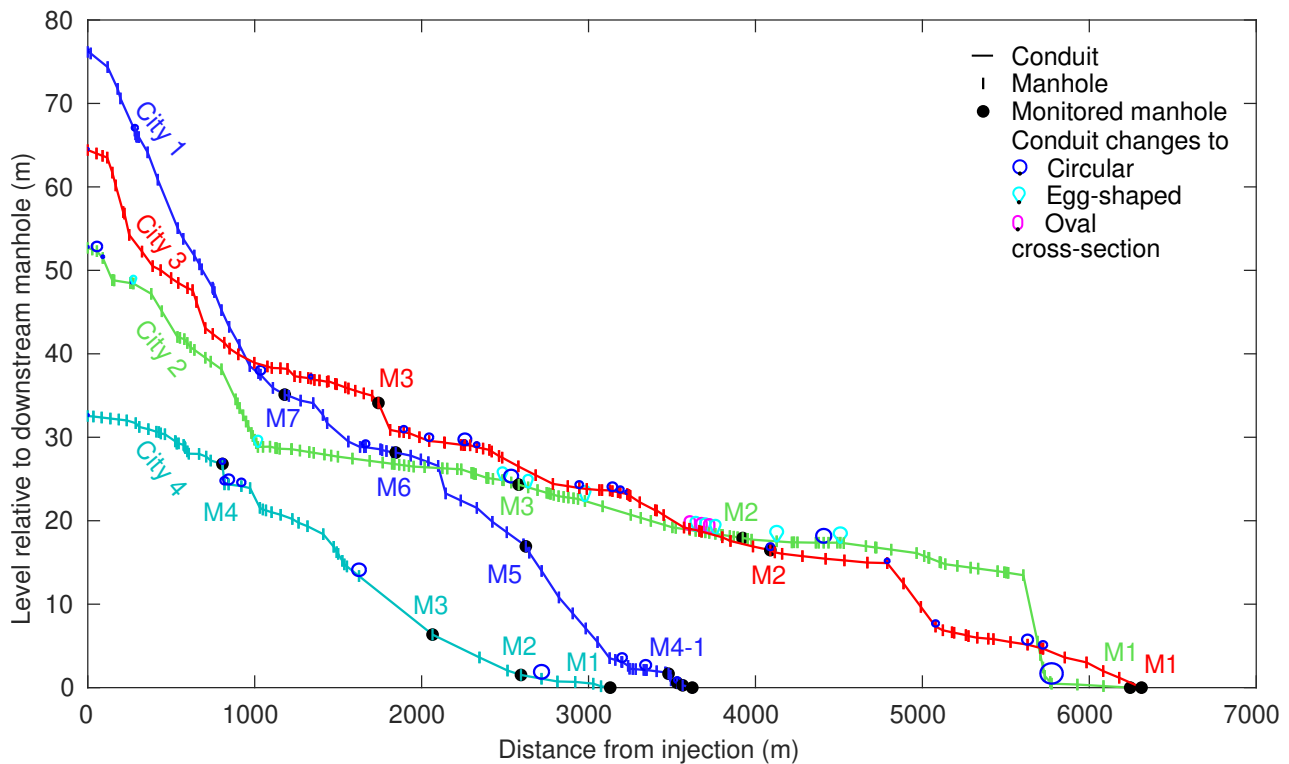


Figure 1: Long sections and monitored (M)anholes plotted with 50:1 vertical exaggeration

## References

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