

## Summary Report

### SP4: Development of operational strategies and user guidelines for ventilation

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#### 1. Introduction

The purpose of this summary report is to describe:

- The results of field tests to determine air flow rates in gravity sewers.
- Application of the data to further develop an existing sewer ventilation model.
- Development and testing of a model to measure air velocities induced by drop structures.

#### 2. Measurement of air flow rate in gravity sewers

##### 2.1 Experimental arrangement

The air flow rate in a number of gravity sewers was measured using carbon monoxide as a tracer. The tracer was injected as a series of pulses at an upstream location and the tracer concentration was monitored at a point some distance downstream. The location of both the injection point and the sampling point was in the air space about midway between the water surface and the sewer obvert.

Testing indicated that there was limited axial dispersion of the tracer as it moved down the sewer. Thus a pulse of tracer introduced at the injection point appeared as a pulse at the downstream sampling point. This feature of the experimental results allowed reliable estimation of the air flow rate based on the pulse travel time and the cross sectional area of the air space.

The experimental program included simultaneous measurement of a number of other relevant variables such as sewage velocity and depth, temperatures in the water and gas phases, gas phase pressures etc.

##### 2.2 Experimental sites

Tracer studies were conducted at 4 sites located in Perth and in Adelaide. All of the test sewers included no branches over the test lengths to eliminate the influence of inflows on ventilation rates.

The selected sites are described in Table 1. This table indicates that:

- Two sites were selected with free convection ventilation systems and no drop structure. One of these sites (i.e. South Parklands Main Sewer) had no constraints affecting ventilation rates either upstream or downstream of the test length. This was

not the case with the other test site in this category, the Beenyup Outfall, which terminated some distance downstream at the sea.

- One site, North Whitfords Drop Structure, was selected with a free convection ventilation system and a drop structure.
- One test site, the Bolivar Trunk Main, was a sewer with a forced convection ventilation system.

The Bolivar Trunk Main spanned the length between Manhole 1(M1) and Manhole 4 (M4). There were two intermediate manholes – M2 and M3. A suction fan was provided at M4 which ventilated the section between M1 and M4. The air space in this length of sewer was isolated from the upstream and downstream air spaces by structures within the system. Ventilation air was normally admitted through an induct at M1 and vented through an educt at M4. Standpipes (2m high and 90 mm diameter) were also fitted at M1, M2 and M3 as part of the test program. These standpipes were sometimes open and sometimes closed during the trials.

*Table 1. List of tracer study sewer test sites*

<b>Air flow</b>	<b>Drop structure</b>	<b>Sewer Name</b>	<b>Location</b>	<b>Sewer Type</b>	<b>Diameter and length</b>	<b>Comments</b>
Free	No	South Parklands Main Sewer	Adelaide	Gravity	611 mm dia, 512 m long	
		Beenyup Outfall Sewer	Perth	Gravity	1950-2250 mm dia, 702 m long	Downstream bottleneck
	Yes	North Whitfords Drop Structure	Perth	Gravity	533-610 mm dia, 242 m long	4.3 m drop
Forced	No	Bolivar Trunk Main	Adelaide	Gravity	1894-1935 mm dia, 412 m long	Forced ventilation

## 2.3 Test results - free convection

The results of gas tracer tests in the South Parklands Main Sewer where there was no forced ventilation are presented in Figure 1. The results show that measured air velocities averaged about 50% of the water velocity at low water velocities in the range 0.3 to 0.7 m/sec. Similar data in Figure 2 for the Beenyp Outfall Sewer show lower air velocities around 10% of the water velocity when the water velocity is in the range 0.9 to 1.2 m/sec.

There are several possible reasons for the lower observed air flow rates in the Beenyp Outfall Sewer but it is quite possible that the lower results arose because of the downstream 'bottleneck' presented by the discharge into the sea.

The results of air velocity measurements in the Bolivar Trunk Main are included in Figure 3. This figure includes data obtained when the ventilation fans were not operating. Interpretation of the data is complicated because of the wide range of operating conditions but general conclusions are:

1. The data labelled *Fans off, M1 Induct uncovered* presents results obtained during a period when there was no forced ventilation operating between M1 and M4. Air velocities under these circumstances decreased from about 65% to 30% of the water velocity as the water velocity increased from 0.5 to 1.1 m/sec.

Opening an intermediate vent at M3 did not influence the air flow rate. This is the expected outcome if the ventilation rate is determined by the balance between the drag force exerted by the moving water phase and the friction force with the pipe wall (Section 3).

2. The data labelled *Fans off, M1 Induct covered, stand pipe open* were obtained during a period where air was admitted to the sewer at M1 through a standpipe rather than the induct structure. The results indicate lower air velocities around 0.1 m/sec that are independent of water velocities between 1.0 and 1.3 m/sec. This observation implies that the 90 mm standpipe at M1 imposed a greater restriction to air flow than the M1 induct.

This data includes test results obtained with *All fans off* (ie the fans upstream and downstream of the test section as well as the fans at either end of the test section turned off), *Post M4 fan only on* (ie the fan downstream of the test section turned on) and *Pre M1 and post M4 fans only on*. The similarity between the data under these 3 conditions indicates that the fans beyond the test section did not influence measured air flow rates.

The principal difference between the operating conditions applicable during the test periods described in (a) and (b) above is the difference between operation of the induct at M1. This change was probably responsible for the threefold change in air velocities. The general conclusion is that passive ventilation structures can have a large influence on free convection air velocities in sewers.

The data in Figure 3 is also presented in Figure 4 except that in this case the test results labelled *Fans off, M1 induct covered, stand pipe open* have been differentiated to show the influence of wind speed. The data indicates no influence of wind speed up to speeds of 6

m/sec (ie 20 kmh). A similar conclusion arises from the data labelled *Fans off, Induct uncovered*.

Similar data to that in Figure 3 is also presented in Figure 5 except that the data has been differentiated to show the effect of the difference between the temperature of sewer air and ambient air. In this case, the sets of data labelled *Fans off, Induct uncovered* and *Fans off, induct covered, stand pipe open* show no variation due to temperature difference.

The general conclusion arising from the present investigation is the air velocity in free convection sewers is determined primarily by the characteristics of passive ventilation structures. As a consequence, it is difficult to develop a reliable quantitative estimate but a rough rule of thumb, based on the present test data, is that air velocities in free convection sewers typically range between 10% and 50% of the water velocity.

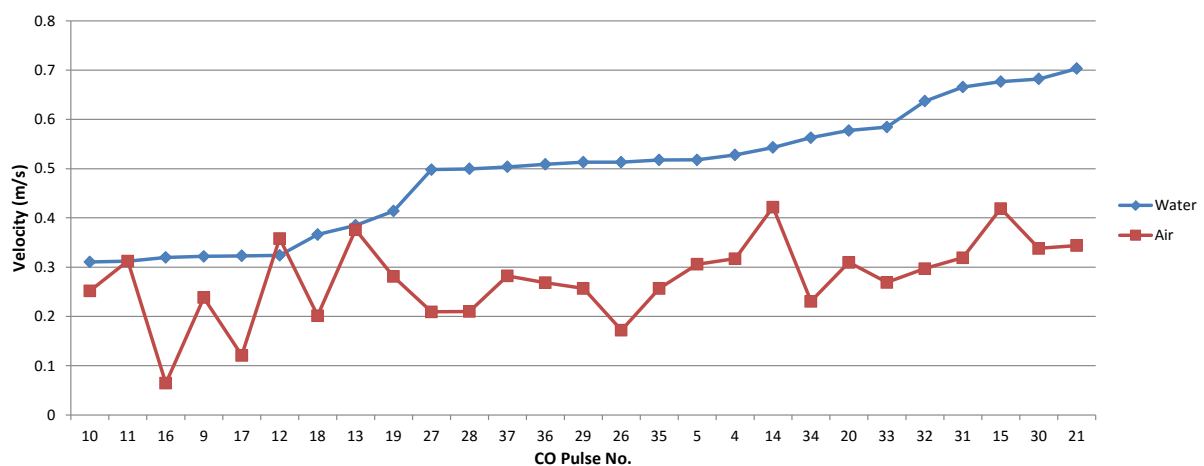


Figure 1. Correlation between the air velocity and the water velocity for South Parklands Main Sewer (no forced ventilation)

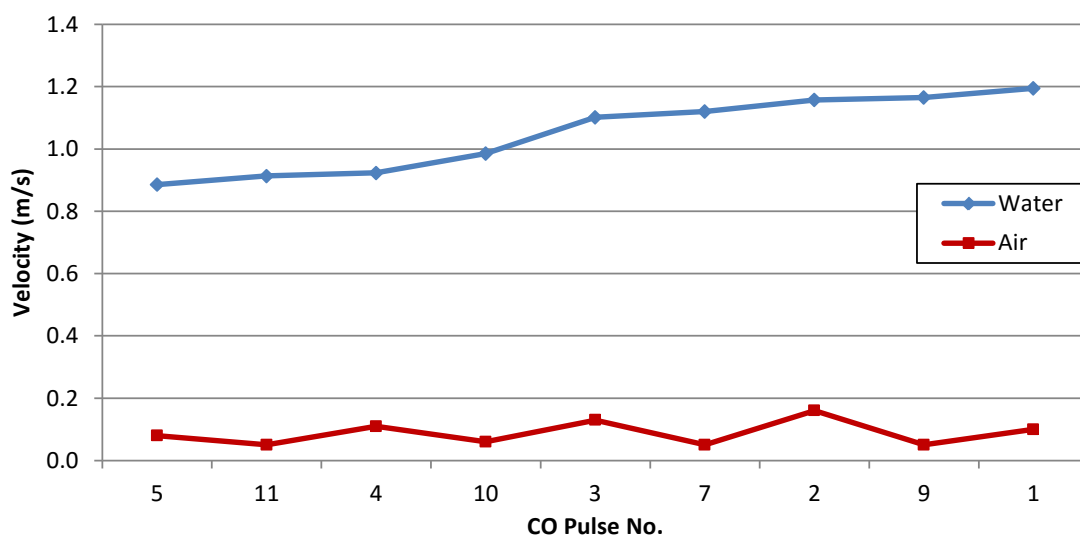


Figure 2. Correlation between the air velocity and the water velocity for Beenyup Outfall Sewer (no forced ventilation)

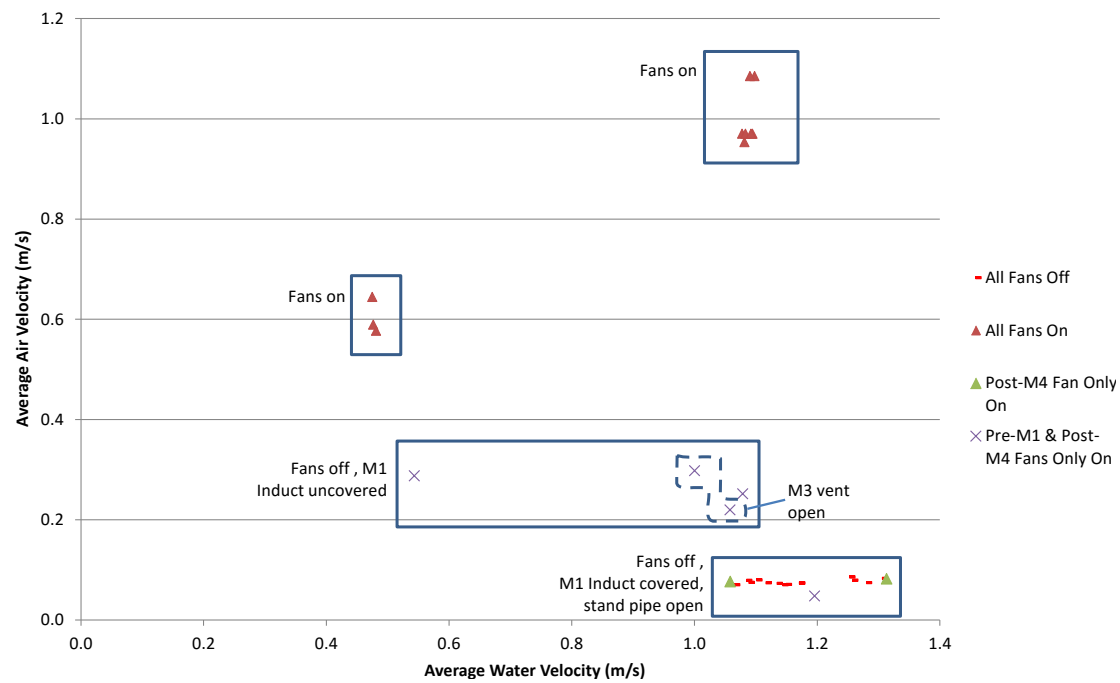


Figure 3. Correlation between the air and water velocity under different ventilation conditions in the Bolivar Trunk Main

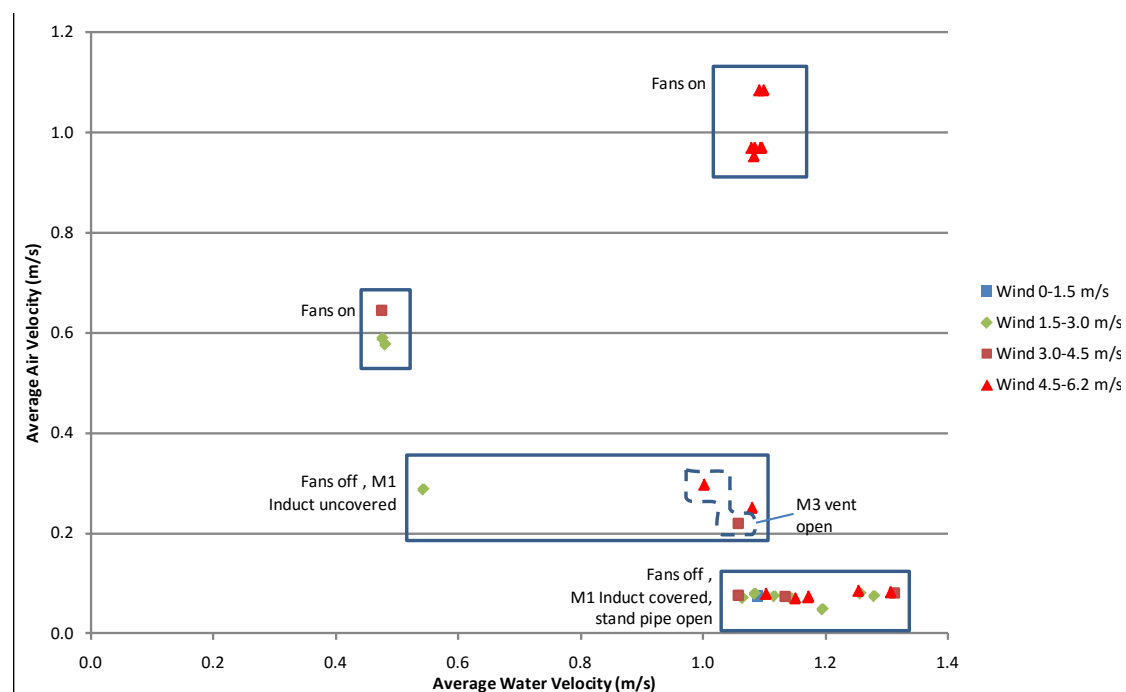


Figure 4. Correlation between the air and water velocity in the Bolivar Trunk Main at different wind velocities

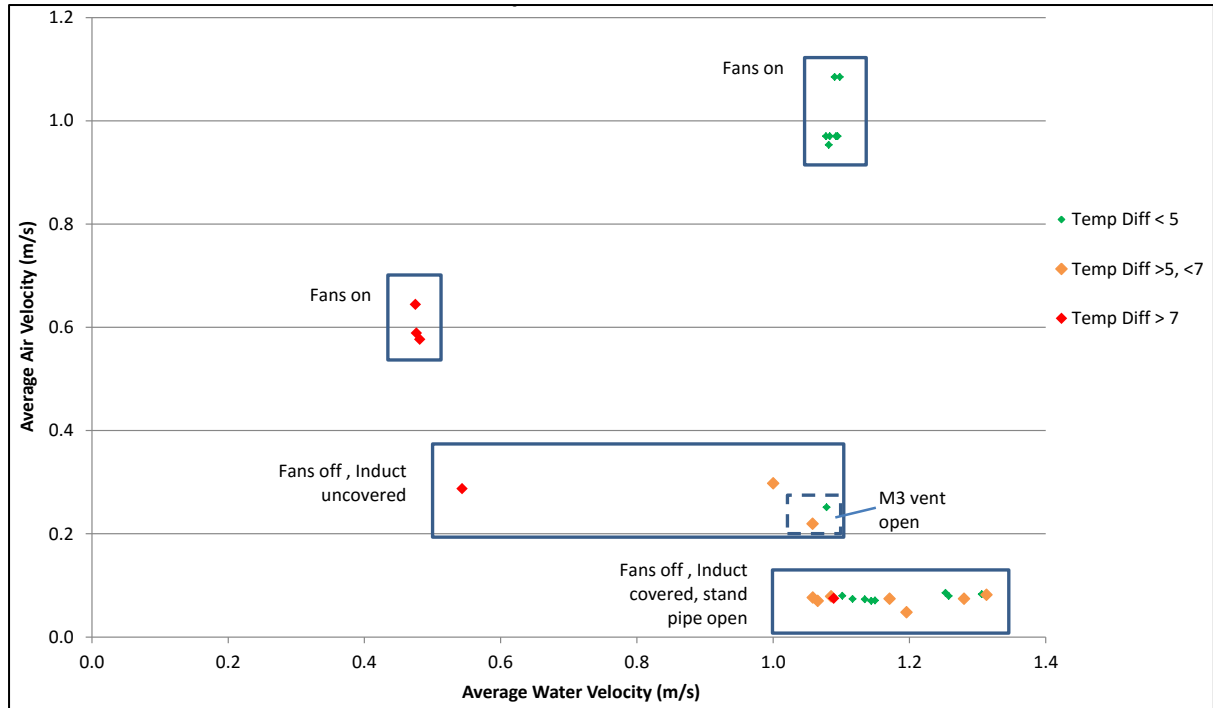


Figure 5. Correlation between the air and water velocity in the Bolivar Trunk Main at different air temperatures

### 3. Ventilation model

A ventilation model for a gravity sewer is proposed based upon the model proposed by Apgar et al. (2009). The model considers the force balance on the headspace air system as follows:

$$\frac{\Delta Mom}{\Delta t} = \Delta F_{Pres} + \Delta F_{Grav} + \Delta F_{Drag} - \Delta F_{Fric} \quad (1)$$

where  $\Delta Mom/\Delta t$  is the net rate of change of momentum for the headspace air control volume, and the terms on the right side represent forces acting on the headspace air due to net pressure at the system boundaries ( $\Delta F_{Press}$ ), gravity ( $\Delta F_{Grav}$ ), liquid drag ( $\Delta F_{Drag}$ ), and friction at the pipe walls ( $\Delta F_{Fric}$ ).

All the force terms in the above equation can be estimated using well-established relationships that take into account the air properties, pipe properties and the hydraulic conditions.

For steady state conditions, the above equation applied between 2 points A and B becomes:

$$(A_{air} r V^2)_B - (A_{air} r V^2)_{A'} = A_{air} (P_{A'} - P_B) + A_{air} L r \times g \frac{(z_{A'} - z_B)}{L} + F_{Drag} - F_{Fric} \quad (2)$$

The drag and friction terms can be expressed as:

$$F_{Drag} - F_{Fric} = r \cdot \left[ \frac{1}{2} C_D (V_{WW} - V)^2 WL - \frac{f}{8} V^2 P_{air} L \right] \quad (3)$$

where:

- $A_{air}$  = Headspace cross sectional area (m<sup>2</sup>)
- $\rho$  = Density of sewer air (kg/m<sup>3</sup>)
- $V$  = Average air velocity (m/s)
- $P$  = Static absolute pressure (Pa)
- $L$  = Length of sewer (m)
- $g$  = Acceleration due to gravity (9.81 m/s<sup>2</sup>)
- $z_{A'}$  = Head end elevation of air cross section centroid from mean sea level (m)
- $z_B$  = Tail end elevation of air cross section centroid from mean sea level (m)
- $C_D$  = Drag coefficient (Dimensionless)
- $V_{WW}$  = Velocity of wastewater (m/s)
- $f$  = Friction factor (dimensionless)
- $W$  = Water surface width (m)
- $P_{air}$  = Headspace air dry perimeter (m)
- $P_{A'}$  = Head end absolute pressure (Pa)
- $P_B$  = Tail end absolute pressure (Pa)

### 3.1 Determination of drag coefficient

The drag force at the air/water interface can be estimated from the air-water Reynolds number,  $Re_{air\_water}$  :

$$Re_{air\_water} = R_H \cdot 4 \cdot \frac{|V_{WW} - V|}{\nu} \quad (4)$$

where  $R_H$  is the hydraulic radius of the air space defined in the usual way as the ratio of the flow area to wetted perimeter and  $\nu$  is the kinematic viscosity of air. The expected relationship between  $Re_{air\_water}$  and  $f$  is given by the Colebrook equation:

$$f_{air\_water} = \frac{1}{\left[ -1.8 \log_{10} \left( \frac{6.9}{Re_{air\_water}} \right) \right]^2} \quad (5)$$

Once the friction factor at the air/water interface is known, the drag coefficient at the air/water interface,  $C_D$ , can be calculated as follows:

$$C_D = \frac{f_{air\_water}}{4} \quad (6)$$

The reliability of this approach for estimating the effect of drag at the air/water interface was evaluated by considering the data in Figure 3 labelled *Fans off, M1 Induct covered, stand pipe open*. This data was obtained with the sewer headspace open at one standpipe but closed elsewhere, resulting in very low air velocities. Under conditions where the air velocity is low, the influence of friction at the pipe wall is small. Thus the pressure distribution within the sewer can be assumed to be determined by the effects of the drag force at the air/water interface.

The values of measured and calculated pressure differences in the 1900 mm Bolivar Trunk Main under these conditions of very low air velocity are presented in Figure 6. The figure includes upper and lower bounds for the measured pressure difference which arise because the pressure measurements had a precision of about 2 Pa. This limitation notwithstanding, the data in Figure 6 indicates that the calculated pressure differentials were typically about 25% lower than the measured values although the discrepancy was 50% in some cases. The likely level of agreement in smaller sewers is unknown.

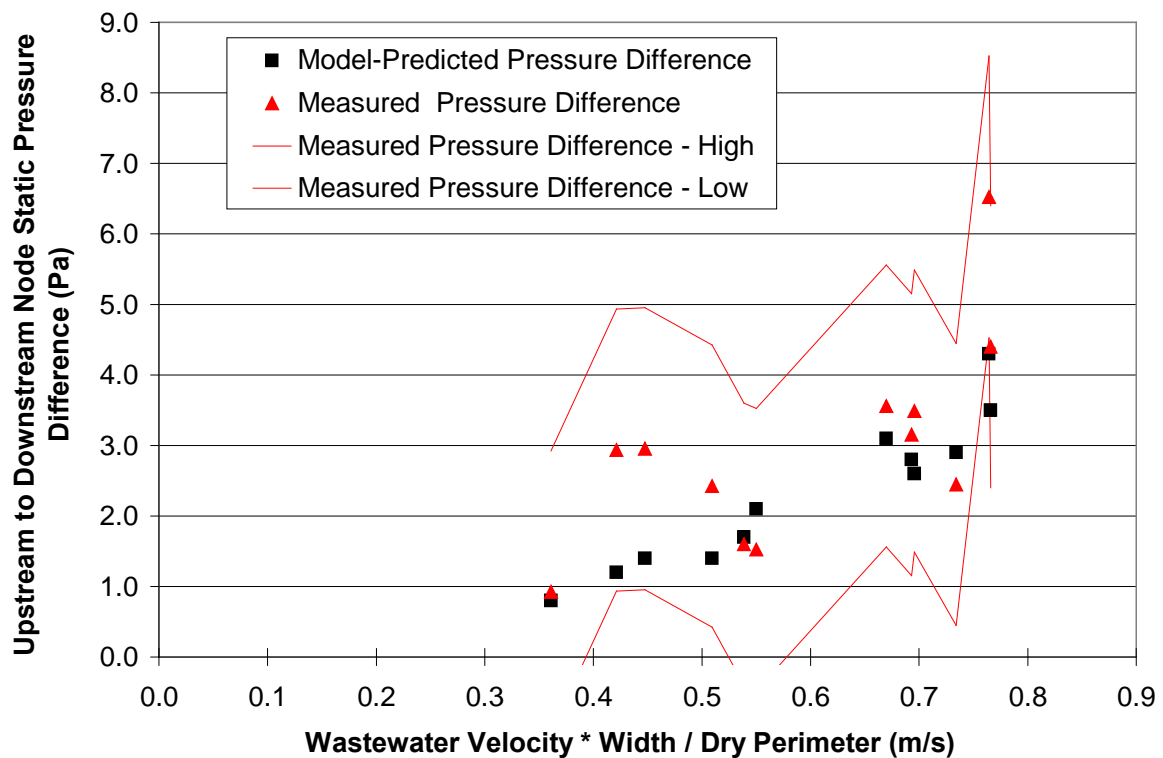


Figure 6. Measured versus model-predicted upstream-to-downstream pressure difference in the Bolivar Trunk Main at low air velocities



### 3.2 Determination of air/pipe friction

The Reynolds number at the air/wall interface,  $Re_{air\_wall}$  is given by:

$$Re_{air\_wall} = R_H \times 4 \times \frac{|V|}{\eta} \quad (7)$$

The relationship between the friction factor at the wall and the Reynolds number of the air flow in a pipe is a standard problem and the present analysis used the following correlation:

$$f_{air\_wall} = 0.5 \cdot \frac{1}{\left[ -1.8 \log_{10} \left\{ \left( \frac{\delta}{3.7} \right)^{1.11} + \frac{6.9}{Re_{air\_wall}} \right\} \right]^2} + 0.5 \cdot \frac{64}{Re_{air\_wall}} \quad (8)$$

where  $\delta$  is the relative pipe roughness, equal to the actual roughness,  $\epsilon$ , divided by the head space hydraulic diameter.

The first term on the right hand side of equation (9) is the Haaland equation which provides a correlation for measured values of  $f$  in turbulent pipe flow and the second term is the well-known analytical solution for  $f$  in laminar pipe flow. The current approach uses the average of these two terms to estimate the value of  $f$ .

The reliability of this approach for estimating air velocities was evaluated by considering the test data in Figure 3 labelled *Fans on*. Under the conditions where the ventilation fans were on, the data indicates that the observed air velocities were very close to the water velocity. There was therefore negligible drag at the air/water interface and the axial pressure differential in the sewer was determined by the friction at the pipe walls.

A comparison between the measured air velocities in the 1900 mm Bolivar Trunk Main with the fans on and air velocities calculated using the approach outlined above is provided in Figure 7. The upper and lower bounds in this figure arise because of the pressure measurements had a precision of about 2 kPa.

The data in Figure 7 assumes a pipe actual roughness of 2 cm. This high value was adopted to improve the level of agreement between the measured and calculated values. The data in Figure 7 indicates that calculated air velocities were typically 50% of the measured values following this adjustment. The likely level of agreement in smaller sewers is unknown.

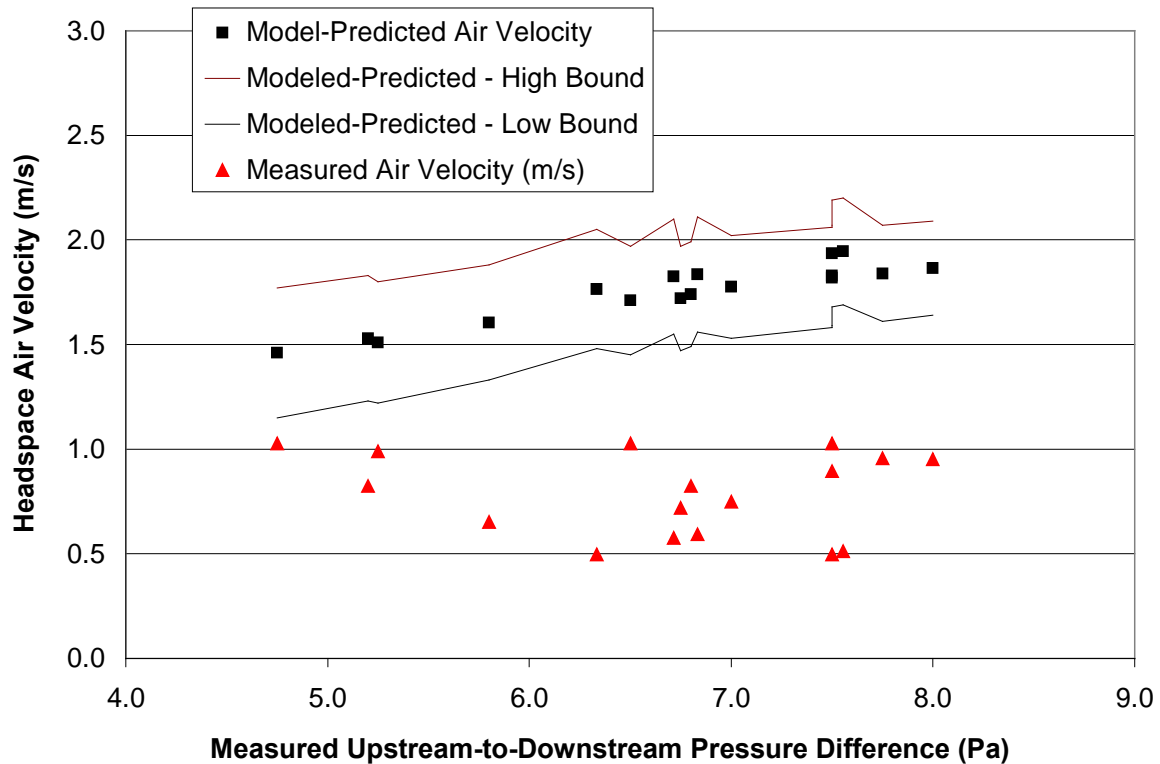


Figure 7. Comparison of measured and calculated air velocities in the Bolivar Trunk Main with the ventilation fans operating

## 4. Ventilation calculation

### 4.1 Calculation tool

The approach described in Section (3) has been incorporated into an [excel spreadsheet](#) and a [User Manual](#) that perform the calculations by iteration. The conceptual situation considered by the spreadsheet is illustrated in Figure 8.

The calculation considers a section of gravity sewer. The sewer includes a number of 'reaches' which span between 'nodes'. A node is a point at which water may enter the sewer and air may either enter or leave the sewer. Two types of nodes are included. In one case (e.g. nodes 1 and 5 above) air is allowed to enter or leave through a ventilation structure. In other cases, (e.g. nodes 2, 3 and 4 above), air may enter though a side stream connection but there is no ventilation structure. Thus the model considers a length of gravity sewer between two ventilation structures and assumes that intermediate manholes are sealed.

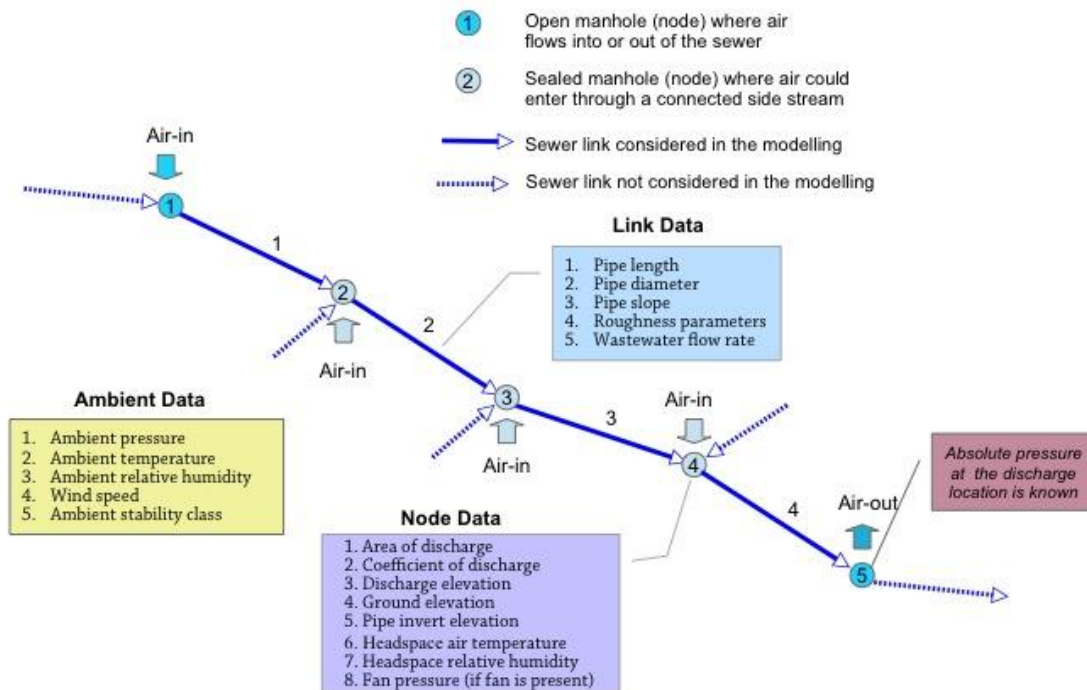


Figure 8. Schematic of the sewer network used for ventilation modelling

The calculation procedure includes an estimate of the water velocity in each sewer link. This estimate is based on Manning's equation:

$$V_{ww} = \frac{S^{0.5}}{n} \left( \frac{A_{water}}{P_w} \right)^{\frac{2}{3}} \quad (9)$$

Where,

S = pipe slope, n = Manning's coefficient,  $A_{water}$  = Area of water flow,  $P_w$  = Wetted perimeter

The XL spreadsheet calculation is an automated iterative procedure which, in the case of a sewer without a fan, provides an estimate of the:

- Absolute air pressure at each node and
- The air flow rate in each sewer reach.

In the alternate case, where a fan is provided, the user is required to enter an estimate of the pressure head provided by the fan. The spreadsheet then calculates the pressure at each node and the air flow rate in each reach. The user then has to use an iterative procedure to ensure that the fan conditions lie on the operating curve. Thus the spreadsheet can be used to determine:

- The air flow rate in the sewer at a zero pressure differential. That is, the spreadsheet can be used to determine the air flow rate in the sewer in the absence of a fan.
- The air flow rate in a sewer provided with a forced convection ventilation system.

## 4.2 Reliability of calculation tool

The reliability of the calculation tool was evaluated against data collected from trials in the Beenyup Outfall.

A comparison of measured and calculated pressures at a single node under a range of flow conditions is shown in Figure 9. This comparison indicates that calculated node pressures were typically within about plus or minus 30% of the measured values.

A similar comparison of air velocities in the Beenyup Outfall is shown in Figure 10. This figure indicates that calculated air velocities typically scattered about the measured velocities by plus or minus 50%.

Figure 10 also includes velocities calculated using the 'Prescod and Price extrapolation'. These values are consistently higher than the measured velocities by a factor of 2 and the present model appears more reliable.

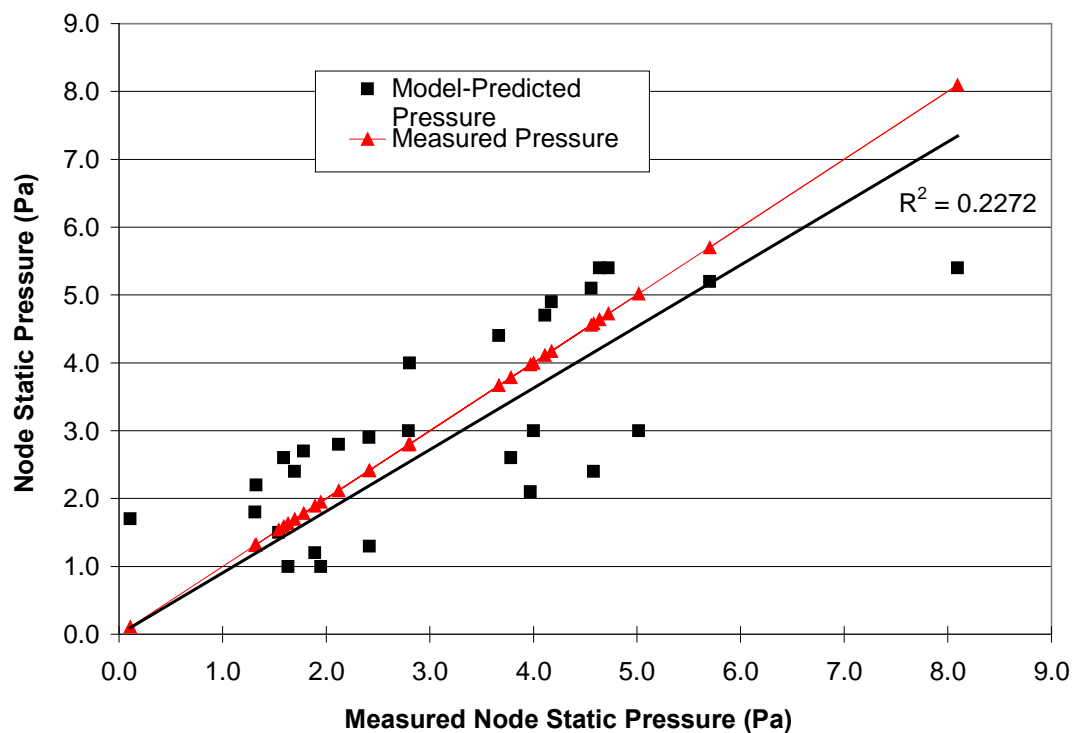


Figure 9. Comparison of measured and calculated air pressures at the downstream node in the Beenyup Outfall with no forced convection

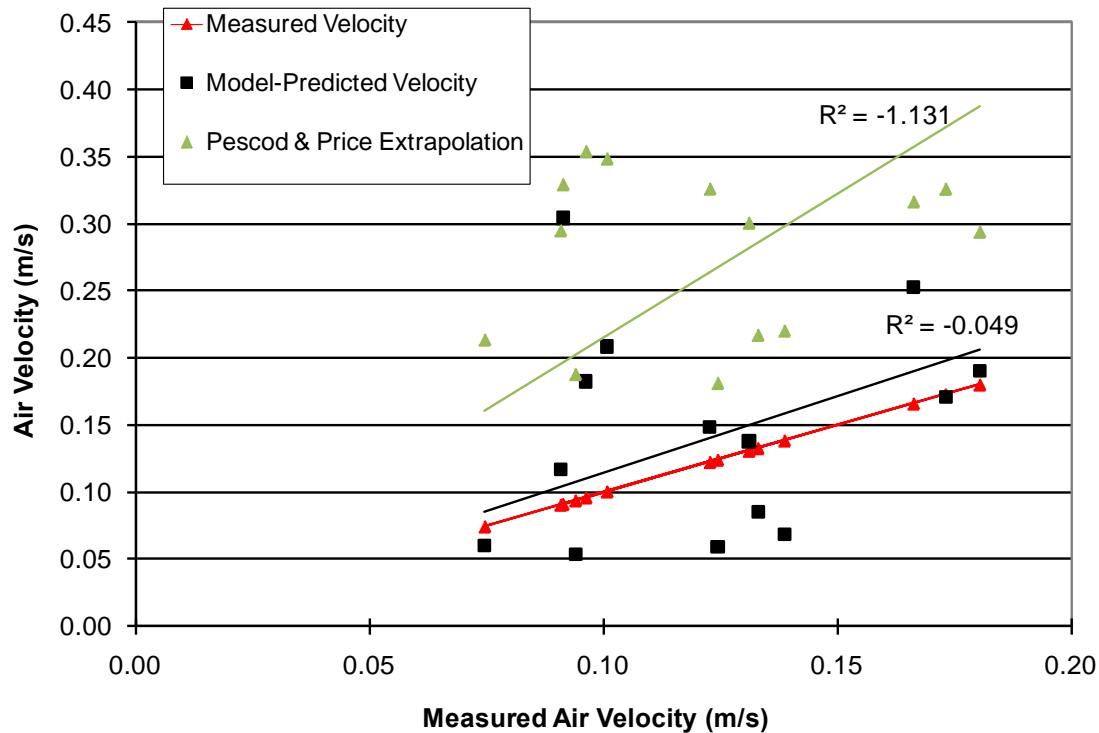


Figure 10. Comparison of measured and calculated air velocities at the downstream node in the Beenyup Outfall with no forced convection

### 4.3 Data requirements

Data requirements for the ventilation calculation tool are summarised in Table 2.

Table 2. Data requirement for ventilation tool

Variable	Units	Notes
<b>Air Conditions</b>		
Ambient temperature	Degrees Celsius, °C	Ground-level atmospheric (ambient) temperature
Headspace air temperature	Degrees Celsius, °C	Sewer headspace air temperature, would depend upon the location (typically 20-30 degree C in Australia)
Ambient relative humidity	%	Ground-level (ambient) relative humidity.
Headspace relative humidity	%	Sewer headspace air relative humidity. Typical range is 50-90%.
<b>Fan</b>		
Fan pressure	Pa	Fan pressure (gauge pressure selected from fan performance curves). If there are no fans associated with the sewer, this parameter is left blank.

Variable	Units	Notes
Fan node	-	The name of the node of the sewer pipe where the fan/fan extraction point is located.
Wind Conditions		
10 m wind speed	m/s	Wind speed measured 10 m above ground level. Typical values range between 1 to 5 m/s.
Ambient stability class	-	Stability class is an indicator of atmospheric turbulence, commonly categorised into 6 classes – A, B, C, D, E, and F. A- very unstable (day time), B-Unstable (daytime only), C- Slightly unstable (day time only), D-neutral, day and night, E-Stable, night time only, F-Very stable, night time only
<b>Sewer Characteristics</b>		
Link name	-	The user-defined name of a pipe link.
Pipe length	m	Length of link.
Pipe diameter	m	Diameter of sewer pipe.
Pipe slope	m/m	Slope of the sewer pipe.
Manning's roughness coefficient	s/m <sup>1/3</sup>	The value of Manning's roughness coefficient (n) depends on material of construction. For old concrete pipes, this could be taken as 0.013.
Dry absolute roughness	m	The dry absolute roughness, $\epsilon$ , of the pipe material.
Node discharge area	m <sup>2</sup>	The area of an opening in the pipe that allows air to enter or leave the sewer. For example, pick holes or vent stacks.
Discharge coefficient	dimensionless	This is the discharge coefficient for air across an orifice or fitting. Typical value is 0.5-0.7.
Node discharge elevation	m	The elevation of a discharge points e.g. a vent pipe or stack.
Ground elevation of each node	m	Ground elevation above sea level
Pipe rise	m	This parameter is calculated from pipe slope.
Pipe invert elevation	m	Pipe invert elevation above the datum (sea level) of the upstream end of a reach.
Entering wastewater flow	m <sup>3</sup> /s	Flow of wastewater entering at each node. Normally wastewater enters at the upstream node, but side stream flows can enter at other nodes (e.g. rising main discharge)

The outputs of the calculation tool are listed in Table 3.

Table 3. List of outputs of the ventilation tool

Variable	Units	Description
Node static pressure	Pa	Static pressure at the upstream end of each link.
Node Discharge Driving Force	Pa	The differential pressure between the atmosphere and the discharge level of a manhole (level at which an opening is provided)
Headspace air flowrate	L/s	Headspace air flowrate. Positive values indicate downstream flow.
Headspace air velocity	m/s	Headspace air velocity. Positive values indicate downstream flow.
Outgas flow rate	L/s	Outgas flowrate at the open manholes. Positive values indicate in-gassing, negative values indicate out-gassing.

## 5. Air flow rate through drop structures

Drop structures are known to drag air into the downstream sewer due to the drag force exerted by the falling liquid. The present approach proposes a standard method for determining the air flow rate through a drop structure based on a tracer test.

### 5.1 Drop structure model

A conceptual description of a drop structure is presented in Figure 15. The key aspects include the idea that there is a vertical downwards air flow induced by the falling water,  $Q_{\text{drop}}$ , and a recycle air flow rate in the structure equal to  $Q_{\text{return}}$ . The volumetric throughput is  $Q_{\text{through}}$ .

The envisaged situation for analysis is a pulse injection of the tracer, carbon monoxide, at the inlet. The mass of tracer during the pulse is  $q_{\text{tracer}}$ .

The subsequent concentration of tracer is measured at the point shown in Figure 11 at the bottom of the drop structure. The peak initial tracer concentration is designated as  $C_i$ .

The value of  $C_i$  is given by:

$$C_i = q_{\text{tracer}}/Q_{\text{drop}} \quad (10)$$

The drop structure is regarded as a well-mixed reactor with an initial tracer concentration equal to  $C_i$ . The tracer concentration some-time after the peak concentration occurs is:

$$C(t) = C_i e^{-kt} \quad (11)$$

$$\text{where } k = Q_{\text{through}}/V_{\text{DS}} \quad (12)$$

where  $V_{\text{DS}}$  is the volume of the drop structure.

The experimental concept which arises from this analysis is that a measurement of  $C(t)$  against time can be used to determine  $k$  from Equation (11) and  $Q_{\text{through}}$  from Equation 12.  $Q_{\text{drop}}$  can be determined if required from Equation (10).

## 5.2 Model validation

The results of 3 separate tracer tests in the North Whitfords drop structure (Table 1) are presented in Figure 12. The measured tracer concentration follows the expected exponential form and the value of the exponent suggests a value of  $Q_{\text{through}} = 0.15 \text{ m}^3/\text{sec}$ . The consequent estimate of air velocity in the downstream sewer was about 10% of the water velocity. This is at the lower end of the free convection air velocities discussed in Section 2.3.

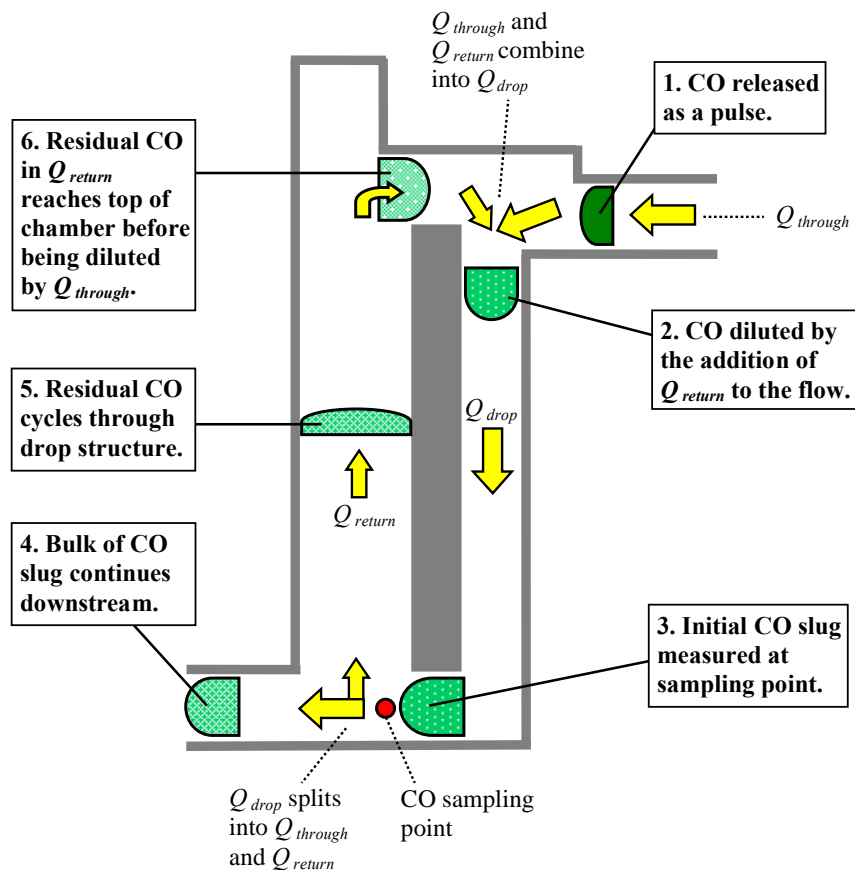


Figure 11. Initial path of tracer gas slug through drop structure



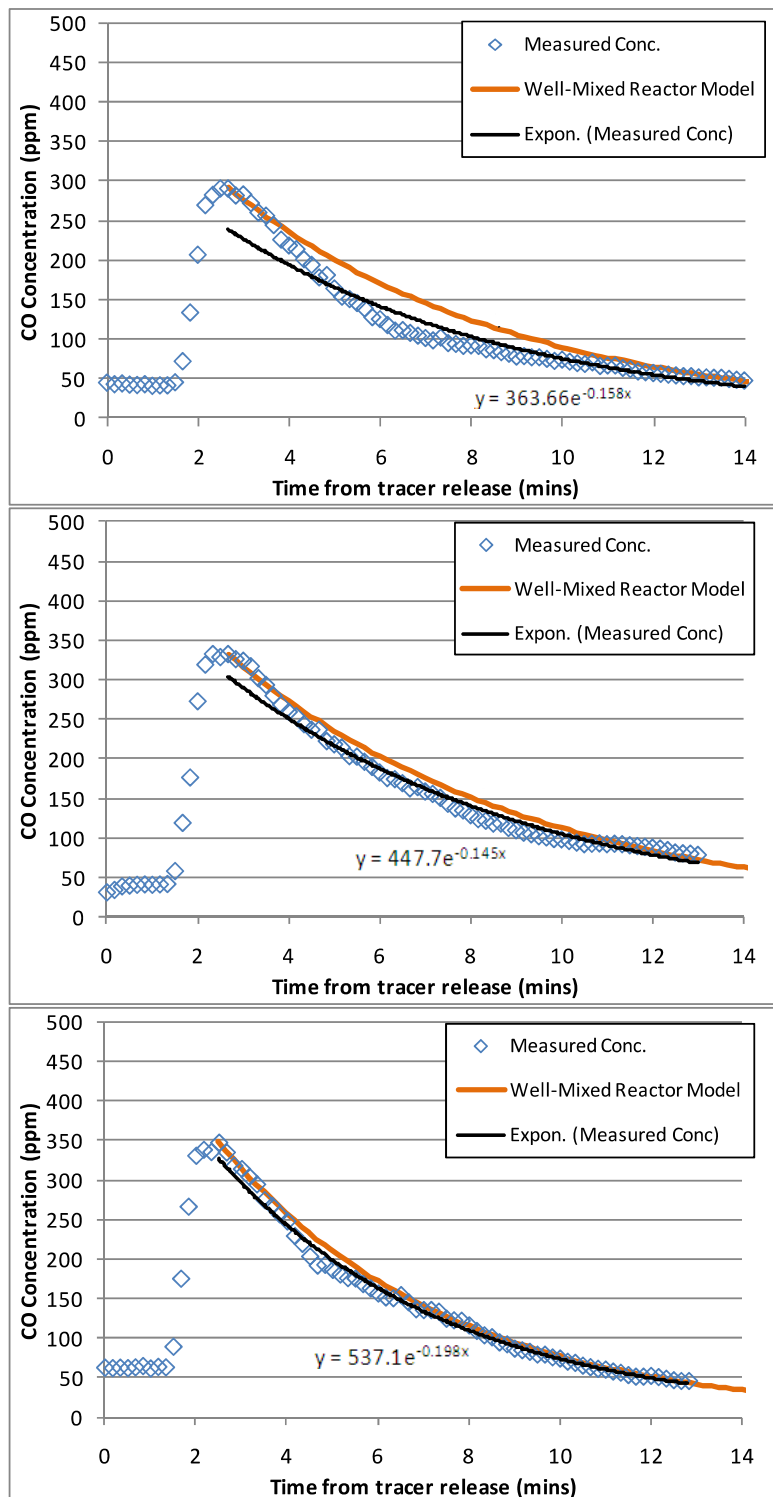


Figure 12. Tracer test results in the North Whitfords drop structure

**For additional information please refer to the following documents:**

- 1 [SCORE Project SP4 Final Report](#)
- 2 [Paper: “A sewer ventilation model applying conservation of momentum”, by M. Ward, G. Hamer, A. McDonald, J. Witherspoon, E. Loh, W. Parker published on Water Science and Technology in 2011](#)

A draft copy of the same paper is available [here](#).

- 3 [WERF Project 04-CTS-1: Minimization of Odors and Corrosion in Collection Systems Phase 1 Report, Chapter 6](#)