SP4: Development of operational strategies and user guidelines for ventilation

Draft summary

(1) Background

The project *Optimal management of corrosion and odour problems in sewer systems* included development of approaches to:

- Determining ventilation rates in gravity sewers with no forced ventilation system and
- Developing and testing a test method to determine ventilation rates through drop structures.

(2) Measurement of ventilation rates in gravity sewers with no forced convection

Ventilation rates in a number of gravity sewers were determined using carbon monoxide as a tracer. The tracer was injected at the upstream location as a pulse. There was minimal axial dispersion of the pulse as it moved downstream and the travel time could therefore be determined reliably.

Tests results were obtained from 3 gravity sewers operating without a forced convection ventilation system. Air velocities in the first of the test sewers were about 50% of the water velocity at low water velocities of about 0.5 m/sec. Lower air velocities around 10% of the water velocity were observed in the second sewer at water velocities around 1 m/sec.

More extensive testing in the third sewer indicated that air velocities were not influenced by wind speed or the temperature difference between sewer and ambient air. In this case, the principal factor determining air flow rates was the position of adjustable vents in ventilation structures. Adjustment of the position of these vents caused a threefold variation in ventilation rates.

The general conclusion arising from the work was that ventilation rates in free convection sewers are determined primarily by the characteristics of ventilation control structures. This observation complicates development of general guidelines but a rule of thumb based on the present study is that air velocities in sewers without forced ventilation range between 10% and 20% of the water velocity.

(3) Estimation of ventilation rates in gravity sewers with no forced convection

The present study adopted a sewer ventilation model proposed earlier by Apgar et al (2009). The model is based on a force balance over the air space in the sewer. This force balance assumes that the rate of change in air momentum between two locations is given by the sum of the:

- Pressure force arising because of longitudinal changes in head space pressure and
- Drag force due to drag at the air/water interface and
- Friction force at the air/sewer interface.

The analysis adapts existing correlations based on pipe flow to estimate the drag and friction force terms.

The analysis has been consolidated into an excel spreadsheet. The spreadsheet assumes the sewerage system comprises a number of 'links' which span between 'nodes'. A link is a length of sewer pipe of constant diameter and slope and a node is a point where there is either a ventilation structure or an interconnecting sewer.

The model requires the user to input data about air conditions (eg temperature and humidity), wind conditions, sewer characteristics and sewage flow rate. The calculated output is a set of values for the expected air flow rate in each link and the absolute air pressure at each node. That is, the spreadsheet estimates the system curve (ie the variation in air flow rate with differential pressure) for each sewer link at the specified sewage flow rate.

The system curve can be used to determine:

- The ventilation rate at zero pressure differential (ie if there is no forced convection)

- The operating point by overlaying the fan curve if a forced ventilation system is adopted.

The reliability of the calculation tool was determined by comparing estimated node pressures and air flow rates with values measured in a single gravity sewer operating without a forced ventilation system. The node pressure scattered around the measured values by plus or minus 30% and the air velocities differed from measured values by plus or minus 50%.

(4) Ventilation rates through a drop structure.

The study developed a theoretical description of the expected concentration of a tracer gas in the gas space within a drop structure following injection of a single pulse of tracer into the upstream air flow. The model was based on the assumption that the gas space was well mixed. The outcome was that the change in tracer concentration was expected to decline exponentially with time following injection of the tracer pulse with an exponent dependent of the ventilation rate through the structure.

The reliability of the model was evaluated using carbon monoxide as a tracer during tests conducted on a single drop structure in a gravity sewer operating without forced ventilation. The results showed the expected exponential relationship between tracer concentration and time following injection of a single tracer pulse. The consequent estimate of the ventilation rate was about 10% of the sewage flow rate.

The general conclusion is that the transient tracer test method and the analysis based on the well mixed gas space model provide a reliable approach to determining ventilation rates through existing drop structures. However further tests are required on other drop structures to develop useful rules of thumb for predictive use.

SP4: Development of operational strategies and user guidelines for ventilation

Draft

(1) Introduction

This section of the *Optimal management of corrosion and odour problems in sewer systems* manual describes:

- 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 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 there:

- Two sites were selected with free convection ventilation systems and no drop structure. One of these sites (ie South Parklands Main Sewer) had no constraints affecting ventilation rates either upstream of downstream of the test length. This was not the case with the other test site in this category, the Beenyup Outfall.
- One site 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. Fans were provided at M1 and at M4. There were also other fans upstream and downstream of the test section. The ventilation systems were provided with flaps that allowed isolation of inducts (ie isolation of air entry points) and isolation of vents (ie isolation of air exit points).

Table 1. List of tracer study sewer test sites

Air flow	**Drop structure**	**Sewer Name**	**Location**	**Sewer Type**	**Diameter and length**	**Comments**
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 Beenyup 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 Beenyup Outfall Sewer but it is quite possible that the lower results arose because of the downstream 'bottleneck'.

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:

a) The data labelled *Fans off, M1 induct uncovered* presents results obtained during a period where only the upstream and downstream fans were operating. 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.

b) The data labelled *Fans off, M1 induct covered, stand pipe open* shows air velocities around 0.1 m/sec that are independent of water velocities between 1.0 and 1.3 m/sec.

   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).

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. However 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)

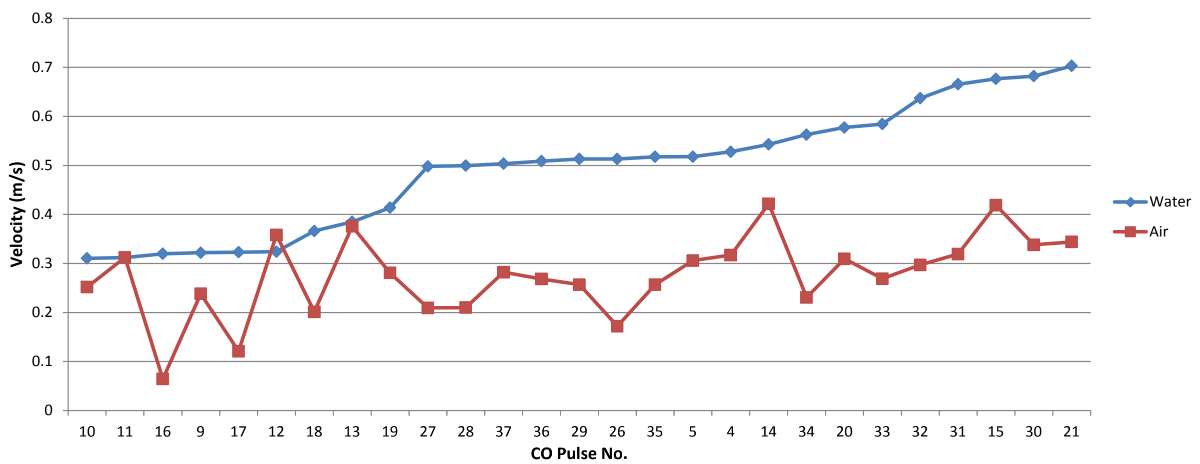


Figure 2: Correlation between the air velocity and the water velocity for Beenyup Outfall Sewer (no forced ventilation)

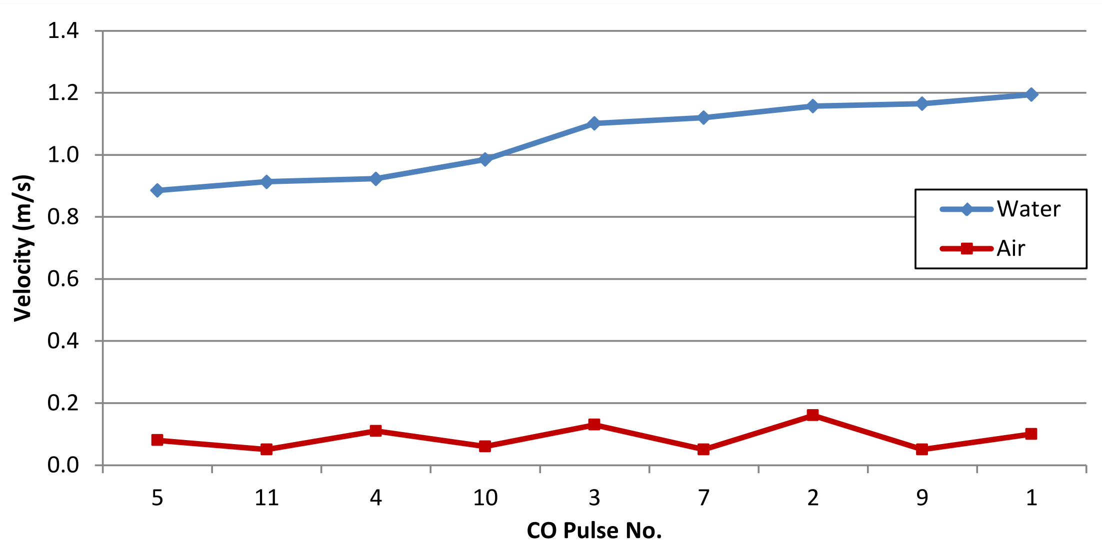


Figure 3: Correlation between the air and water velocity under different ventilation conditions in the Bolivar Trunk Main

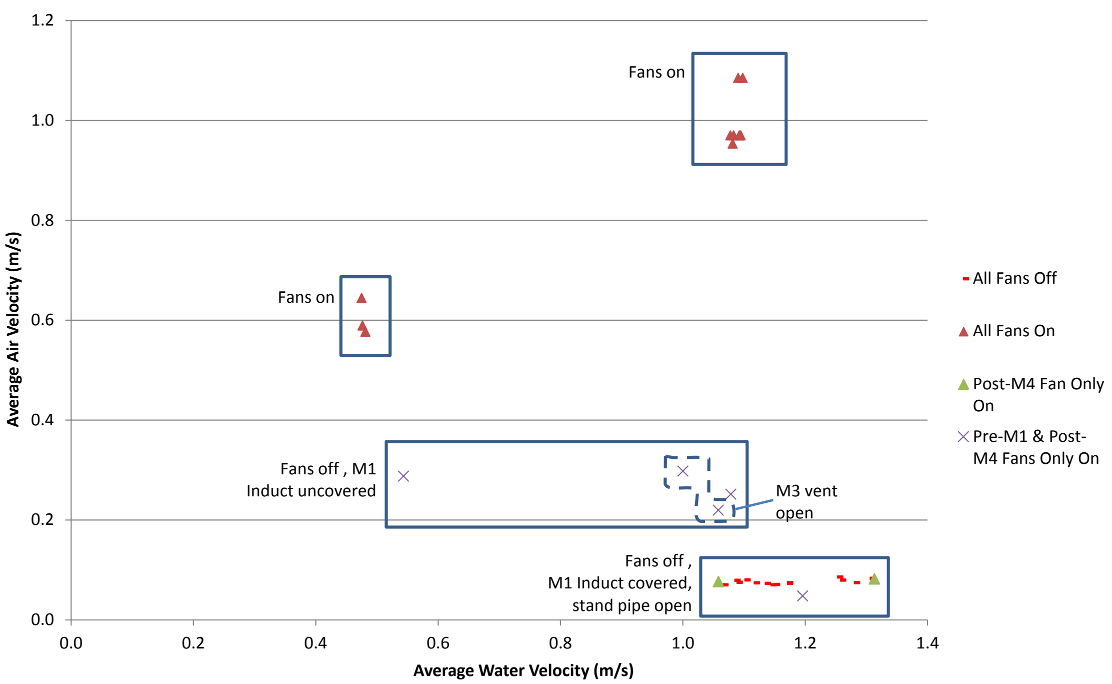


Figure 4: Correlation between the air and water velocity in the Bolivar Trunk Main at different wind velocities

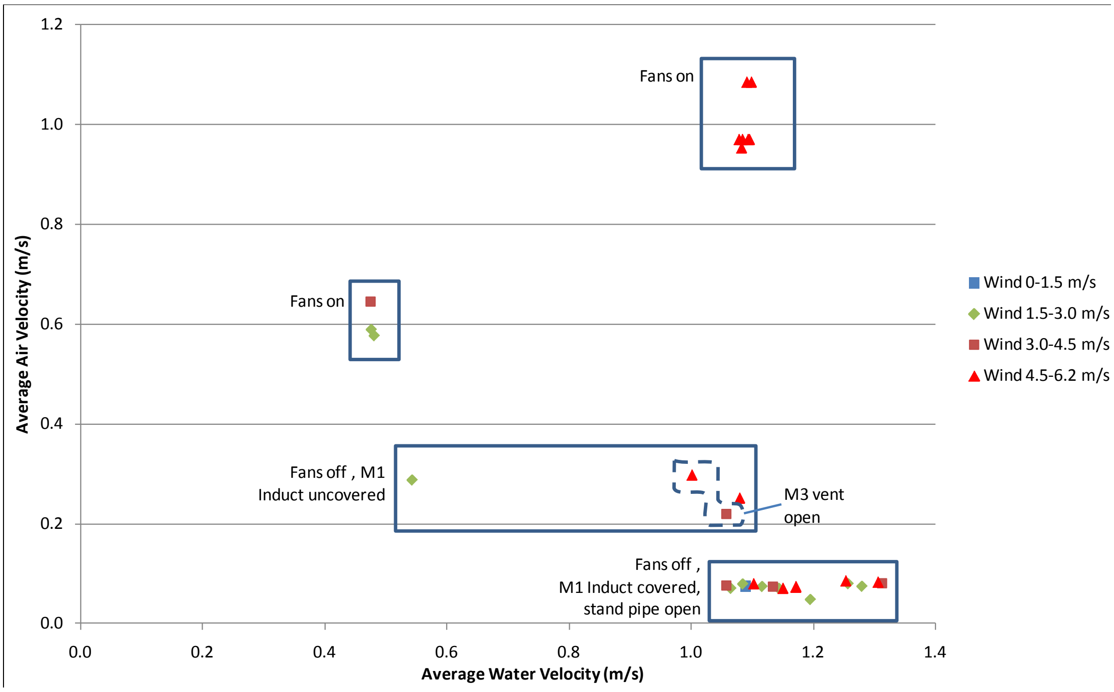
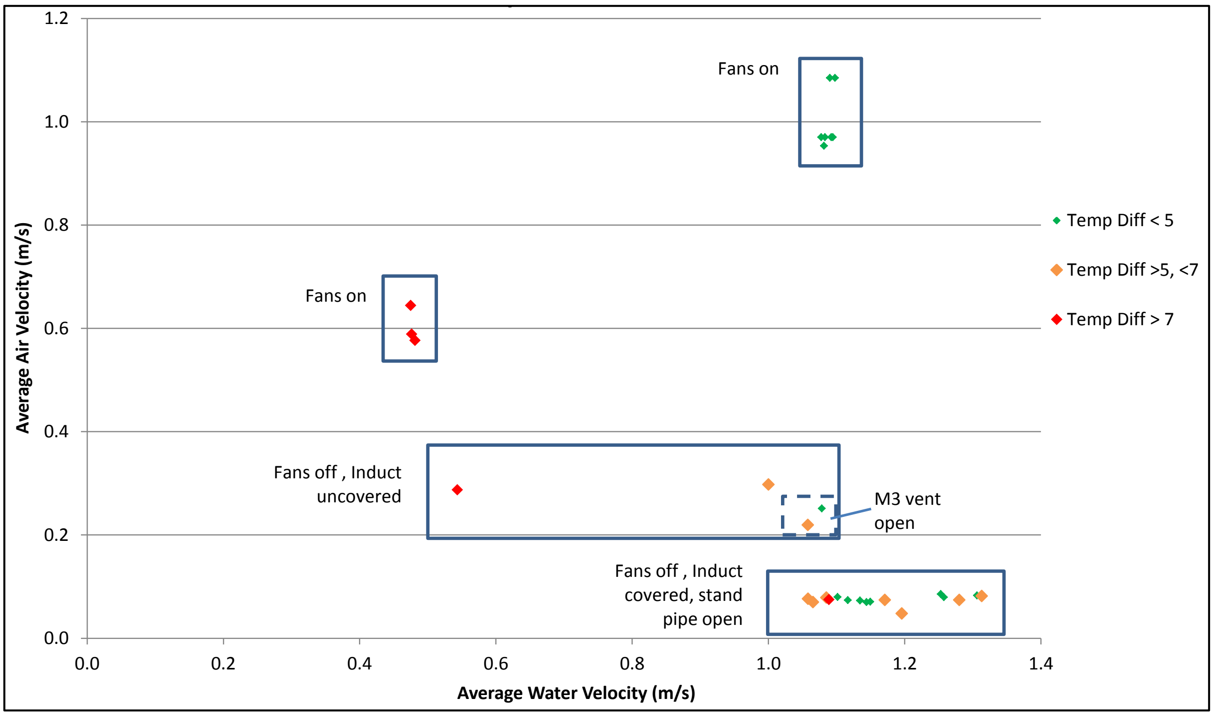


Figure 5: Correlation between the air and water velocity in the Bolivar Trunk Main at different air temperatures



(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:

Force balance on the headspace air system can be described as:

$$\frac{\Delta Mom}{\Delta t} = \Delta F_{\Pr es} + \Delta F_{Grav} + \Delta F_{Drag} - \Delta F_{Fric} \tag{2}$$

where ΔMom/Δt 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 (ΔF_{Press}), gravity (ΔF_{Grav}), liquid drag (ΔF_{Drag}), and friction at the pipe walls (ΔF_{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 becomes

$$(A_{air}\rho V^2)_B - (A_{air}\rho V^2)_{A'} = A_{air}(P_{A'} - P_B) + A_{air}L\rho \cdot g\frac{(z_{A'} - z_B)}{L} + F_{Drag} - F_{Fric} \tag{3}$$

$$F_{Drag} - F_{Fric} = \rho \cdot \left[\frac{1}{2}C_D(V_{WW} - V)^2 WL - \frac{f}{8}V^2 P_{air} L\right] \tag{4}$$

where

A_{air} = Headspace cross sectional area (m^2)
ρ = Density of air (kg/m^3)
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^2)
$z_{A'}$ = 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)

Average air velocity can be calculated using Equations 3 and 4 above provided that all the other terms are known.

Determination of Drag Coefficient

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

$$\mathrm{Re}_{air\_water} = R_H \cdot 4 \cdot \frac{|V_{WW} - V|}{\nu} \tag{5}$$

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 ν is the kinematic viscosity of air. The expected relationship between Re_{air_water} and f is given by the Colebrook equation:

$$f_{air\_water} = \frac{1}{\left[-1.8\log_{10}\left(\frac{6.9}{\mathrm{Re}_{air\_water}}\right)\right]^2} \tag{6}$$

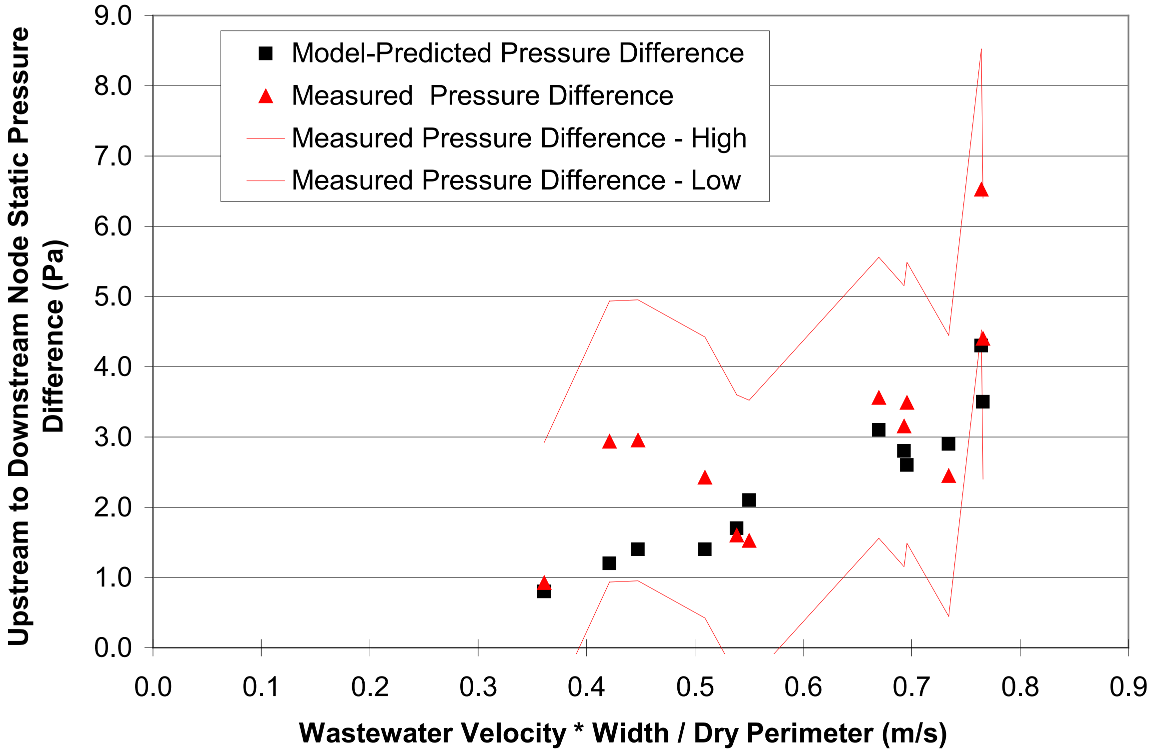
Once the friction factor at the air/water interface is known, the drag coefficient at the air/water interface, C_D, can be calculated as follows:

$$C_D = \frac{f_{air\_water}}{4} \tag{7}$$

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 the upstream end and 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 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 kPa. 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.

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



Determination of Air/Pipe Friction

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

$$\mathrm{Re}_{air\_wall} = R_H \cdot 4 \cdot \frac{|V|}{\nu} \tag{8}$$

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:

$$f_{air\_wall} = 0.5 \cdot \frac{1}{\left[-1.8\log_{10}\left\{\left(\frac{\delta}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}_{air\_wall}}\right\}\right]^2} + 0.5 \cdot \frac{64}{\mathrm{Re}_{air\_wall}} \tag{9}$$

where δ is the relative pipe roughness, equal to the actual roughness divided by the head space hydraulic diameter.

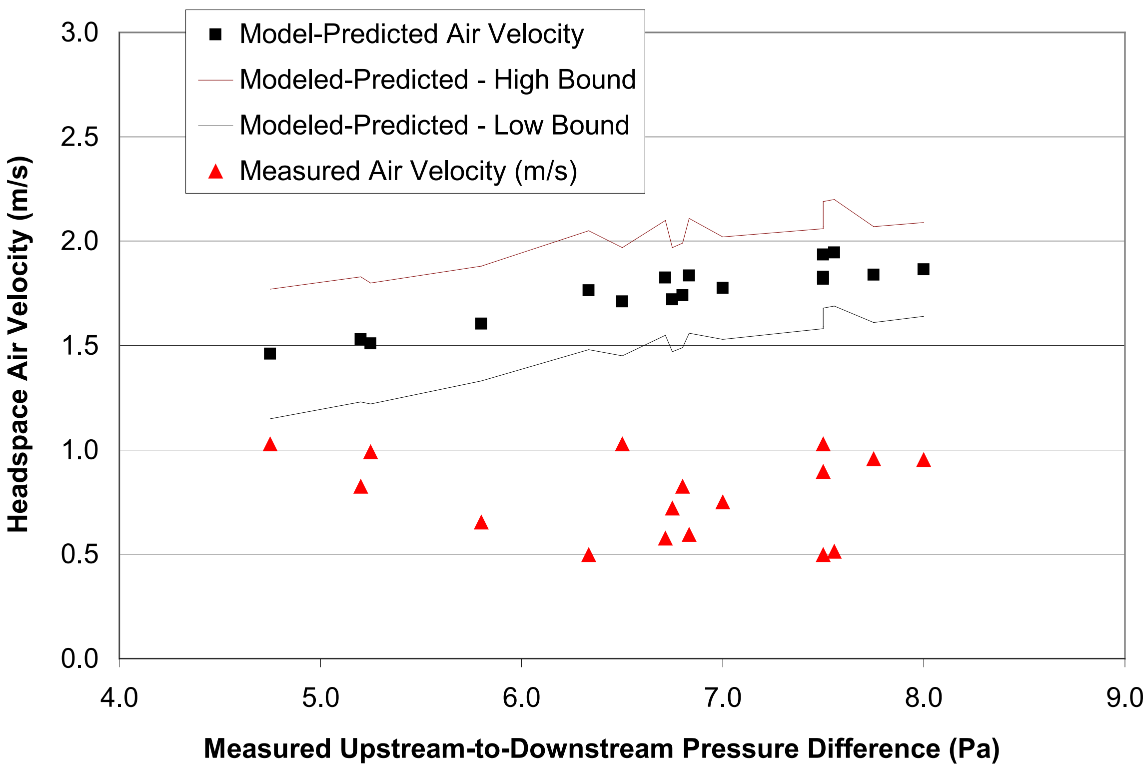
The first term on the right hand side of equation (9) is the Haaland equation which provides a correlation for measured values of f in turbulent pipe flow and the second term is the well known analytical solution for f in laminar pipe flow. The current approach uses the average of these two terms to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

The reliability of this approach to 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 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.

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

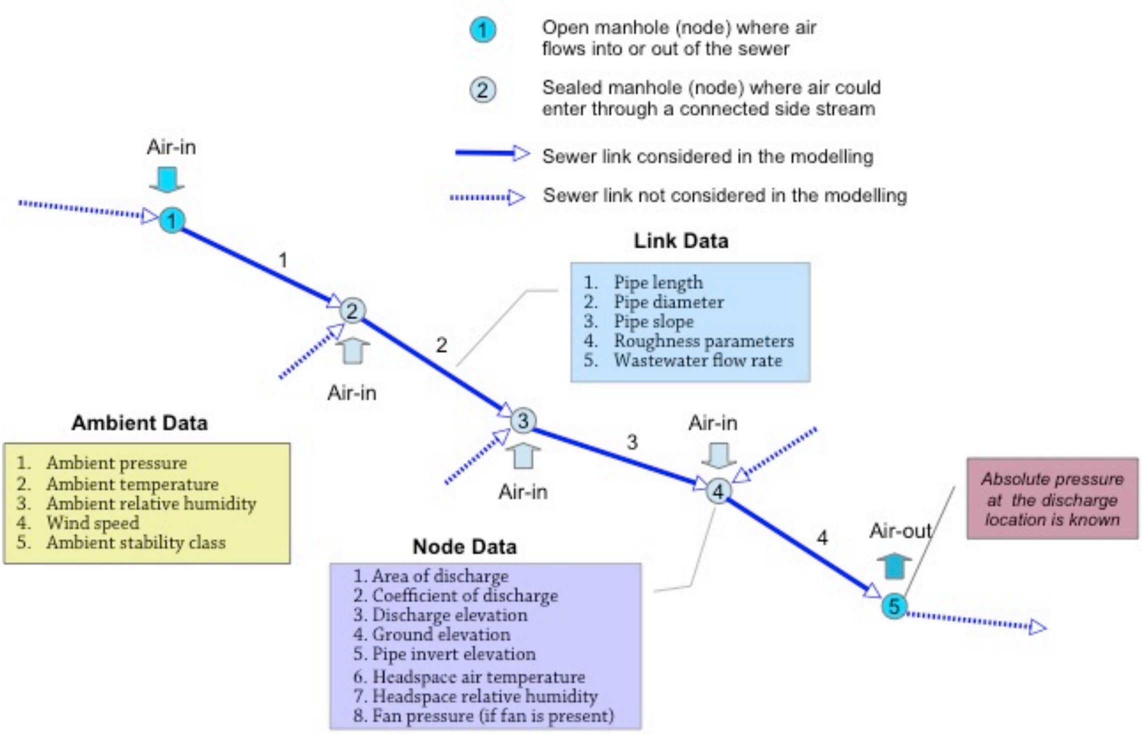


(4) Ventilation calculation

(4.1) Calculation tool

The approach described in Section (3) has been incorporated into an excel spreadsheet that performs the calculations by iteration. The conceptual situation considered by the spreadsheet is illustrated in Figure 8.

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



The calculation considers a section of gravity sewer. The sewer includes a number of 'links' which span between nodes. A node is a point at which air may either enter of leave the sewer. Two types of nodes are included. In one case (eg nodes 1 and 5 above) air is allowed to enter through a ventilation structure. In other cases,(eg 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.

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

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

Where,

S = pipe slope

n = Manning coefficient

A_{water} = Area of water flow

P_w = Wetted perimeter

The XL spreadsheet calculation is an automated iterative procedure which provides an estimate of the:

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

Thus the calculation tool provides a system curve (ie a plot of air flow rate versus pressure differential) for each sewer link. This curve can be:

- Used to determine the air flow rate in the sewer at a zero pressure differential. That is, the system curve can be used to determine the air flow rate in the sewer in the absence of a fan.
- Matched with the performance curve for a fan to determine the operating point for 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

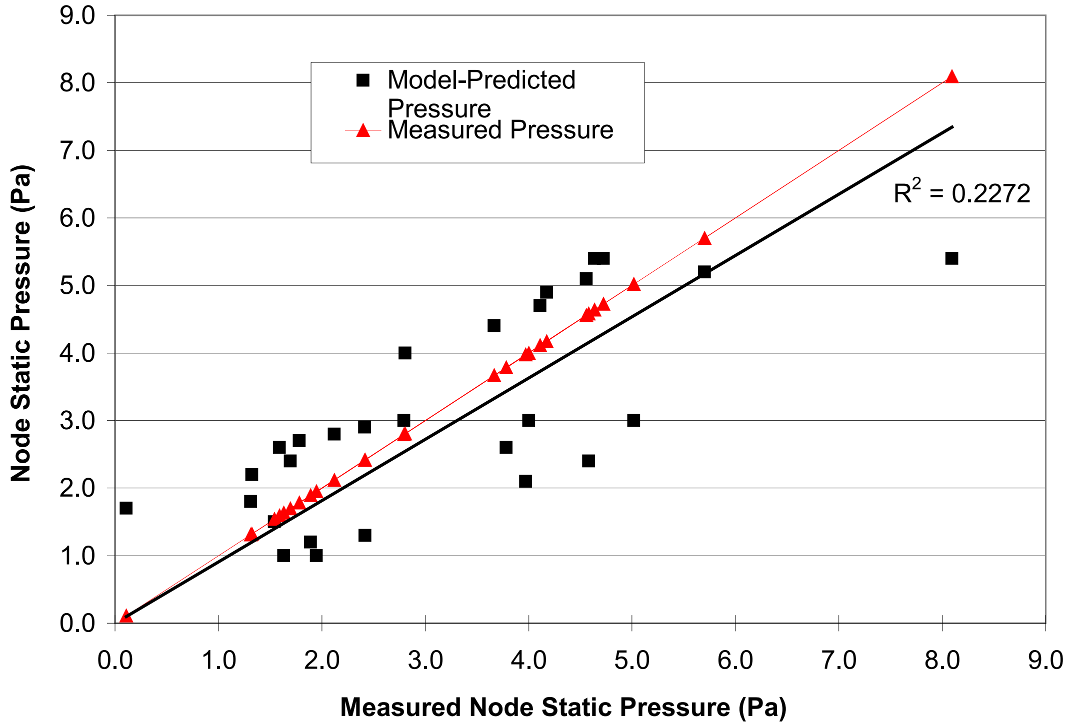
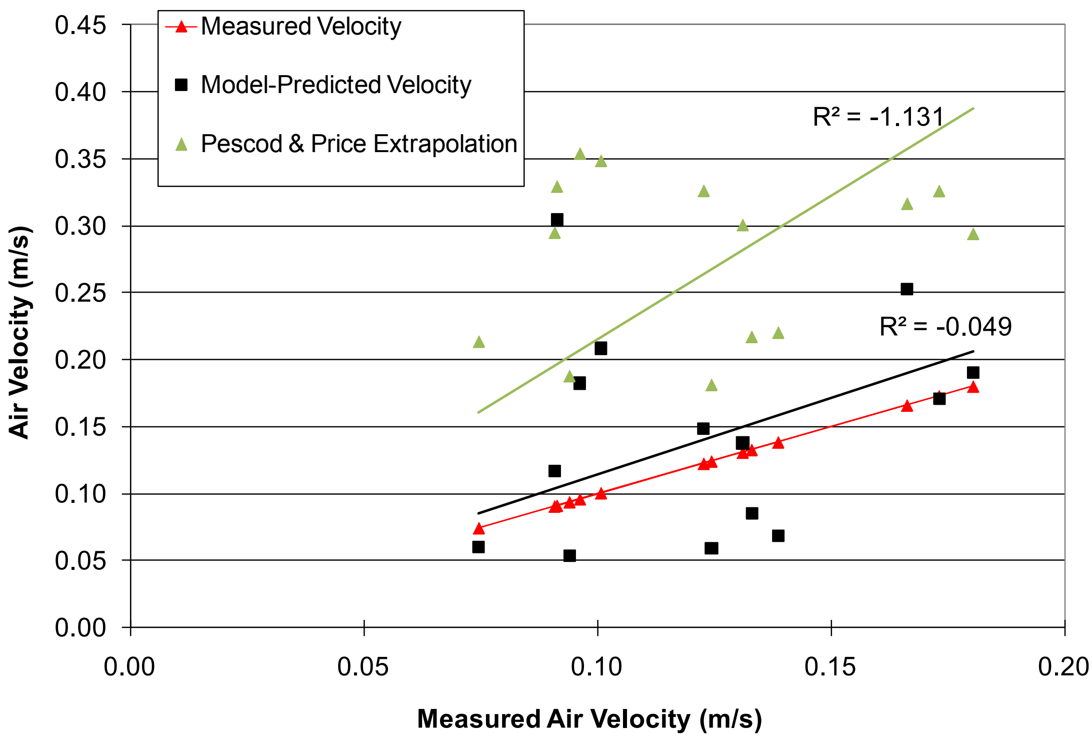


Figure 10: Comparison of measured an calculated air velocities at the downstream node in the Beenyup Outfall with no forced convection



(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
Air Conditions		
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%.
Fan		
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.
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
Sewer Characteristics		
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	$s/m^{1/3}$	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 (δ) of the pipe material.

Variable	Units	Notes
Node discharge area	m^2	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^3/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 approach to 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_{drop}, and a recycle air flow rate in the structure equal to Q_{return}. The volumetric throughput is $Q_{through}$.

The envisaged situation for analysis is a pulse injection of the tracer, carbon monoxide, at the inlet. The flow rate during the pulse is q_{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:

$$C_i = q_{tracer}/Q_{drop} \qquad (1)$$

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:

$$C(t) = C_i e^{-kt} \qquad (2)$$

where $k = Q_{through}/V_{DS}$ (3)

where V_{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 (2), $Q_{through}$ from equation 3. Q_{drop} can be determined if required from equation (1).

(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 suggested a value of $Q_{through}$ = 0.15 m^3/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

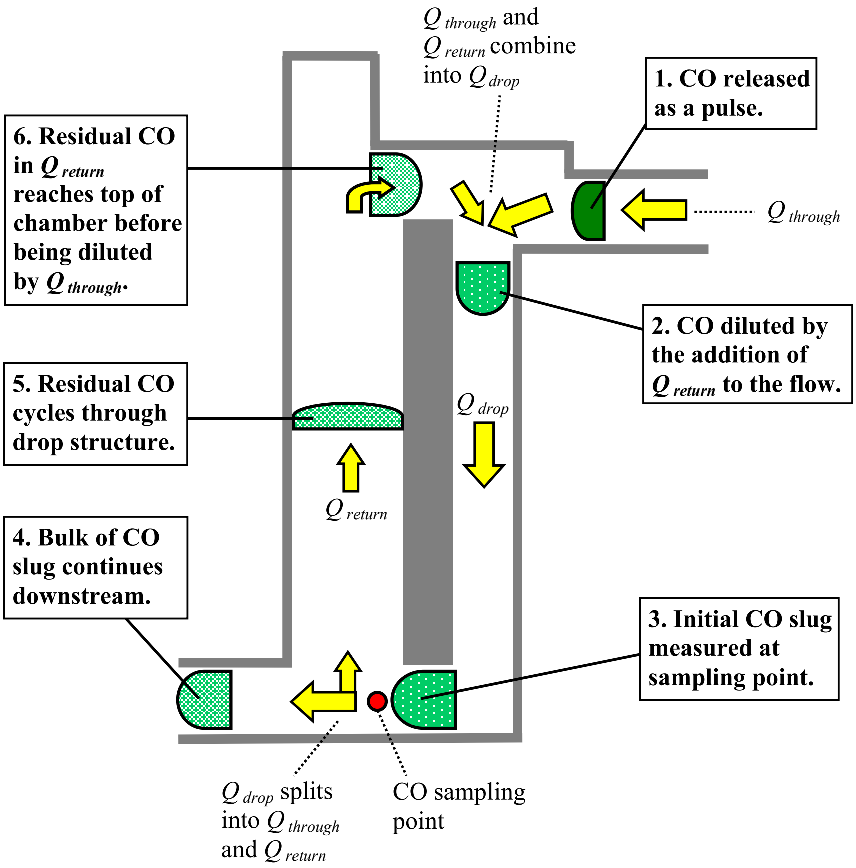
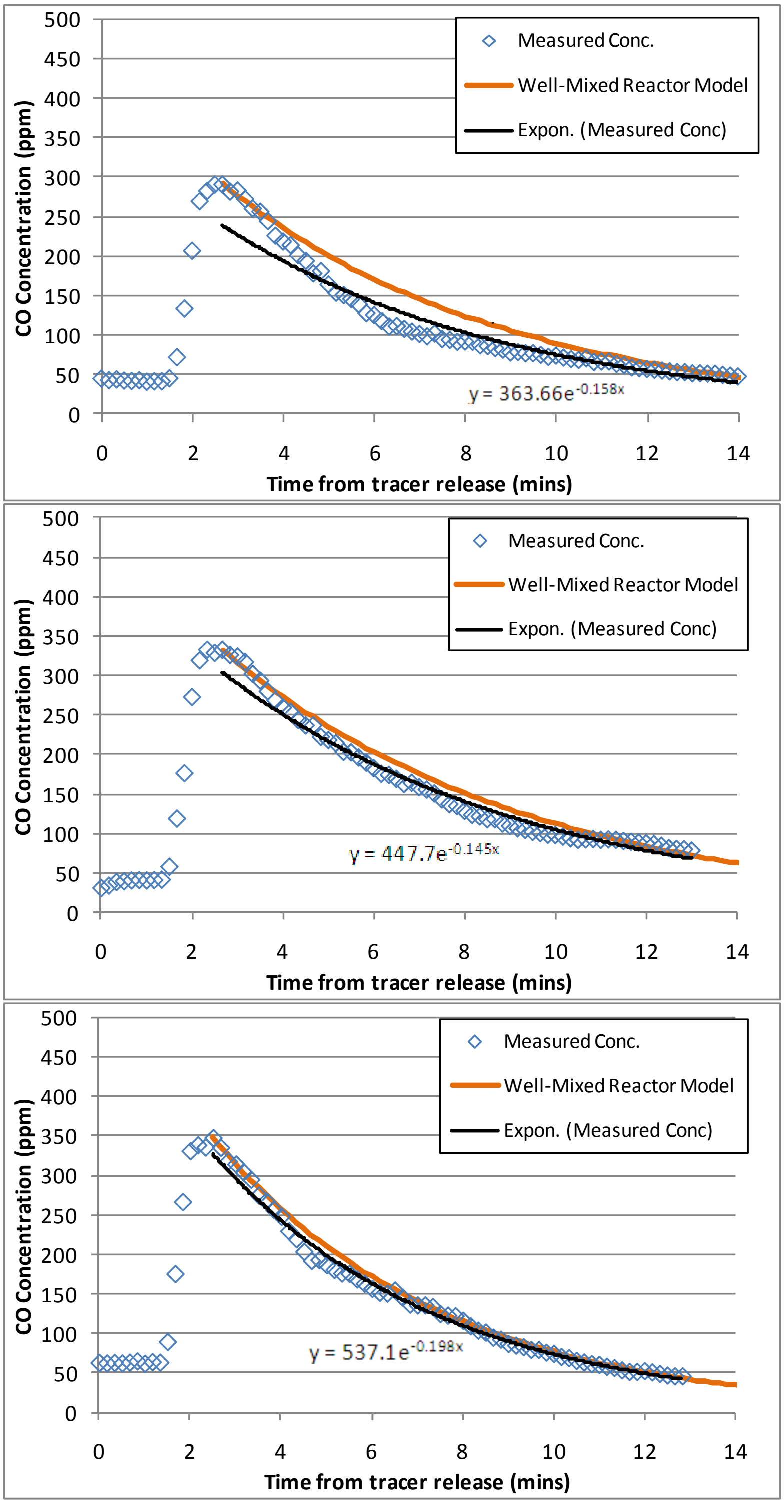


Figure 12. Tracer test results in the North Whitfords drop structure.



What value of $Q_{through}$ arose from these tests. How does the calculated air velocity compare with the liquid velocity – is it large compared with what we would expect from the free convection work discussed earlier in this section. That is, does the work demonstrate that drop structures are significant factors affecting ventilation or not?