A sewer ventilation model applying conservation of momentum

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ABSTRACT

The work presented herein was completed in an effort to characterize the forces influencing ventilation in gravity sewers and to develop a mathematical model, based on conservation of momentum, capable of accounting for friction at the headspace/pipe interface, drag at the air/water interface, and buoyancy caused by air density differences between a sewer headspace and ambient. Experiments were completed on two full scale sewer reaches in Australia. A carbon monoxide-based tracer technique was used to measure the ventilation rate within the sewer headspaces. Additionally, measurements of pressure, relative humidity, and temperature were measured in the ambient air and sewer headspace. The first location was a five kilometre long sewer outfall beginning at a wastewater treatment plant and terminating at the ocean. The second location was a large gravity sewer reach fitted with ventilation fans. At the first location the headspace was entirely sealed except for openings that were controlled during the experiments. In this situation forces acting on the headspace air manifested mostly as a pressure distribution within the reach, effectively eliminating friction at the pipe wall. At the second location, air was forced to move near the same velocity as the wastewater, effectively eliminating drag at the air/water interface. These experiments allowed individual terms of the momentum equation to be evaluated. Experimental results were compared to the proposed mathematical model. Conclusions regarding model accuracy are provided along with model application guidance and assumptions.

Key words | sewer, ventilation, odour, corrosion, drag, tracer

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INTRODUCTION

The work presented in this paper is part of on-going research to improve understanding of ventilation dynamics in wastewater collection systems and develop improved tools for ventilation modelling. Phase I of the 2007 Water Environment Research Foundation (WERF) project 'Odour and Corrosion in Wastewater Collection Systems' (Apgar *et al.* 2007) consisted of a comprehensive literature search and review of all published and gray literature on the topic generated during the previous 20 years. A team of leading experts from industry, consulting and academia were assembled to review the most relevant literature and identify subtopic areas in most need of new research. Phase I culminated in a list of 13 priority research topic areas, and sewer ventilation was deemed the first priority.

As part of Phase II (Apgar *et al.* 2009), WERF funded a research project with several goals related to sewer ventilation: (1) measure sewer ventilation in full-scale collection system components and simultaneously measure parameters thought to influence ventilation; and (2) evaluate existing sewer ventilation models and compare performance against measured data; and (3) identify strengths and weaknesses of existing models and propose a model that improves on current technology.

The Phase II ventilation research was completed in four gravity sewer components located in Los Angeles, California and Seattle, Washington. The model evaluation component of the Phase II research compared measured headspace air velocities to model predicted values for three existing models:

- Empirical model based on extrapolations from laboratory-scale air ventilation measurements (Pescod & Price 1981, 1982).

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- Model based on curve fits to computational fluid dynamics modeling of a generic gravity sewer (Edwini-Bonsu & Steffler 2004).
- Thermodynamic model based on heat balance on the air in a gravity sewer (Olson *et al.* 1997b).

The results of the Phase II ventilation research showed that existing models tended to over-estimate and, in general, failed to reflect real-world variability. This may be because, in the case of the empirical and CFD-based models, only water velocity and pipe geometry were used to predict air velocity. Forces are not accounted directly and forces associated with air density are not considered. The thermodynamic model, which is based on conservation of energy, suffered from inaccuracies associated with summing heat-related terms with work-related terms that are several orders of magnitude smaller. The thermodynamic model did, however, perform well for cases where buoyancy was a significant factor – in-gassing sewer during cool, dry ambient conditions. Additionally, existing models were not able to account for forces directly (i.e. a force balance on the air was not done) and provided no way to account for the interactions between connected sewer components. To address these deficiencies, a new modeling approach was proposed which applied conservation of momentum to a sewer component headspace and used a force balance to describe influences bearing on ventilation. The proposed model is described by Equation (1) in which forces acting on the air in a sewer component headspace, such as the one represented by Figure 1, equal the net change in momentum of air entering and leaving the system:

$$\Delta Momentum = \Delta Force_{Pres} + Force_{Grav} + Force_{Drag} - Force_{Fric} \tag{1}$$

where $\Delta Momentum$ (N) is the change in the momentum flow rate within a sewer headspace – effectively zero for a sewer in which there is little change of mass flow or velocity along a reach. Static pressure at the reach boundaries is represented by $\Delta Force_{Pres}$ (N) as shown by Equation (2):

$$\Delta Force_{Pres} = Area_{air} \times [(Pressure)_{Upstream} - (Pressure)_{Downstream}] \tag{2}$$

where $Area_{air}$ (m^2) is the headspace cross-sectional area. Gravity acting in the downstream direction is $Force_{Grav}$ (N), as shown by Equation (3):

$$Force_{Grav} = Slope \times Density_{air} \times Area_{air} \times Length \tag{3}$$

in which $Slope$ (m/m) is the pipe slope, $Density_{air}$ (kg/m^3) is the headspace air density, and $Length$ (m) is the pipe length. Drag at the air/water interface, $Force_{Drag}$ (N), is represented by Equation (4):

$$Force_{Drag} = Density_{air}\left[\frac{1}{2}C_D(Velocity_{water} - Velocity_{air})^2 \times Width \times Length\right] \tag{4}$$

in which C_D (unitless) is a drag coefficient analogous to that

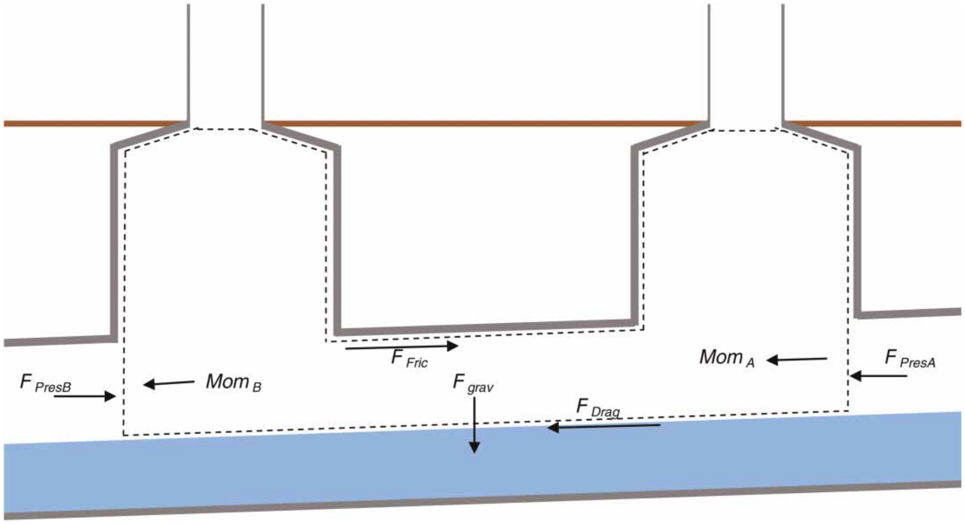

Figure 1 | Schematic diagram of a gravity sewer headspace (figure reproduced from WERF report 04-CTS-1A, Apgar *et al.* 2009).

of flat plate drag, $Velocity_{water}$ (m/s) is the wastewater velocity, $Velocity_{air}$ (m/s) is the headspace air velocity, and $Width$ (m) is the water surface width. Friction between the headspace air and pipe walls, $Force_{Fric}$ (N) is represented by Equation (5):

$$Force_{Fric} = Density_{air}\left[\frac{f}{8}Velocity_{air}^{2} \times Perimeter_{air} \times Length\right] \tag{5}$$

in which f (unitless) is the Darcy friction factor and $Perimeter_{air}$ (m) is the headspace non-wetted perimeter. Equations (4) and (5) are analogous to the approach used by Olson *et al.* (1997a, b) to describe work (as opposed to force) done on the air in a sewer headspace due to drag at the air/water interface.

With the exception of the Darcy friction factor, f, and drag coefficient C_D, each term in this model can be populated from the hydraulic geometry of a gravity system or obtained from easily measured parameters using the experimental protocol developed in the Phase II WERF study (Apgar 2009). While accurate coefficients for friction and drag are available for single-phase pipe flow, no such coefficients have been determined for two-phase flow such as exists in a gravity sewer. Nevertheless, conditions in a gravity sewer headspace can be approximated as a single air duct, with friction and drag coefficients adapted from values in common usage for pipes and applied to the two different surfaces composing a sewer headspace 'duct'– pipe walls and liquid.

If it were assumed that the non-round headspace in sewers could be approximated by a round duct with the same cross-sectional area as the actual headspace for a given wastewater flow/depth, Reynold's numbers and other hydraulic parameters can be calculated based on the equivalent air diameter of the round duct. Estimates for friction/drag at the air/water and air/pipe interfaces could then be approximated from common fluid mechanics tools such as the Haaland (Haaland 1983) and Colbrook (Colbrook 1939) equations which estimate friction factors based on Reynolds number and pipe roughness. However, the accuracy of such approximations is currently unknown. In addition, the selection of roughness values for the air/water interface lacks certainty as little information is available for fluid surfaces with standing waves.

For sewer components with significant air exchange with the ambient environment, humidity and temperature could easily influence the force balance described in Equations (1) through (5). For example, heat transfer would occur where cool dry air enters a warm humid sewer headspace. The relative density of the entering air and headspace air would manifest in the pressure and gravity terms of the force balance (Equations (2) and (3), respectively) and could be accounted by using measured pressures or by calculating the static pressure difference due to the two different air densities. This buoyancy effect increases with both depth of the sewer below ground and air density difference between ambient and sewer headspace. In this study, air density differences were slight and did not contribute significantly. The discussion, therefore, focuses on the drag and friction terms of the force balance.

To evaluate the proposed model, experiments specifically designed to measure friction and drag forces within gravity sewers were conducted. This work was taken up in 2009 by the Sewer Corrosion & Odour Research (SCORe) Project being funded by the Australian Research Council (ARC) and leading members of the Australian water industry. The SCORe project sought to measure forces within gravity sewer components, determine coefficients needed to develop the proposed ventilation model, and then compare measured and modelled ventilation results. Experiments were completed at gravity sewer locations in Perth and Adelaide, Australia. This paper presents the experimental methodology used and demonstrates the predictive ability of the proposed model relative to measured results.

METHODOLOGY

Experiments were completed at two locations, the Beenyup Outfall in Perth, Australia, and the Bolivar Trunk in Adelaide, Australia. The locations were selected on the basis of suitability for reducing interference from variables not being tested. For example, both locations had no intersecting sewers within the subject reach. Also, the sewers needed to be large enough that the resolution in upstream-to-downstream pressure could be measureable given the limitations of available field instruments. The Beenyup site was well suited because it was fully sealed with gasketed manholes and had no intersecting sewers along the reach. The Bolivar Trunk had the advantage of being equipped with fans which could be used to ventilate the air within the sewer at a velocity similar to the wastewater velocity. The Beenyup Outfall consisted of seven pipes beginning at a wastewater treatment plant and terminating at the ocean. The Bolivar Trunk consisted of three gravity pipes isolated from upstream and downstream portions of the reach by barriers designed to permit water flow and block headspace air flow. Table 1 provides a summary of the physical characteristics of the sewer reaches at each location.

At the Beenyup Outfall, measurements were completed at four consecutive manholes that were located between the upstream and downstream ends of the reach. At the Bolivar site, measurements were made in the middle manhole of the reach. The fan was pulling air from the downstream manhole.

At each location measurements were completed within the subject reach to determine simultaneously the air ventilation rate, ambient air density, headspace air density, and static pressure. Figure 2 shows a schematic diagram of the belowground and aboveground apparatus, respectively that were employed in this study. Instruments that were employed below ground were selected to be robust and able to tolerate the humid and potentially corrosive conditions inside a municipal sewer. Aboveground apparatus was constructed so that it could be disassembled, packed in cases, reassembled in the field, and taken down at the end of each sampling day. Analytical equipment was selected to allow sufficient portability, response time, accuracy, and logging capability.

At each sampling site a number of steps were completed to obtain field measurements. Sample trains were leak-tested and data loggers were tested or calibrated where appropriate. Electrochemical carbon monoxide sensors were used to measure the tracer gas. Dual thermistor-capacitive polymer sensors were employed for headspace temperature and relative humidity measurements, and dual hot wire anemometer-pressure transducer instruments were used to measure air flow through stand pipes and the differential pressure between ambient and headspace points. An ultrasonic Doppler wastewater flow (or depth) meter was installed at each location and initialized using hand-measured depth measurements and surface-timed tracers. Standpipes were used at selected manholes to allow air to enter or exit the headspace at a measureable (using the anemometers) rate. In some cases, stand pipes were capped to assess conditions where the reach was sealed to the atmosphere.

Using a method adapted from the work of Parker & Ryan (2001), carbon monoxide gas pulses were released at the upstream end of the subject reach and concentration measured downstream to determine air travel time. In some cases the air flow direction was not obvious and air flow direction was determined by trial and error with pulse releases from upstream and downstream manholes. Carbon monoxide was dosed through rotometers sized appropriately to deliver a dose that would result in a downstream concentration in the range of the sensors (0 to 1,000 ppm). This required initial trial and error. Once an approximate dose rate was established experiments were carried out with pulsed doses released periodically over the course of a day.

The carbon-monoxide sampling train was installed at the downstream manhole to pull air from the belowground velocity port, through a train including a desiccant column, an activated carbon column, and the carbon-monoxide sensor. A second carbon monoxide sensor with a visual readout was used to monitor concentrations in real time. During the experiments instruments were checked periodically to verify reasonableness of results. To verify lack of interference from out-side sources, ambient and upstream carbon monoxide concentrations were monitored and found to be non-detectable during the experiments. Following the experiments, the carbon monoxide sensors were recalibrated to determine drift.

Air travel time was determined from the difference in pulse release time and downstream concentration peak. Air velocity was then calculated as the pipe length divided by the travel time. Ambient and headspace air density was calculated based on measured temperature and relative humidity.

Belowground data loggers, temperature and relative humidity sensors, and wastewater temperature meters were set to log at 1 min intervals and installed in the headspace located as shown in Figure 2. Pitot tubes were connected to the pressure tube that lead to the stagnation port and the tracer sample train tube (downstream manhole) or tracer dose tube (upstream manhole) to the velocity port.

Table 1 | Summary of field testing locations

Location	Pipe Number	Diameter (mm)	Length (m)	Average slope	Wastewater velocity range (m/s)	Wastewater flow range (L/s)
Beenyup Outfall	7	1,950 – 2,250	4,511	0.00076	0.72–1.3	514–2,150
Bolivar Trunk	3	1,935	614	0.00068	0.43–0.89	74–885

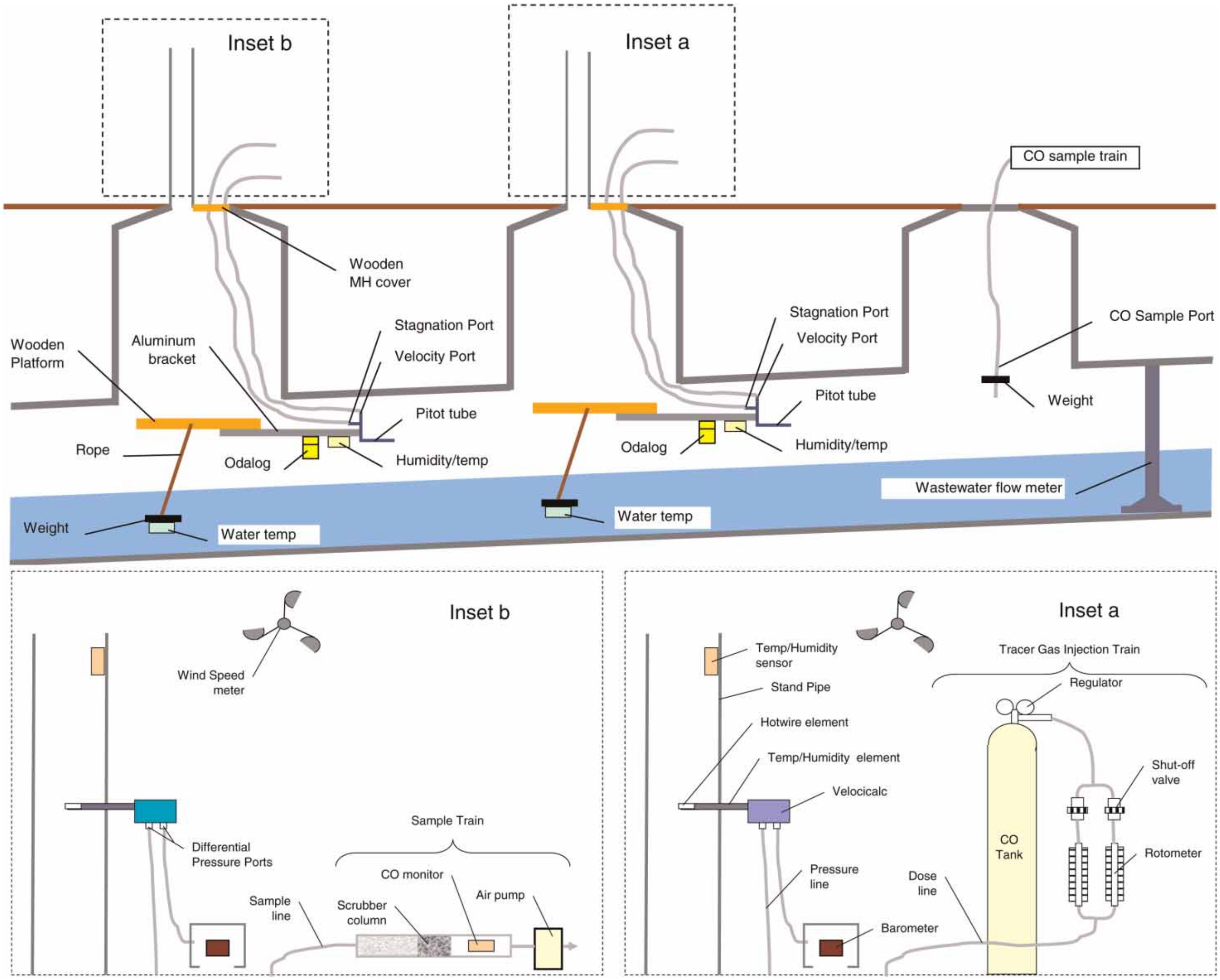

Figure 2 | Configuration of belowground apparatus (figure reproduced from WERF report 04-CTS-1A, Apgar *et al.* 2009).

Aboveground data loggers, wind speed meter, barometer, temperature and relative humidity meters, hotwire anemometer, differential pressure monitors, and carbon monoxide monitors were set to log at 1 min intervals and installed as shown in Figure 2. Silicone was used to seal all openings except for the stand pipe openings.

RESULTS

In the proposed momentum model of sewer ventilation as described by Equation (1), the pressure and gravitational force terms were directly measureable by a single differential pressure measurement instrument (i.e. the gravity term was included in the reading because the tubes attached to the differential pressure gauges have air columns contributing the gravity component to the reading). Static pressure was measured at upstream and downstream nodes, air density was determined from temperature and relative humidity measurements, and pipe geometry was obtained from as-built drawings of the subject reaches. The drag and friction terms (Equations (4) and (5), respectively) could not be directly measured. Therefore, two conditions were considered in order to permit these terms to be estimated. In the first, experiments were completed at Bolivar Trunk, which was equipped with a fan to extract air out of the downstream node at a rate such that the air velocity within the reach was within 25% of the wastewater velocity. This condition resulted in the air/water drag term being small compared to the air/pipe friction term, enabling air/pipe friction to be evaluated independently from air/water drag. In the second, experiments were completed at

Beenyup Outfall in which the entire reach was essentially sealed with just enough air movement to allow pulse tracer tests to be completed. With air velocity minimized, air/pipe friction was small compared to air/water drag, so air/water drag could be evaluated separately from the influence of air/pipe friction. A third condition was evaluated at the Beenyup location in which the downstream end of the reach was opened to the atmosphere thereby permitting significant ventilation. This case was used to evaluate the momentum model overall with all four force terms acting.

Bolivar Trunk – determination of air/pipe friction

The Bolivar Trunk location was not completely sealed from the influence of the upstream and downstream forces. For this reason, a single pipe with evaluated using the measured static pressure at the upstream and downstream nodes to specify the boundary conditions of the system. The air velocity within the pipe was induced with forced ventilation by a fan. The resulting velocities were near those of the wastewater, effectively eliminating the air/liquid drag force within the pipe. The measured downstream-to-upstream pressure difference could then be assumed to be entirely caused by air/pipe friction since no other forces were acting between the nodes.

The use of established relationships for predicting friction factors was assessed by employing the Haaland equation (Haaland 1983) to estimate friction factors for ducts with equivalent cross-sectional areas to the headspace. The momentum model was then employed to predict the headspace velocity and the predicted values were compared to the measured velocities. Absolute roughness was varied to achieve the best agreement between model-predicted and measured air velocities. Figure 3 presents the velocity values versus the measured pressure difference between the upstream and downstream points. The potential range of model-predicted values based on combined pressure measurement accuracy of ±2 Pa is also presented.

These results suggest that air/pipe friction was under-predicted by the Haaland relationship resulting in the velocity being over-predicted by a factor of approximately 2. The results were observed in spite of the fact that a value for absolute roughness of 2 cm was selected as the highest likely value for old, partially corroded concrete and the friction force term was still under-predicted. While these results show that, while the model tended to under-estimate the friction force, it predicted values that were in the same range as the observed values and was a significant improvement over other available methods which either do not account for friction at the pipe walls in terms of a physical force, or require computational fluid dynamics customized to a specific reach. Calibration of the friction factors that are employed in the model with experimental data is currently being evaluated.

Beenyup Outfall – determination of air/liquid drag

At the Beenyup Outfall location the upstream and downstream ends of the reach were constrained by physical

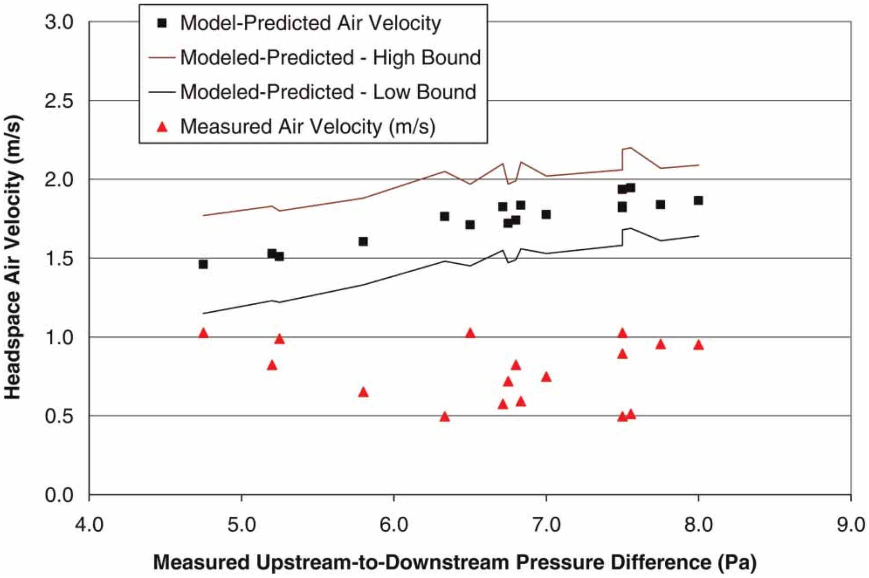

Figure 3 | Air velocity versus measured upstream-to-downstream static pressure difference at Bolivar Trunk.

barriers. This enabled the boundary conditions to be specified independently from the pressure measurements. In the first set of experiments at Beenyup Outfall, the sewer headspace was open at the upstream end and at one standpipe, but sealed elsewhere. This resulted in very low air velocities and represented conditions where it was assumed that the air/pipe friction force was small compared to the air/water drag force. In other words, the effect of the air/water drag force was manifested entirely as a pressure distribution within the sewer.

In this part of the model assessment, the feasibility of using drag coefficients from the Colbrook relationship was assessed by employing these drag coefficients in the momentum model and comparing model predictions with the experimental data. Figure 4 presents the measured versus model-predicted pressure difference between two nodes within the reach as a function of water surface velocity times surface width divided by dry perimeter, a parameter used generally to indicate the drag force. The solid lines represent the bounds resulting from the combined accuracy of the differential pressure measurement devices of ±2 Pa.

Figure 4 shows that predicted pressure differences agreed well with the measured values and fell within instrument accuracy for pressure measurements. An assumption of a smooth air/water interface resulted in the best agreement between measured and modelled results. This assumption reflected the observation that waves in sewers are standing waves and would not contribute to drag per se as a travelling wave would. The results show that the air/liquid drag component of the ventilation with drag coefficients determined by the Colbrook equation performed well.

Beenyup Outfall – modelled versus measured results

A second condition at the Beenyup Outfall was considered where an opening was made in the downstream end of the reach. This permitted much greater air movement than the sealed condition, so forces due to air/pipe friction, and air/water drag were simultaneously present. In this application, the ability of the momentum model, with Haaland and Colbrook relationships employed to estimate friction and drag coefficients respectively, to describe experimental data was assessed. Measured versus modelled results for pressure and headspace velocity were compared and are presented in Figures 5 and 6 respectively. In both figures the measured data is plotted against itself to form a perfect-fit line. The model predictions are then compared relative to the perfect fit line.

From both figures it can be observed that the trends in the model-predicted values followed the observed values. In both cases, there was scatter in the model-predicted values with considerably more scatter present for the velocity data. Despite the scatter in the data, the results suggest that the momentum model was capable of describing the combined effects of air/pipe friction and liquid drag for this application. As a comparison, model-predicted values were plotted in Figure 6 to show the performance of

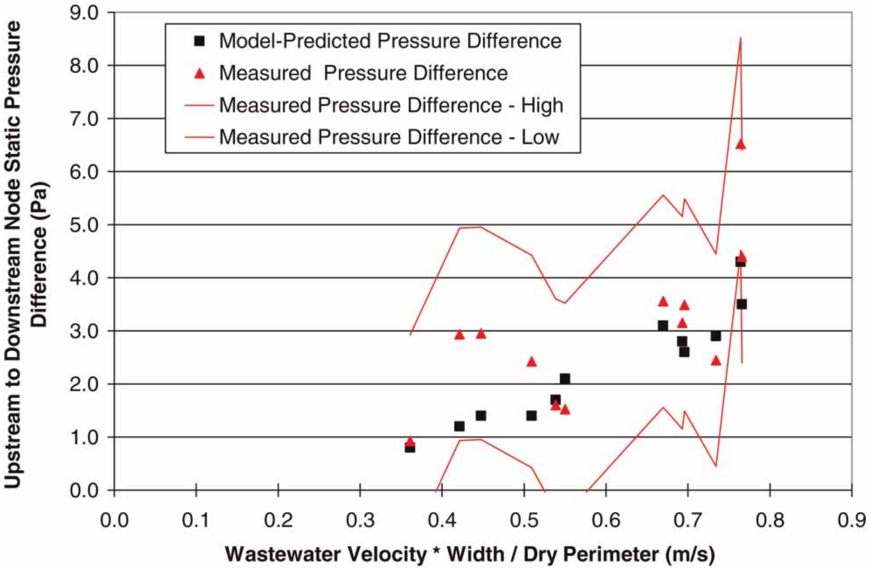

Figure 4 | Measured versus model-predicted upstream-to-downstream pressure difference at Beenyup Outfall, sealed condition.

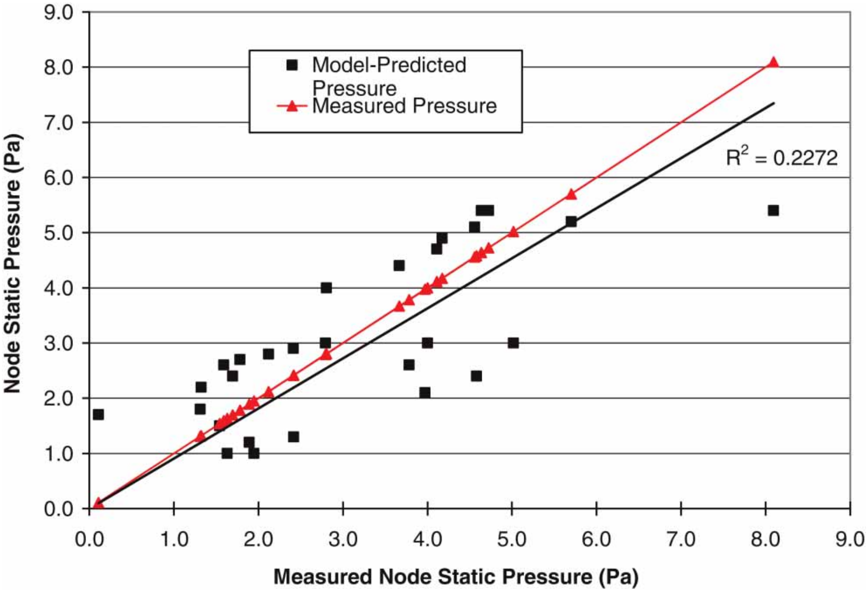

Figure 5 | Model-predicted versus measured node static pressure at Beenyup, open ventilation condition.

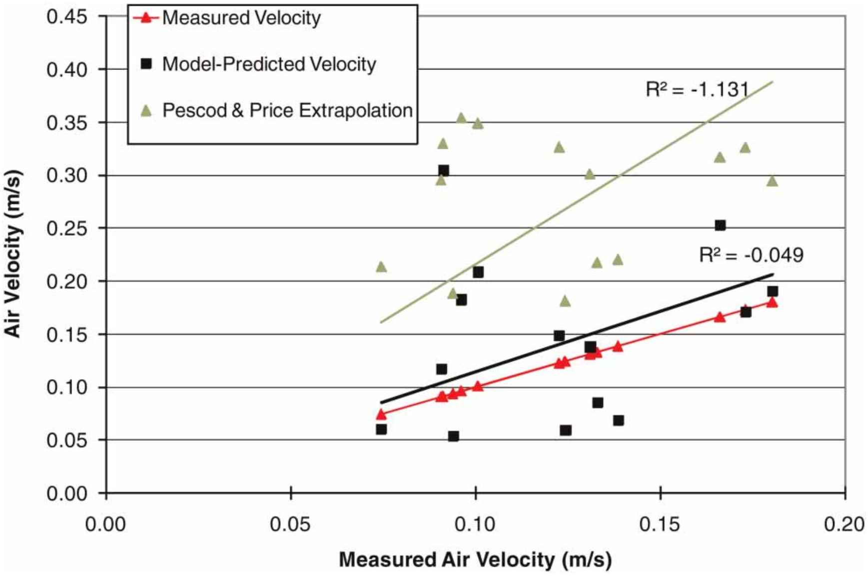

Figure 6 | Predicted versus measured headspace air velocities at Beenyup Outfall, open ventilation condition (momentum and empirical models).

the model based on empirical extrapolations from Pescod & Price (1981) experiments. This empirical model was found to be the best performing of the models evaluated during the Phase II WERF study (Apgar *et al.* 2009). Also the open condition would be the condition most likely to be accurately modelled by the empirical model tended to over-predict air velocity and does not account for pressure. Even so, the empirical model was less precise and over-predicted by more than 100% as compared to the momentum-based model which over-predicted by approximately 14%. Testing of the model with additional datasets that are being developed as part of this study is ongoing.

CONCLUSIONS

Several conclusions were drawn:

(1) Experiments were successfully used to evaluate, individually, the terms of a sewer ventilation model applying

conservation of momentum with terms accounting for forces acting on the headspace air within a gravity sewer component.

(2) The friction at the air/pipe wall interface was estimated by a Darcy friction factor for a duct with equivalent cross-sectional area to that of the gravity sewer headspace. The approach resulted in an underestimate of the air/pipe drag force even while erring high with the estimate of absolute roughness. The air/pipe friction term, nevertheless provided approximate values and could be employed in cases where the friction force is expected to be small compared to other forces.

(3) The drag at the air/water interface appeared to be well-described by the model with predicted pressure values well within instrument accuracy. Given that for natural ventilation conditions (ventilation resulting from natural forces rather than mechanically generated) air/water drag is dominant compared to air/pipe friction, the momentum based model overall showed good promise.

(4) The assumption of a smooth air/water interface resulted in best model performance. This assumption makes physical sense because the waves within a sewer are standing waves and would not be expected to contribute to drag as would travelling waves.

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