# A new approach for estimating volatile organic compound emissions from sewers: methodology and associated errors

David A. Olson, Sunil Varma, Richard L. Corsi

**ABSTRACT:** Previous studies have indicated the potential for emissions of volatile organic compounds (VOCs) from industrial and municipal sewers. However, existing estimation methods can significantly overestimate emissions of VOCs over a wide range of sewer operating conditions. This paper reviews three methods for estimating emissions from sewer reaches: equilibrium, open trench, and cocurrent ventilation. A new methodology is presented that combines both equilibrium and open-trench approaches. The maximum error associated with this combined model is shown mathematically to be 58% and independent of flow and reach characteristics. *Water Environ. Res.*, **70**, 276 (1998).

**KEYWORDS:** volatile organic compounds, sewers, emissions, stripping, models.

## Introduction

New federal and state regulations have focused attention on airborne emissions of hazardous air pollutants (HAPs) from a wide range of industries and industrial processes. One process that has received significant scrutiny is on-site industrial sewers, particularly with respect to emissions of volatile organic compounds (VOCs). Municipal sewers are currently receiving regulatory scrutiny as sources of HAPs, though it is unclear whether federal regulations will be developed to control such emissions.

Emissions of VOCs can occur from several different locations within an industrial sewer network. One such location is along sewer reaches, which are typically used to convey wastewater from the process drains and connecting pipes contained within specific process units. Wastewater from industrial sewers is generally discharged in one of three ways: (1) conveyance to an on-site impoundment and/or wastewater treatment plant with subsequent discharge to the natural environment, (2) conveyance to on-site treatment with disposal to a municipal sewer, or (3) discharge untreated to a municipal sewer for treatment in a publicly owned treatment works.

Previous studies have indicated that a significant fraction of VOCs can be released to the environment by gas–liquid mass transfer and air exchange between sewer and ambient atmospheres (Corsi, 1997). However, existing methods for estimating VOC emissions are often conservative and do not account for limitations regarding the nature of the mass-transfer process. In this paper, a simple model is proposed for estimating VOC emissions from sewer reaches. The model is conservative in nature but should provide improved emissions estimates relative to equilibrium or open-trench models.

## Background

Emissions of VOCs from sewers involve three major steps: discharge, mass transfer of volatile contaminants from wastewater to adjacent air, and air exchange between the headspace and the ambient atmosphere. Figure 1 illustrates these factors for a sewer reach, where the mass transferred from liquid to air is transported by sewer ventilation and released to the ambient atmosphere.

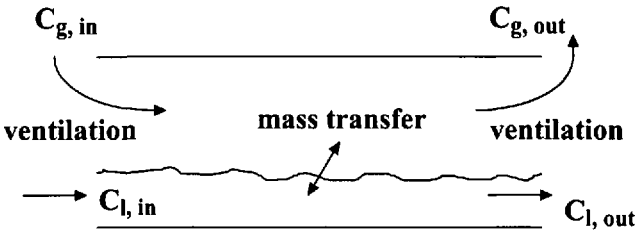


**Figure 1—Schematic displaying behavior of VOC emissions along reaches ($C_g$ and $C_l$ are the concentrations of the chemical in the gas and liquid phases, respectively).**

**Mass Transfer.** Chemical mass transfer can occur at many locations in sewers, such as from the falling film in process (drain) flow, from splashing in the underlying channel, along channel or sewer reaches, and at drop structures. Factors affecting the rate of mass transfer include the physicochemical properties of chemicals, fluid and flow characteristics, and interfacial surface area. The transfer of a chemical across an air–water interface is typically modeled as

$$R_v = -K_L A\left(C_l - \frac{C_g}{H_c}\right) \tag{1}$$

Where

$R_v$ = rate of mass transfer from water to adjacent air, mg/s;
$K_L$ = overall mass transfer coefficient, m/s;
$A$ = surface area, m$^2$;
$C_l$ = concentration of the chemical in the liquid phase, mg/m$^3$;
$C_g$ = concentration of the chemical in the gas phase, mg/m$^3$; and
$H_c$ = Henry's law coefficient for the chemical, m$^3$ liquid/m$^3$ gas.

The term in parenthesis is often referred to as a "concentration driving force" and describes a system's proximity to a state of chemical equilibrium. The term $C_g/H_c$ refers to the liquid concentration that would be attained if a state of equilibrium existed between liquid and adjacent air. A system characterized

by high ventilation rates or high compound volatility (large $H_c$) will have negligible compound accumulation in the gas phase, thereby reducing $C_g/H_c$ and creating the largest possible driving force for mass transfer to the air. Conversely, a system with restricted ventilation or low compound volatility will have a higher gas-phase concentration and hence a lower driving force for mass transfer. The subject of mass transfer at process drains and drop structures has been discussed elsewhere (Corsi and Quigley, 1996; Shepherd and Corsi, 1996; and Stubbe and Corsi, 1997).

Little research has been completed addressing the effects of VOC emissions from industrial sewer reaches, though several studies have been completed for municipal sewer reaches. Corsi *et al.* (1992) conducted field experiments for two operating collection systems. Pipe diameters ranged from 0.5 to 2.6 m, channel slopes from 0.063 to 0.24%, and wastewater flow rates from 60 to 2 600 L/s. Forced-ventilation rates ranged from 20 to 1 800 L/s. Sulfur hexafluoride ($SF_6$) was injected in the sewer inlets so that gas flow rates could be confirmed by analysis of sulfur hexafluoride dilution. Deuterated chloroform ($CDCl_3$) was used as a volatile tracer for measurement of stripping efficiencies along each sewer reach. Predicted and measured mass-transfer coefficients were within 30% of one another. Predicted values were obtained from oxygen-transfer correlations (Parkhurst and Pomeroy, 1972) with theoretical extrapolation to VOCs.

Whitmore and Corsi (1994) completed field experiments in two operating sewer reaches using deuterated chloroform ($CDCl_3$) and 1,1,1-trichloroethane (TCA) as volatile tracers. Pipe diameters ranged from 0.5 to 1.2 m, channel slopes from 0.10 to 3.5%, and wastewater flow rates from 70 to 100 L/s. Experiments were completed under conditions of forced ventilation, where ventilation rates were varied from 30 to 180 L/s. Headspace ventilation rates were determined by analyzing dilutions of sulfur hexafluoride injections. Overall mass-transfer coefficients varied from 0.014 m/h to 0.15 m/h and were reasonably correlated with oxygen-transfer results from Parkhurst and Pomeroy (1972) with extrapolation to VOCs. Results from this and other studies were found to be highly correlated with the rate of potential energy dissipation, corroborating previous predictions by Parkhurst and Pomeroy (1972). Experimental results were also used to predict sewer half-lengths, that is, the length of sewer required to strip 50% of TCA. Half-lengths ranged from 1.0 km for high-ventilation conditions to 70 km for low-ventilation conditions.

Quigley and Corsi (1995) completed field experiments on a large sewer interceptor that received significant amounts of industrial discharges. Concentration measurements were made for benzene, toluene, ethylbenzene, total xylenes, and tetrachloroethane. Reach characteristics included a total length of 1.6 km, slopes ranging from 0.25 to 1.0%, pipe diameters from 0.9 to 1.2 m, 17 manholes, and 4 drop structures ranging in drop height from 0.15 to 3.0 m. Headspace ventilation rates were measured to be as high as 2 300 $m^3/h$, which was noted to be significantly higher than previously reported data. The highest measured emission rate was for toluene, which approached 100 g/h for one manhole cover during midday of a 24-hour sampling period.

**Air Exchange.** Another important factor affecting VOC emissions from sewers is air exchange between sewer and ambient atmospheres. Previous studies (Alpha-Gamma, 1994; Pescod and Price, 1981 and 1982; Pomeroy, 1945; Thistlethwayte, 1972; and U.S. EPA, 1985 and 1988) have identified several factors that affect the rate of air exchange in sewers, including liquid drag, wind eduction, buoyancy, barometric pressure, and wastewater level. As discussed previously, highly ventilated sewers can have significant potential for volatilization because of the increased concentration driving force, whereas poorly ventilated sewers that approach a state of chemical equilibrium can suppress the rate of mass transfer. In addition, the ventilation rate can affect the overall mass-transfer coefficient ($K_L$), particularly in cases where gas-phase resistance to mass transfer is significant. Estimation of air exchange rates in sewers has been discussed elsewhere (Olson *et al.*, 1997a and 1997b, and Varma *et al.*, 1996). There is little existing research related to assessment of ventilation patterns in sewer networks. It has been noted in previous observations that a sewer headspace dominated by buoyant air flows will tend to travel countercurrent to wastewater (Metcalf & Eddy, Inc., 1981) and that one dominated by liquid drag will tend to travel cocurrent with wastewater (Quigley and Corsi, 1995).

The following section discusses different methods for estimating emissions along sewer reaches, including a new approach that substantially reduces the errors inherent in existing methods.

## Theoretical Development

Several analytical expressions have been derived in previous studies to estimate emissions of VOCs from a sewer reach (Corsi *et al.*, 1992; U.S. EPA, 1994; and Whitmore and Corsi, 1994). These models differ in their assumptions regarding the nature of the mass transfer process and headspace air flows, as discussed below. The following models are considered: equilibrium, open trench, and cocurrent ventilation. For each of the models discussed below, it is assumed that negligible contaminant concentration exists in the gas phase on entering the reach and that contaminants maintain their integrity and do not react with each other in the gas phase.

**Equilibrium.** For an equilibrium-based approach, it is assumed that chemical equilibrium exists between liquid and adjacent air in the reach, that is, $C_{g,\,out} = H_c\, C_{l,\,out}$ in Figure 1. A mass balance performed on both liquid and gas phases results in the following expression:

$$Q_l C_{l,\,in} + Q_g C_{g,\,in} = Q_l C_{l,\,out} + Q_g C_{g,\,out} = Q_l C_{l,\,out} + Q_g C_{l,\,out} H_c \quad (2)$$

Where

$Q_l$ = liquid flow rate, $m^3/s$;
$C_{l,\,in}$ = inlet chemical concentration in the liquid phase, $mg/m^3$;
$Q_g$ = air flow rate, $m^3/s$;
$C_{g,\,in}$ = inlet chemical concentration in the gas phase, $mg/m^3$;
$C_{l,\,out}$ = outlet chemical concentration in the liquid phase, $mg/m^3$; and
$C_{g,\,out}$ = outlet chemical concentration in the gas phase, $mg/m^3$.

Assuming $C_{g,\,in} = 0$, the expression in Equation 2 can be written in terms of stripping efficiency as

$$\eta_{eq} = 1 - \frac{C_{l,\,\mathrm{out}}}{C_{l,\,\mathrm{in}}} = \frac{H_c Q_g/Q_l}{1 + H_c Q_g/Q_l} \tag{3}$$

where $\eta_{eq}$ = stripping efficiency using an equilibrium assumption. The assumption of chemical equilibrium is most appropriate under conditions of long residence times—that is, low ventilation rates—and/or low compound volatility. The term $H_c Q_g/Q_l$, hereafter referred to as a *stripping factor,* provides an indication of the extent of mass transfer. As indicated by Equation 3, as this factor becomes much less than one, the stripping efficiency should become very small. Such a condition can occur for compounds with low Henry's law coefficients (for example, methanol), for poorly ventilated systems (for example, low $Q_g$), or for large wastewater flow rates. In contrast, if the stripping factor equals unity, equilibrium conditions lead to a stripping efficiency of 50%. If the stripping factor is much greater than unity, values of the numerator and denominator approach one another and the predicted stripping efficiency can become large (approaching 100% in the limit as the stripping factor approaches infinity).

**Open Trench.** In this model, there is assumed to be negligible chemical accumulation in the gas phase ($C_{g,\,\mathrm{out}} = 0$ in Figure 1). The stripping of contaminants under open-trench conditions can be determined from a steady-state mass balance on a differential element in the liquid phase under plug-flow conditions:

$$\frac{dC_l}{dx} + \frac{K_L W}{Q_l} C_l = 0 \tag{4}$$

Where

$x$ = axial distance along the sewer reach, m; and
$W$ = width of the air–water interface, m.

Integration of Equation 4 from $C_l = C_{l,\,\mathrm{in}}$ at $x = 0$ to $C_l = C_{l,\,\mathrm{out}}$ at $x = L$, where $L$ is the sewer length (in metres), results in the following expression for stripping efficiency:

$$\eta_{ot} = 1 - \exp\left[-\frac{K_L W L}{Q_l}\right] \tag{5}$$

where $\eta_{ot}$ = stripping efficiency based on an open-trench assumption. The assumption of open-trench conditions is most appropriate under conditions of high ventilation rates and/or high compound volatility.

**Cocurrent Ventilation.** The most sophisticated and accurate method for estimating VOC emissions is to use mass-transfer kinetics, with proper accounting for mass accumulation in the gas phase. The direction of air flow relative to wastewater flow must be prescribed, as it can affect overall emissions by influencing the concentration driving force. For cocurrent ventilation, air and water are assumed to flow in the same direction. Steady-state mass balances on differential elements in the gas and liquid phases result in the following:

$$\frac{dC_l}{dx} + \frac{K_L W}{Q_l} C_l = \frac{K_L W}{H_c Q_l} C_g \tag{6}$$

$$\frac{dC_g}{dx} + \frac{K_L W}{H_c Q_g} C_g = \frac{K_L W}{Q_l} C_l \tag{7}$$

Integration of Equations 6 and 7 from $C_l = C_{l,\,\mathrm{in}}$ and $C_g = 0$ at $x = 0$ to $C_l = C_{l,\,\mathrm{out}}$ and $C_g = C_{g,\,\mathrm{out}}$ at $x = L$ results in the following expression for stripping efficiency:

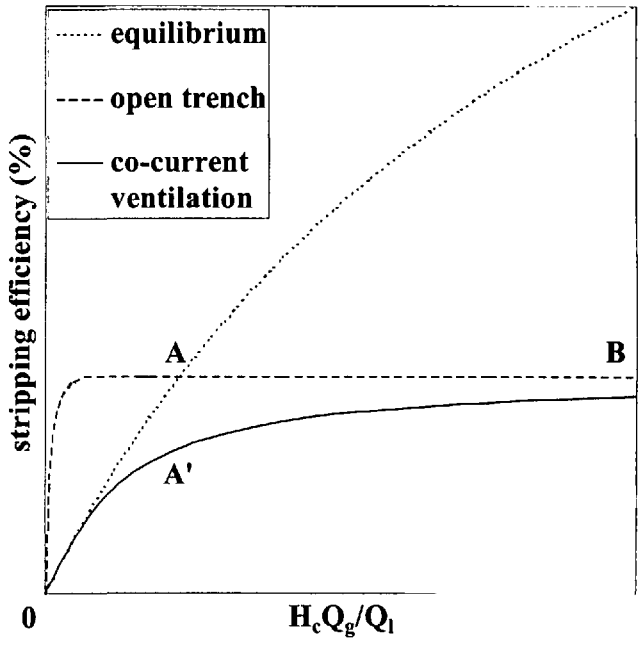


**Figure 2—Stripping efficiency versus stripping factor for all three models.**

$$\eta_{cc} = \frac{H_c Q_g/Q_l}{1 + H_c Q_g/Q_l}\left\{1 - \exp\left[-\frac{K_L W L}{Q_l}\left(\frac{1 + H_c Q_g/Q_l}{H_c Q_g/Q_l}\right)\right]\right\} \tag{8}$$

where $\eta_{cc}$ = stripping efficiency using a cocurrent ventilation assumption.

The stripping efficiency for other ventilation patterns, for example countercurrent or uniform ventilation, can be derived from Equations 6 and 7 using appropriate boundary conditions. For example, the countercurrent ventilation case would involve integration from $C_l = C_{l,\,\mathrm{in}}$ and $C_g = C_{g,\,\mathrm{out}}$ at $x = 0$ to $C_l = C_{l,\,\mathrm{out}}$ and $C_g = 0$ at $x = L$. For the ranges of input parameters used in this paper, the maximum relative difference between the cocurrent-, countercurrent-, and uniform-ventilation patterns is approximately 20%, and this occurs at very low air flow rates for which emissions will generally be low. Because the three ventilation patterns described above yield reasonably similar results, the countercurrent and uniform cases will not be discussed further in this paper. As expected, the cocurrent ventilation model (Equation 8) reduces to the equilibrium model (Equation 3) for low values of $H_c$ or $Q_g$ and high values of $L$: that is, conditions under which an equilibrium assumption is most appropriate. Correspondingly, the cocurrent model reduces to the open-trench model (Equation 5) for high values of $H_c$ or $Q_g$ and low values of $L$.

**Comparison of Models.** Figure 2 illustrates the effects of ventilation rate and compound volatility on stripping efficiency. Predicted stripping efficiencies for each of the three models are plotted as a function of the stripping factor $H_c Q_g/Q_l$.

The open-trench model neglects gas-phase accumulation and is thus independent of air flow rate, as suggested by Equation 4. This analysis neglects the change in gas-phase resistance as a function of air flow rate, which is important at low values of $H_c Q_g/Q_l$. Thus, the stripping efficiency should approach zero as $H_c$ becomes small. However, there is currently no published information regarding the mechanistic effects of ventilation

rates on gas-phase resistance to mass transfer in process drains or sewers. When the stripping factor is small, the open-trench model should overestimate stripping when compared with the cocurrent ventilation method. As $H_cQ_g/Q_l$ increases, the cocurrent ventilation predictions asymptotically approach the open-trench stripping efficiency. Comparison of Equations 5 and 8 indicates that stripping efficiencies predicted by the open-trench solution are always greater than those predicted by the cocurrent solution.

Predicted values using an equilibrium-based approach increase steadily with increasing stripping factor. As indicated by Equation 3, predicted stripping efficiencies in Figure 2 are independent of reach characteristics because chemical equilibrium is assumed throughout. At low values of $H_cQ_g/Q_l$, the equilibrium model reasonably approximates the cocurrent model. As $H_cQ_g/Q_l$ increases, the stripping efficiencies predicted by the equilibrium model are significantly higher than those predicted by either the open-trench or cocurrent model.

These trends can be explained in terms of limiting factors of the mass-transfer process. At low values of $H_cQ_g/Q_l$, mass transfer along the reach is limited by equilibrium considerations; that is, the amount of gas-phase accumulation is limited by the value of the Henry's law coefficient. At high values of $H_cQ_g/Q_l$, mass transfer is inhibited by kinetic considerations; that is, the amount of gas-phase accumulation is limited by the magnitude of the mass-transfer coefficient.

The performance of the equilibrium and open-trench models can be evaluated with respect to the cocurrent model using a relative error, which can be defined as follows:

$$\varepsilon_r = \frac{\eta - \eta_{cc}}{\eta_{cc}} \tag{9}$$

Where

$\varepsilon_r$ = relative error, and
$\eta = \eta_{eq}$ or $\eta_{ot}$.

In Figure 3, the relative error is plotted for both models as a function of stripping factor. At low values of $H_cQ_g/Q_l$, the equilibrium method has a low relative error, while the open-trench method approaches infinity. Conversely, as $H_cQ_g/Q_l$ increases, the equilibrium method has a higher relative error and the open-trench method a lower relative error. The following section will describe a combined approach that effectively reduces the error associated with these two models.

**Combined Approach: Methodology and Associated Errors.** Although a two-phase mass-transfer model, for example cocurrent or countercurrent flow, is the most accurate approach for estimating emissions along a reach, complications arise when extending this methodology from single reaches to sewer networks. To estimate emissions from a sewer network using a cocurrent or countercurrent approach, the chemical concentration in the gas phase must be known at each location in the network. For this approach, a ventilation pattern prescribing the magnitude and location of inlet and outlet air flows must be assigned. However, there is no published information regarding analysis of air-flow patterns in sewer networks.

Existing models, such as WATER8 (U.S. EPA, 1994), use the equilibrium approach for predicting chemical emissions from sewer reaches. As discussed previously, this is a reasonable assumption for low-volatility compounds or low ventilation

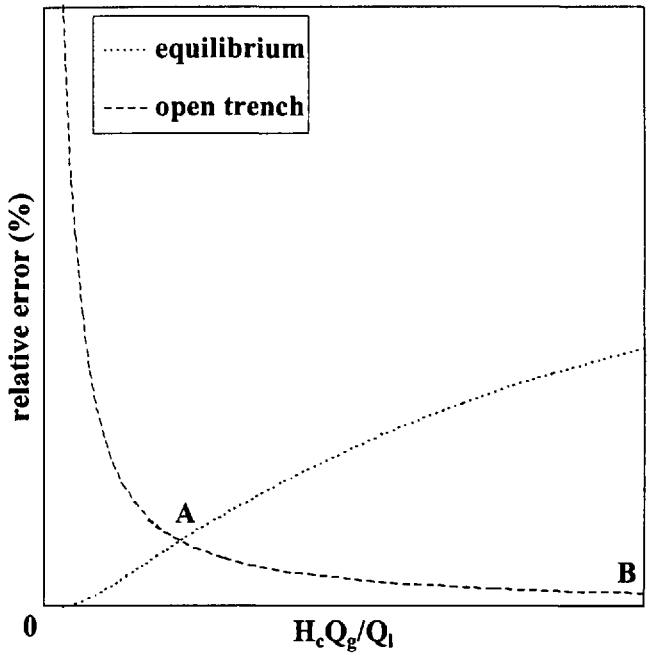


**Figure 3—Relative error for equilibrium and open-trench models.**

rates. However, given the uncertainty in $Q_g$ values, the use of an equilibrium model can result in significant uncertainty in emission rates. For higher volatility compounds, an open-trench assumption may be appropriate and precludes the need to estimate $Q_g$. Both equilibrium and open-trench models should generally lead to conservative estimates of stripping efficiencies.

A combined equilibrium and open-trench approach, though conservative, can be used to prescribe bounds on VOC emissions, particularly in cases where equilibrium or kinetic limitations are approached. This method would use the equilibrium model for conditions characterized by equilibrium limitations and the open-trench model for conditions characterized by kinetic limitations. Use of a combined model would result in predictions that are conservative, but with less potential error than an exclusively equilibrium– or open-trench–based approach.

The combined approach is illustrated in Figure 2. At values of $H_cQ_g/Q_l$ less than that at point A in Figure 2, the equilibrium model is used. At values of $H_cQ_g/Q_l$ greater than that at point A, the open-trench model is used. The relevant pathway for the combined approach is shown as 0-A-B in Figure 2. Clearly, the relative error will be substantially reduced by using a combined approach, as shown by the path 0-A-B in Figure 3. In effect, the 0-A-B path in Figure 2 is constructed by choosing the *lower value* obtained from equilibrium and open-trench models.

The maximum error associated with this method occurs at an $H_cQ_g/Q_l$ value corresponding to point A shown in Figures 2 and 3. As shown in Figure 2, the relative error between the combined and cocurrent models is proportional to the distance from A to A′. Because point A is located where the equilibrium and open trench lines intersect, the value of the stripping factor at that location can be determined through simultaneous solution of Equations 3 and 5, such that $\eta_{eq} = \eta_{ot}$:

$$\frac{H_cQ_g/Q_l}{1 + H_cQ_g/Q_l} = 1 - \exp\left[-\frac{K_lWL}{Q_l}\right] \tag{10}$$

When the value of $H_cQ_g/Q_l$ obtained from Equation 10 is substituted into Equation 8, the cocurrent stripping efficiency at point A is given by

$$\eta_{cc} = (1 - e^{-\alpha})\left[1 - \exp\left(-\frac{\alpha}{1 - e^{-\alpha}}\right)\right] \quad (11)$$

where $\alpha = (K_LWL)/Q_l$. The relative difference between the combined and cocurrent models at point A is then

$$\varepsilon_r = \frac{\eta - \eta_{cc}}{\eta_{cc}}$$

$$= \frac{(1 - e^{-\alpha}) - (1 - e^{-\alpha})\left[1 - \exp\left(-\frac{\alpha}{1 - e^{-\alpha}}\right)\right]}{(1 - e^{-\alpha})\left[1 - \exp\left(-\frac{\alpha}{1 - e^{-\alpha}}\right)\right]}$$

$$= \frac{1}{\exp\left(\frac{\alpha}{1 - e^{-\alpha}}\right) - 1} \quad (12)$$

Because the relative error between A and A′ is functionally dependent only on $\alpha$, the maximum value of $\varepsilon_r$ can be determined by differentiating Equation 12 with respect to $\alpha$, then setting the resulting expression equal to zero yields the following:

$$\frac{d\varepsilon_r}{d\alpha} = \frac{d}{d\alpha}\left[\frac{1}{\exp\left(\frac{\alpha}{1 - e^{-\alpha}}\right) - 1}\right]$$

$$= \frac{[e^{-\alpha}(\alpha + 1) - 1]\exp\left(-\frac{\alpha}{1 - e^{-\alpha}}\right)}{(1 - e^{-\alpha})^2\left[\exp\left(-\frac{\alpha}{1 - e^{-\alpha}}\right) - 1\right]^2} = 0 \quad (13)$$

Equation 13 is a monotonic increasing function that asymptotically approaches zero from the negative side. There are no roots to Equation 13 that represent local minima or maxima in Equation 12. Equation 13 approaches a value of zero as $\alpha$ approaches infinity, but substitution of this value of $\alpha$ into Equation 12 yields the trivial solution $\varepsilon_r = 0$. A maximum value of $\varepsilon_r$ can be found by restricting the values of $\alpha$ to be greater than or equal to zero, that is, physically meaningful values. The exact value of the relative error ($\varepsilon_r$) can be obtained by substituting a value of $\alpha$ approaching zero into Equation 12, with corresponding use of L'Hôpital's rule to resolve the indeterminate form 0/0:

$$\varepsilon_{max} = \lim_{\alpha \to 0} \frac{1}{\exp\left(\frac{\alpha}{1 - e^{-\alpha}}\right) - 1} = \frac{1}{\exp\left(\lim_{\alpha \to 0} \frac{\alpha}{1 - e^{-\alpha}}\right) - 1}$$

$$= \frac{1}{\exp\left[\lim_{\alpha \to 0} \frac{\frac{d}{d\alpha}\alpha}{\frac{d}{d\alpha}(1 - e^{-\alpha})}\right] - 1} = \frac{1}{e^1 - 1} = 0.58 \quad (14)$$

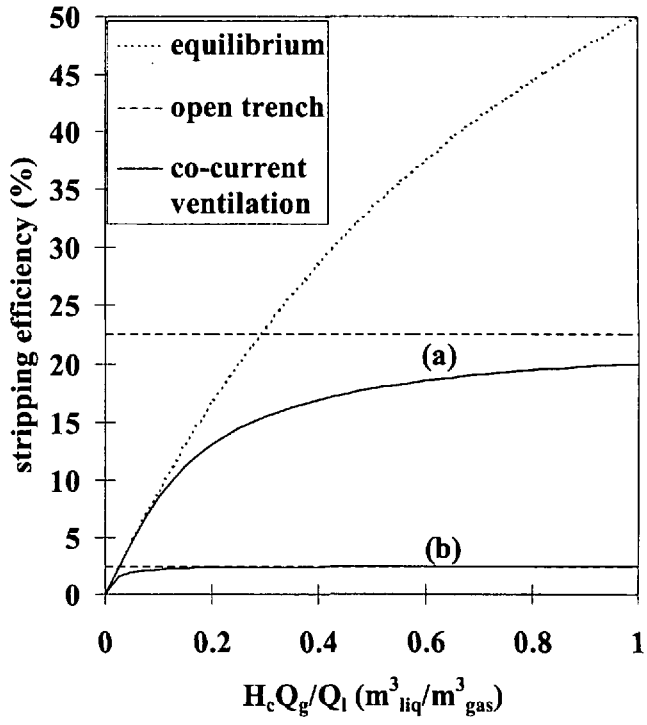


**Figure 4—Stripping efficiency versus stripping factor for all three models: (a) $L$ = 1 000 m, diameter = 1.0 m, relative depth = 0.25, and slope = 1%; and (b) $L$ = 100 m, diameter = 1.0 m, relative depth = 0.25, and slope = 1%.**

where $\varepsilon_{max}$ = maximum relative error. This derivation is significant because it establishes that the maximum deviation between combined and cocurrent models is 58%. This result is particularly important, as Equation 14 was derived independent of sewer configuration. In other words, the maximum error associated with the combined approach is 58%, irrespective of flow and sewer characteristics.

## Applications

The results shown in the previous section can be applied to any reach, given the appropriate hydraulic conditions and sewer configuration. Results for two such reaches are shown in Figure 4. The plot was generated using two sewer reaches that have the same diameter (1.0 m), relative depth of flow (0.25), and slope (1%), but are of different lengths [(a) 1 000 m and (b) 100 m]. Values of $W$ and $Q_l$ were based on uniform flow hydraulics and corresponding use of Manning's equation. Values of $K_L$ were based on estimates of oxygen-transfer coefficients (Parkhurst and Pomeroy, 1972) with theoretical extrapolation to VOCs (Whitmore and Corsi, 1994).

The results shown in Figure 4 are similar to those shown in Figure 2. The equilibrium model closely approximates the cocurrent solution at low stripping factors, while the open-trench model approaches the cocurrent solution at high stripping factors. Another noteworthy finding is that the equilibrium curve is identical for the two reaches because an equilibrium-based approach is independent of reach characteristics. The cocurrent and open-trench curves shift downward for a decrease in sewer length at given slope and diameter, an effect that can be attributed to shorter residence times along the reach.

The curves shown in Figure 4 can also be applied to specific

compounds. Three compounds have been chosen for this discussion: acetone, benzene, and cyclohexane. The Henry's law coefficient for each compound is shown in Table 1 for a temperature of 25°C (Ashworth *et al.*, 1988). A $Q_g/Q_l$ ratio of 1.0 is chosen for this discussion. The values of stripping efficiencies for each compound are listed in Table 2 for the two reaches under consideration.

The stripping factor for acetone is 0.001 5 at a $Q_g/Q_l$ ratio of 1.0. The equilibrium and cocurrent models predict identical stripping efficiencies for this value of $H_cQ_g/Q_l$ for both reaches under consideration, indicating that chemical equilibrium is a reasonable assumption for acetone under these conditions. The open-trench model overpredicts the cocurrent model by factors of 17 and 150 for the 100 m and 1 000 m reaches, respectively.

The stripping factor for benzene is 0.23 at the given $Q_g/Q_l$ ratio. The equilibrium model performs slightly better than the open-trench model for a sewer length of 1 000 m, though differences between the two are relatively minor for these conditions. It is interesting to note that the open-trench solution is substantially more accurate than the equilibrium solution for the 100 m reach. This indicates that even for moderate ventilation rates with compounds of moderate volatility, infinite ventilation conditions can be approached.

The stripping factor for cyclohexane is 7.3 at the given $Q_g/Q_l$ ratio. As expected, the open-trench model performs significantly better than the equilibrium model, clearly suggesting a condition approaching infinite ventilation. The equilibrium model overpredicts the cocurrent model by factors of 35 and 4 for the 100 m and 1 000 m reaches, respectively.

## Summary and Conclusions

Three analytical methods for estimating VOC emissions along sewer reaches have been reviewed: equilibrium, open-trench, and cocurrent ventilation. It has been found that an assumption of chemical equilibrium or one of infinite ventilation can be appropriate for certain flow and reach characteristics, but that substantial errors can result from an exclusively equilibrium– or open-trench–based approach. This study has introduced a new, combined approach consisting of both equilibrium and open-trench models. By following this approach, the degree of uncertainty inherent in current emissions estimation methodologies is reduced. Significant conclusions stemming from this research include the following:

- The combined model is constructed by choosing the *lower value* obtained from equilibrium and open-trench models. This practice still gives a conservative estimate of stripping efficiencies along sewer reaches, but results in substantially reduced error.
- The maximum error associated with estimated stripping efficiencies using the combined model is 58%, and this error is independent of flow and reach characteristics.
- Even for moderate ventilation rates with compounds of moderate volatility, conditions of infinite ventilation can be approached.

**Table 1—Henry's law coefficient for three compounds.[a]**

| Compound | $H_c$, m³ liquid/m³ gas |
|---|---|
| Acetone | 0.001 5 |
| Benzene | 0.23 |
| Cyclohexane | 7.3 |

[a] Values for Henry's law coefficients were obtained from Ashworth *et al.* (1988).

**Table 2—Stripping efficiencies predicted by each model for three selected compounds (diameter = 1.0 m; slope = 1%; relative depth = 0.25; $Q_g/Q_l$ = 1.0).**

| Compound | Equilibrium | Open trench | Cocurrent |
|---|---|---|---|
| | | $L$ = 100 m | |
| Acetone | 0.15% | 2.5% | 0.15% |
| Benzene | 18.7% | 2.5% | 2.4% |
| Cyclohexane | 88.0% | 2.5% | 2.5% |
| | | $L$ = 1 000 m | |
| Acetone | 0.15% | 22.5% | 0.15% |
| Benzene | 18.7% | 22.5% | 13.9% |
| Cyclohexane | 88.0% | 22.5% | 22.2% |

The procedure presented in this paper should significantly reduce errors in the estimation of VOC emissions along sewer reaches and will provide reasonable bounds for stripping efficiencies from such systems. It should be emphasized that errors associated with the combined approach are based on the chemical mass balances and subsequent mathematical derivations discussed in the Theoretical Development section and are not based on experimental findings. Future research in this area should involve comparisons of the results in this paper with experimental values.

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**Authors.** At the time this research was conducted, David Olson and Sunil Varma were research engineers and Richard L. Corsi was an assistant professor in the Department of Civil Engineering at The University of Texas at Austin. Correspondence should be addressed to Richard L. Corsi, Department of Civil Engineering (ECJ 8.6), The University of Texas at Austin, Austin, TX 78712.

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## References

Alpha-Gamma Technologies, Inc. (1994) *Low Emission Sewer Systems for Industry.* Water Environ. Res. Foundation, Alexandria, Va.

Ashworth, R.A.; Howe, G.B.; Mullins, M.E.; and Rogers, T.N. (1988) Air-Water Partitioning Coefficients of Organics in Dilute Aqueous Solutions. *J. Haz. Mater.*, **18**, 25.

Corsi, R.L. (1997) VOC Emissions from Municipal Sewers: New Research Findings. *Proc. Control Odors and VOC Emissions, Water Environ. Fed. Spec. Conf. Series,* Houston, Tex., 4-25.

Corsi, R.L.; Chang, D.P.Y.; and Schroeder, E.D. (1992) A Modeling Approach for VOC Emissions from Sewers. *Water Environ. Res.*, **64**, 734.

Corsi, R.L., and Quigley, C.J. (1996) VOC Emissions from Sewer Junc-

tion Boxes and Drop Structures: Estimation Methods and Experimental Results. *J. Air Waste Manage. Assoc.*, **46,** 3, 224.

Metcalf & Eddy, Inc. (1981) *Wastewater Engineering: Collection and Pumping of Wastewater.* G. Tchobanoglous (Ed.), McGraw-Hill, Inc., New York, N.Y., 264.

Olson, D.A.; Rajagopalan, S.; and Corsi, R.L. (1997a) Ventilation of Sewers: The Role of Thermal Gradients. *Adv. Environ. Res.,* **1,** 312.

Olson, D.A.; Rajagopalan, S.; and Corsi, R.L. (1997b) VOC Emissions from Industrial Sewers: A Comparison of Air Exchange Mechanisms. *J. Environ. Eng.,* **123,** 939.

Parkhurst, J.D., and Pomeroy, R.D. (1972) Oxygen Absorption in Streams. *J. Environ. Eng.,* **98,** 101.

Pescod, M.B., and Price, A.C. (1981) Fundamentals of Sewer Ventilation as Applied to the Tyneside Sewerage Scheme. *Water Pollut. Control,* **90,** 17.

Pescod, M.B., and Price, A.C. (1982) Major Factors in Sewer Ventilation. *J. Water Pollut. Control Fed.,* **54,** 385.

Pomeroy, R. (1945) The Pros and Cons of Sewer Ventilation. *Sew. Works J.,* **17,** 203.

Quigley, C.J., and Corsi, R.L. (1995) Emissions of VOCs from a Municipal Sewer. *J. Air Waste Manage. Assoc.,* **45,** 5, 395.

Shepherd, J., and Corsi, R.L. (1996) Mass Transfer of Volatile Organic Compounds from Industrial Process Drains. *Proc. 89th Annu. Meeting Air Waste Manage. Assoc.,* Nashville, Tenn., paper no. 96-RA120.03.

Stubbe, J.K., and Corsi, R.L. (1997) A Multizone Mechanistic Model for Estimating VOC Emissions from Industrial Process Drains. *Proc. 90th Annu. Meeting Exhibition Air Waste Manage. Assoc.,* Toronto, Ont., Can., paper no. 97-RA116.02.

Thistlethwayte, D.K.B. (1972) *The Control of Sulphides in Sewerage Systems.* 1st Ed., Ann Arbor Science Publishers, Ann Arbor, Mich.

U.S. Environmental Protection Agency (1985) *VOC Emissions from Petroleum Refinery Wastewater Systems—Background Information for Proposed Standards.* EPA-450/3-85-001a, Research Triangle Park, N.C.

U.S. Environmental Protection Agency (1988) Control of Volatile Organic Compound Emissions from Industrial Wastewater [preliminary draft]. Research Triangle Park, N.C.

U.S. Environmental Protection Agency (1994) *Air Emissions Models for Waste and Wastewater.* EPA-453/R-94-080A, Research Triangle Park, N.C.

Varma, S.; Olson, D.A.; Corsi, R.L.; and Rajagopalan, S. (1996) Air Exchange between Industrial Sewers and the Ambient Atmosphere. *Proc. 89th Annu. Meeting Air Waste Manage. Assoc.,* Nashville, Tenn.

Whitmore, A., and Corsi, R.L. (1994) Measurement of Gas-Liquid Mass Transfer Coefficients for Volatile Organic Compounds in Sewers. *Environ. Prog.,* **13,** 114.