7. INTERPRETIVE MODELING

This chapter draws on material discussed in Chapters 3 through 6 to assess VOC emissions due to desorption along uniform reaches and drops. It is divided into three major sections. Section 7.1 includes assessment of variations in both single and multiple parameters associated with VOCs traveling through uniform sewer reaches. Section 7.2 includes a parameter variation analysis for desorption from drops. Section 7.3 involves application of predictive models to a series of hypothetical sewer systems characterized by a uniform reach followed by a sudden drop in wastewater elevation. Section 7.4 examines a scenario that might typify the relative losses of chloroform from a residence to the sewage treatment plant.

7.1 PARAMETER ANALYSES - UNIFORM REACHES

This section is intended to provide greater detail regarding effects of parameter variations for uniform reaches. A similar analysis is provided in Section 7.2 for drops.

Applications

CORAL and MATES were used to study effects of parameter variations on VOC emissions along reaches of uniform flow. The CORAL model was used to analyze variations on single parameters for the standard reach listed in Table 7-1. Removal of PERC along the standard reach was 4.5%

The MATES model was used to assess the impact of multiple parameter variations on VOC emissions. Conditions were similar to those listed in Table 7-1, with exceptions and parameter variations listed in Table 7-2. Henry's law constant was varied within a range of common values for VOCs of concern. However, the diffusion parameter ,i was held constant at 0.6 for each

Table 7-1. Standard Conditions used for Parameter Variations on a Uniform Reach

Cell size: 50 m

Time increment: 30 s

Total analysis (simulation) time: 7.5 hours

Reach length: 2000 m

Diameter: 1.0 m i.d.

Depth: 0.5 m

Channel slope: 0.001 m m^{-1}

Roughness coefficient: 0.013

Wastewater flow rate: 0.38 m^3 s^{-1}

Wastewater mean velocity: 0.97 m s^{-1}

VOC transport time in wastewater: 0.58 hours

Ventilation: uniform at 10 volume turnovers per day

VOC: PERC at 20 ^oC ($H = 0.55$; $\Psi = 0.52$)

Discharge: slug at 1000 mg m^{-3} from time = 0 to 300 s

Biodegradation rate constant for bulk liquid: 0.0 hr^{-1}

Biodegradation rate constant for slime layer: 0.0 m hr^{-1}

Solids sorption: 0.0 %

Mass transfer coefficient: 0.0385 hr^{-1}

Table 7-2. Parameter Variations for MATES Analysis of Uniform Reaches

Diameter [m]:	0.050	1.0	2.0		
Relative depth [-]:	0.10	0.25	0.50	0.75	
Slope [m·m^{-1}]:	0.0001	0.0005	0.001	0.002	0.005
Ventilation [day^{-1}]:	1.0	5.0	10.0	20.0	50.0
Henry's constant [-]:	0.10	0.50	1.0		

total combinations: 900

Henry's law constant. Emissions of VOCs for 900 variable combinations were simulated.

MATES Analysis - General Results

Figure 7-1 is a summary of results from application of the MATES model. Only 371 of 900 variable combinations exceeded 10% removal. Sixty-seven exceeded 50% removal. Thirteen exceeded 80% removal, and no combination exceeded 87% removal. A maximum removal of 86.5% was attained for a channel slope of 0.005 $m \cdot m^{-1}$, ventilation rate of 50 TPD (uniform), Henry's law constant of 1.0, relative depth of 0.1 with a pipe diameter of 0.5 m, and mean VOC transport time in liquid of 1.0 hours through the 2000 m reach.

Of the thirteen variable combinations that exceeded 80% removal, the following consistencies were observed:

1. Diameter was always 0.5 m with a relative depth of 0.1 (shallowest depth simulated).
2. Channel slopes were always greater than or equal to 0.001 $m \cdot m^{-1}$.
3. Uniform ventilation rate was always greater than or equal to 10 volume TPD.
4. Henry's law constant was always greater than or equal to 0.5.
5. Mean VOC transport time in wastewater varied from 1.0 to 2.3 hours.

Sixty-two of the 67 combinations that exceeded 50% removal had a diameter of 0.5 m and relative depth of 0.1. The other five were also shallow flows with diameters of 1.0 m and relative depths of 0.1. However, unlike those combinations leading to 80% removal, several of the 67 combinations included Henry's law constant of 0.1, ventilation rate of 1.0 TPD, and/or a channel slope as low as 0.0001 $m \cdot m^{-1}$.

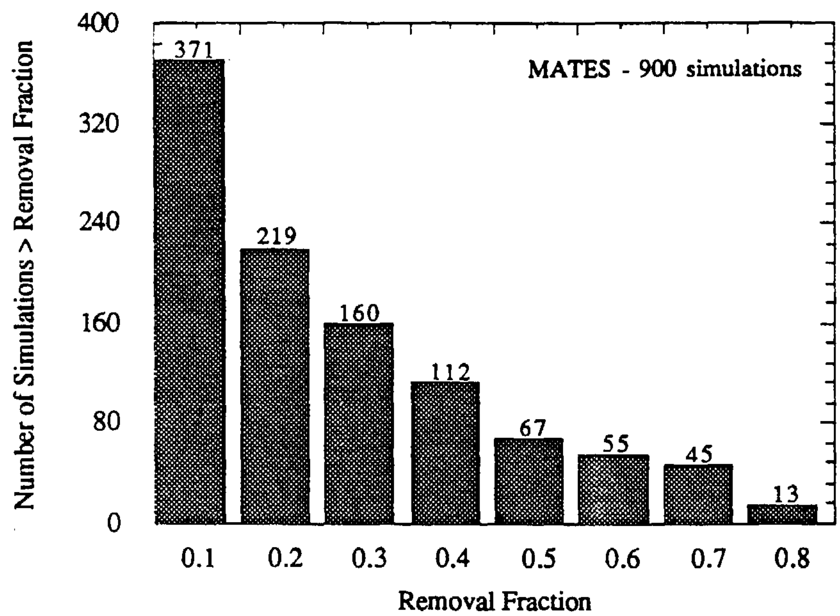

Figure 7-1. Variable Combinations Exceeding Specified Removal for MATES Analysis of Standard Reach

For those combinations which exceeded 50% removal, mass transfer coefficients (normalized by mean hydraulic depth) ranged from 0.21 to 2.1 hr^{-1}. Thus, for at least 50% mass removal along a two kilometer sewer reach, a high mass transfer coefficient (> 0.2 hr^{-1}) and low depth of flow (< 10 cm) were required. Low depth of flow led to the following conditions favorable to VOC desorption:

1. a small depth over which a VOC must be mixed before contacting a wastewater surface,
2. low wastewater velocity and therefore long transport time in a sewer reach, and
3. large gas volume above wastewater capable of storing a greater VOC mass than a smaller head space.

Variations in Model Parameters and System Variables

In this section, effects of individual model parameters and system variables on VOC emissions are described. Comparisons are made with a standard reach described in Table 7-1. Several references are made to a recently published paper by Corsi et al. (1989c), which has been included in Appendix B.

Spatial discretization:

The number of cells comprising liquid and gas phases in the 2000 m standard reach were varied from one to 200, with cell length varying from 2000 m to 10 m, respectively. The former is representative of emissions that would be associated with high axial dispersion, with VOC mass instantaneously mixed across the 2000 m reach. The latter approaches a plug-flow condition with little axial dispersion in either the gas or liquid phase. Total emissions for uniform ventilation at 10 volume turnovers per day differed by only 2% (20.6 grams for 200 cells versus 20.2 grams for 1 cell) between the two extreme conditions. When ventilation rate was reduced to 1.0 volume turnover per day, the difference was still less than 2%. Effects of spatial discretization were also tested under flow-through (in at upstream end, out at downstream end) ventilation. Three and twenty cells were used at a ventilation rate of one volume turnover per day (mean gas velocity of 0.023 $m \cdot s^{-1}$). Emissions were greater than for uniform ventilation by 16 to 25%. The 20 cell grid led to PERC mass emissions of 10.2 grams, as compared to 9.4 grams for three cells (8% difference).

A general result was that predicted relative removal of VOCs from a collection reach was fairly insensitive to spatial discretization of the model. Sensitivity increased as uniform ventilation was replaced by flow-through conditions.

Temporal discretization:

The major problem associated with increasing computational time steps was associated with "stepping past" upstream boundary conditions, i.e. utilizing a time step greater than or inconsistent with the cumulative time of VOC discharge. For the standard reach, numerical instabilities were not observed for time steps between 0.17 and 20.0 minutes, and in all cases absolute emissions differed from those of the standard reach by less than 0.5%.

Ventilation:

Corsi et al. (1989c) predicted that for relatively long collection reaches, e.g. 5000 m, total VOC emissions varied by less than 10% for a wide array of inflow and outflow (ventilation) patterns, given the same ventilation rate. Results of computations using the CORAL model are summarized in Figure 7-2. A hypothetical sewer reach was assumed with a reach length of 5000 m, inside diameter of 1.0 m, relative depth of 0.25, channel slope of 0.002 $m \cdot m^{-1}$, and ventilation rate of 5 TPD. An 82 gram discharge of a VOC with Henry's law constant of 0.75 and Ψ of 0.60 was assumed. Maximum removal to the ambient atmosphere was 26.9 grams for flow-through ventilation. Minimum removal was 24.6 grams for uniform ventilation.

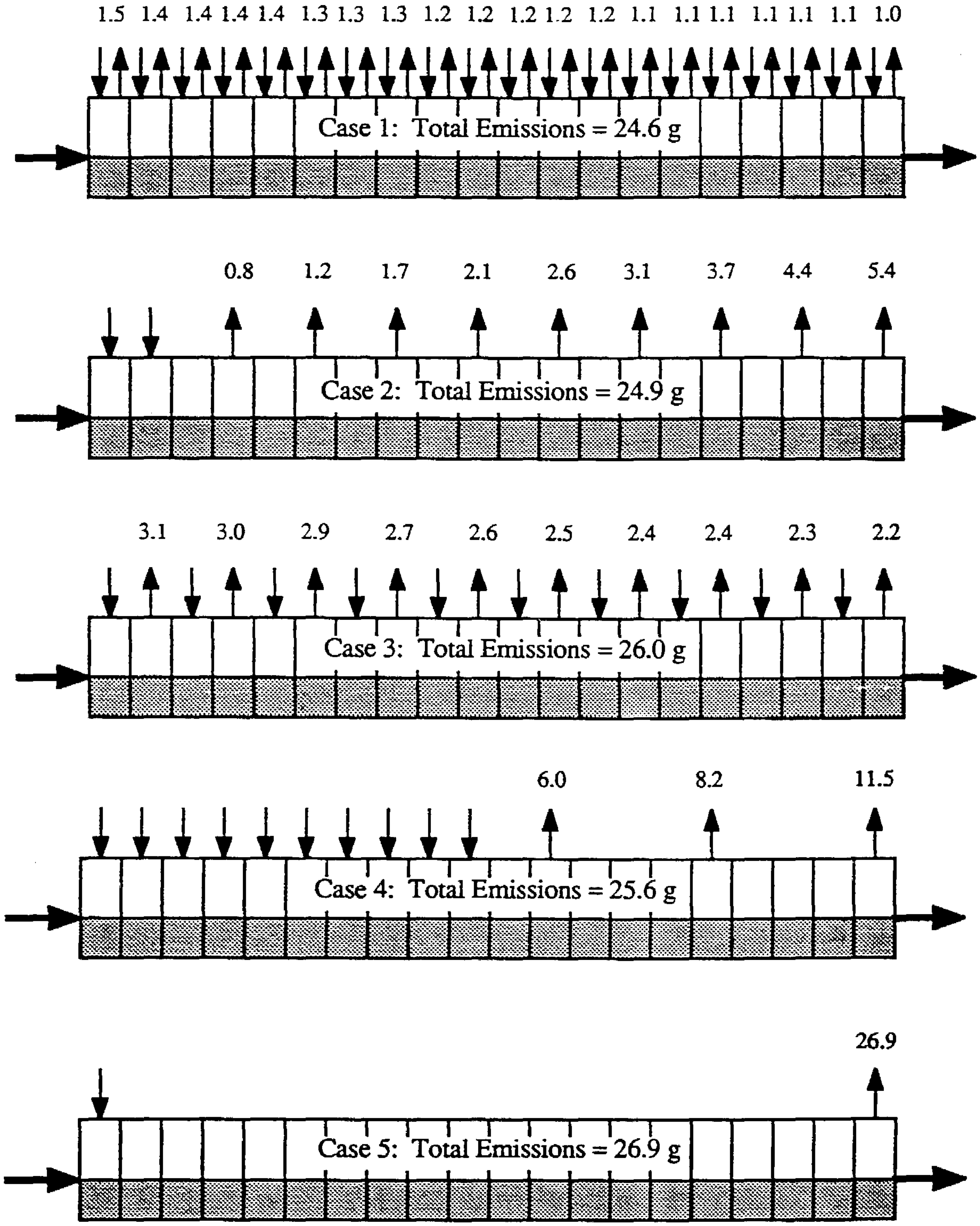

Figure 7-2. Mass Emissions for Hypothetical Sewer Reach Subject to Variations in the Spatial Distribution of Ventilation

(Vertical arrows indicate ambient air inflow or sewer gas exhaust. Horizontal arrows indicate the axial flow of wastewater and sewer gas. Ventilation rate is five turnovers per day. Total inflowing air and exhausted gas distributed equally between inflow cells and outflow cells, respectively.)

Corsi et al. (1989c) discussed the assumption of infinite ventilation as a simplification of computational analyses. It was observed that such an assumption was valid for compounds with high Henry's law constants and conditions of high ventilation rates. The assumption was observed to significantly overestimate VOC emissions (by as much as an order of magnitude) for compounds with low Henry's law constant and/or low ventilation flow rates. Results of applying the CORAL model to a reach similar to that noted above for spatial variations in ventilation are shown in Figures 7-3 and 7-4. Mass removal to the ambient atmosphere is plotted versus ventilation rate. Multiple curves on each figure correspond to various Henry's law constants (Y assumed = 0.6 for each simulation) and depth of flow.

Axial dispersion in gas phase:

Relative effects of axial dispersion in both gas and liquid phases were evident in the discussion of spatial discretization. In terms of actual emissions, computed VOC losses were relatively insensitive to degree of axial dispersion for uniform ventilation, and somewhat more sensitive for flow-through ventilation.

Wastewater flow rate:

For the same VOC discharge, an increase in wastewater flow rate causes:

1. an increase in wastewater mean velocity which tends to increase the mass transfer coefficient and hence emissions,

2. a subsequent decrease in VOC transport time in a collection reach thus favoring a reduction in VOC emissions,

3. an increase in depth of flow causing a reduction in mass transfer coefficient (normalized by hydraulic depth) and hence emissions, and

4. a smaller head space above wastewater with a lower VOC mass capacity prior to reaching equilibrium conditions, thus acting to reduce VOC emissions.

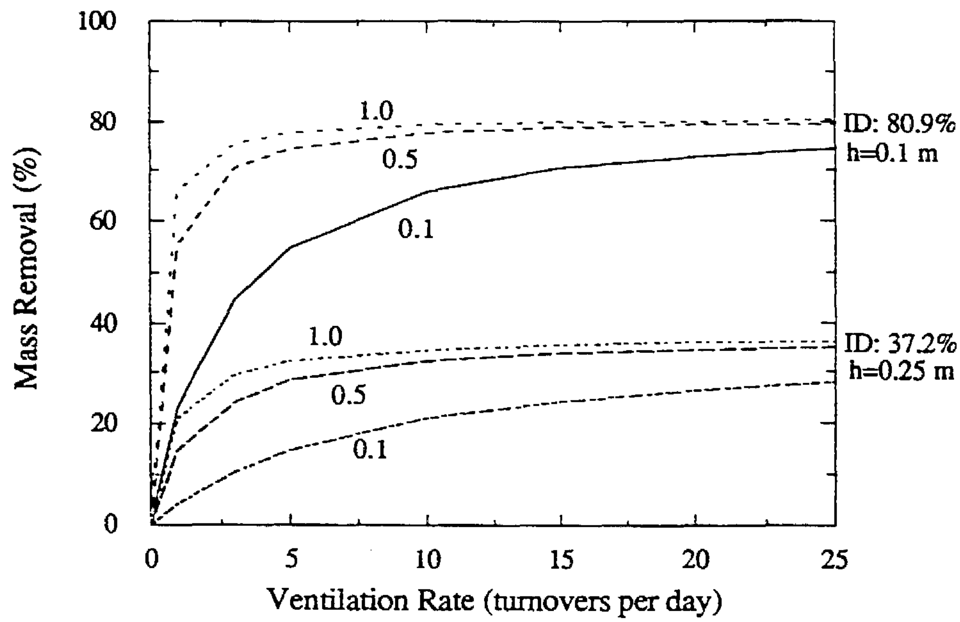

Figure 7-3. Mass Removal Versus Ventilation Rate for Hypothetical Sewer Reach and Dimensionless Henry's Law Constants of 0.1 to 1.0

(Depth of flow denoted as h. Results for infinite dilution denoted as ID)

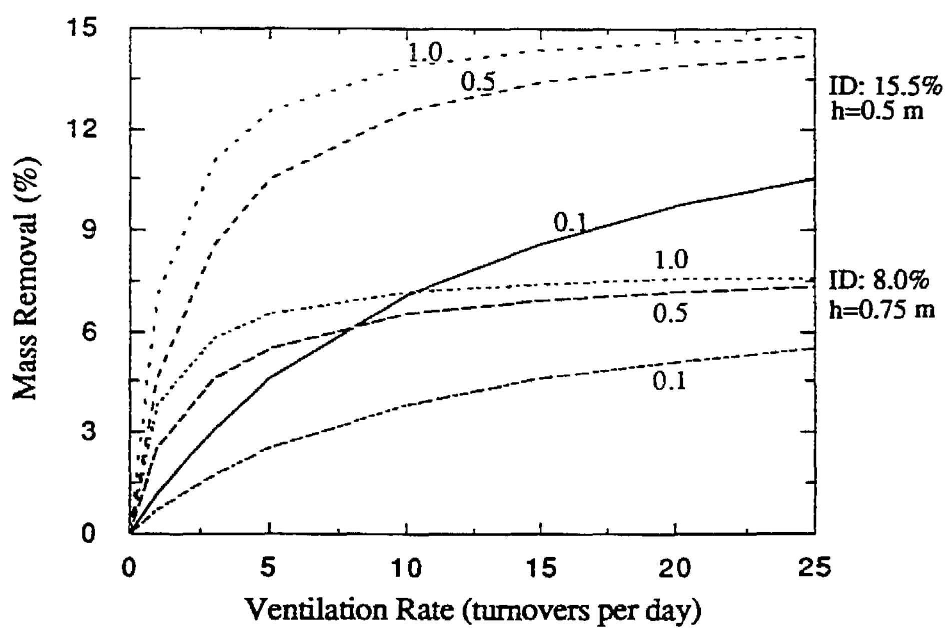

Figure 7-4. Mass Removal Versus Ventilation Rate for Hypothetical Sewer Reach and Dimensionless Henry's Law Constants of 0.1 to 1.0

(Depths of flow denoted as h. Results for infinite dilution denoted as ID.)

Net results for a hypothetical sewer reach (Table 7-3) were presented by Corsi et al. (1989c), and summarized in Figure 7-5. It was shown that for a given mass discharge of VOC, total emissions increase substantially with decreasing wastewater flow rate, e.g. by a factor of five for a relative depth change from 0.75 to 0.25. These results suggest that to reduce emissions from collection systems, certain industrial discharge limitations to sewers should be enforced during periods of low flow, e.g. night. This conflicts with the policies of some POTWs which attempt to equalize flows by encouraging industrial discharges during periods of low flow.

Depth of flow:

Effects of variations in depth of flow are evident in Figures 7-3 through 7-5. Furthermore, application of the MATES model (see Tables 7-1 and 7-2) led to the following observations:

1. When combination of relative depth and diameter led to absolute depth of greater than 0.375 m, 10% removal was not attained for any combination of Henry's law constant, channel slope, and ventilation rate.

2. When absolute depth was less than 0.2 m, 10% removal was attained in at least 85% of the combinations of Henry's law constant, channel slope and ventilation rate.

3. At a relative depth of 0.75, 10% removal was not attained for any combination of the other four variables.

4. At a relative depth of 0.1 and channel slope of 0.0001 m m^{-1}, 10% removal was attained for every combination of the other three variables.

5. At relative depths greater than or equal to 0.5 and a ventilation rate of one TPD, 10% removal was not attained for any combination of the other three variables.

6. At a relative depth of 0.1 and Henry's law constants of greater than or equal to 0.5, 10% removal was met for all combinations of the other three variables.

Table 7-3. Conditions for Example Discharge at Varying Flow Rates

Run	Flow Rate $[m^3 s^{-1}]$	Relative depth [-]	Actual depth [m]	C_{li} $[\mu g\, l^{-1}]$	Transport time in system [hrs]	K_{li} $[m\, hr^{-1}]$
AA	0.164	0.25	0.305	611	3.9	0.040
BB	0.598	0.50	0.610	167	2.7	0.046
CC	1.089	0.75	0.914	92	2.4	0.047

pipe diameter = 1.219 m (48 inches); slope = 0.1%; channel roughness coefficient = 0.014; sewer reach length = 10,000 m; ventilation rate = 5.0 turnovers per day (uniform); slug discharge of 100 mg l^{-1} at rate of 0.001 $m^3 s^{-1}$ for five minutes; slug assumed to be instantaneously mixed with wastewater to yield initial concentration C_{li} noted in table.

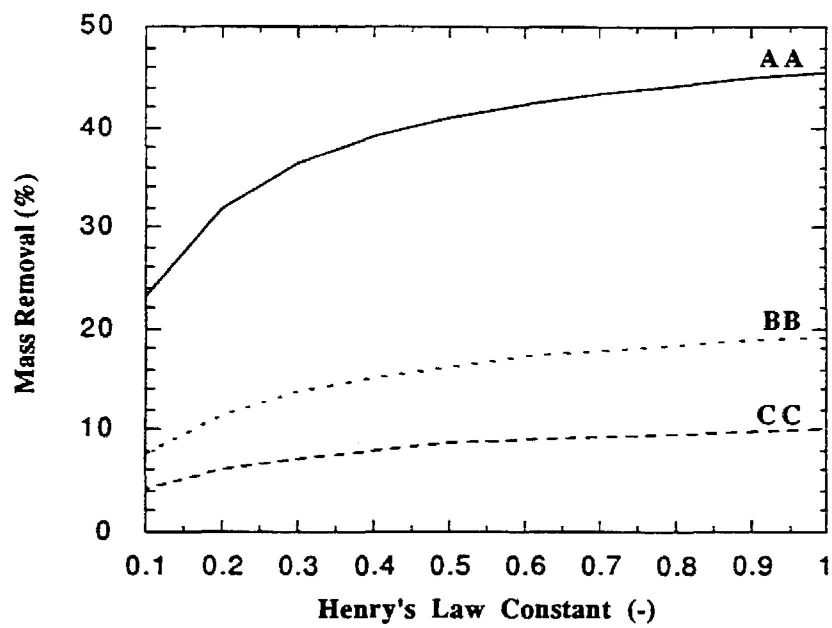

Figure 7-5 VOC Mass Removal Versus Henry's Law Constant for Hypothetical Sewer Reach

(Curves denote results for various wastewater flow rates at a constant channel slope. Model conditions are listed in Table 7-3.)

Channel slope:

An increase in channel slope at a fixed wastewater flow rate tends to:

1. decrease depth of flow, increase mass transfer coefficient, and hence increase VOC emissions,

2. increase wastewater mean velocity and hence increase mass transfer coefficient and VOC emissions, and

3. decrease VOC residence time in a collection reach, thus acting to decrease emissions.

Effects of increasing channel slope were reported by Corsi et al. (1989c) for a hypothetical sewer reach (Table 7-4), and are summarized in Figures 7-6 and 7-7 for ventilation rates of one and ten TPD, respectively.. Increasing channel slope from 0.000125 $m \cdot m^{-1}$ to 0.002 $m \cdot m^{-1}$ increased mass removal of a highly volatile VOC from 6 to 18% at one TPD, and from 8 to 35% at ten TPD.

Table 7-4. Conditions for variable slope analyses at constant flowrate

Run	Slope [%]	Depth [m]	Relative depth [-]	Wastewater mean velocity [m/s]	K_{li} [m/hr]	Infinite dilution removal [%]
A	0.0125	1.00	0.82	0.41	0.014	8.4
B	0.0250	0.76	0.62	0.56	0.021	14.8
C	0.0500	0.61	0.50	0.72	0.030	21.4
D	0.1000	0.50	0.41	0.94	0.044	29.2
E	0.2000	0.42	0.34	1.20	0.065	38.4

pipe diameter = 1.219 m (48 inches); wastewater flowrate = 0.422 m^3/s; channel roughness coefficient = 0.014; sewer reach length = 10,000 m; ventilation rates = 1.0 and 10.0 TPD (uniform); slug discharge of 1000 mg/l for five minutes

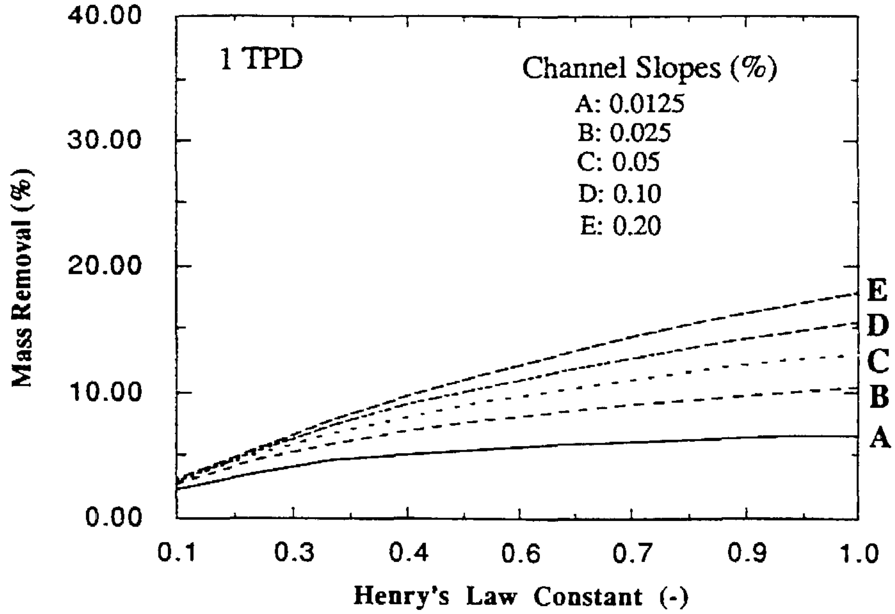

Figure 7-6. VOC Mass Removal Versus Henry's Law Constant for a Hypothetical Sewer Reach

(Uniform ventilation at 1.0 volume turnovers per day. Curves denote results for various channel slopes as listed in Table 7-4.)

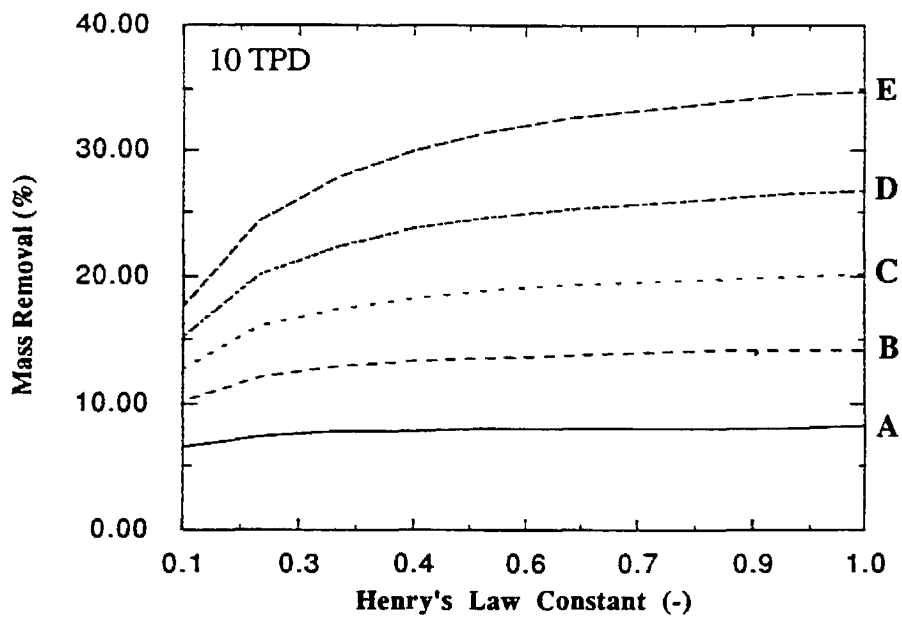

Figure 7-7. VOC Mass Removal Versus Henry's Law Constant for a Hypothetical Sewer Reach

(Uniform ventilation at 10.0 volume turnovers per day. Curves denote results for various channel slopes as listed in Table 7-4).

Wastewater temperature:

Increases in wastewater temperature increase VOC emissions through increases in both Henry's law constant and mass transfer coefficients (as manifested in increased molecular diffusivity). In addition, warm wastewater acts to heat overlying gases, thus increasing buoyancy-driven ventilation flows.

The standard reach described in Table 7-1 was characterized by a wastewater temperature of 20 ^oC. A reasonable range of wastewater temperature based on ambient conditions, soil temperatures adjacent to buried sewer pipe, and discharge of hot wastewater is 10 to 40 ^oC. Mass transfer coefficients on the standard reach with temperatures of 10, 20, and 40 ^oC were 0.031 hr^{-1}, 0.039 hr^{-1}, and 0.059 hr^{-1}, respectively. Henry's law constants for PERC were 0.31, 0.55, and 1.50, respectively. Total PERC emissions were 17.5, 22.4, and 35.2 grams, respectively. For this example, PERC emissions were more sensitive to variations in molecular diffusion as manifested in mass transfer coefficients. Sensitivity to Henry's law constant increased as ventilation rate decreased.

Physico-chemical properties of VOCs:

Two important physico-chemical properties, Henry's law constant and molecular diffusivity, were described above. The importance of such properties will also become evident from large differences in relative removal between TCM, PERC, and VC for the hypothetical scenarios described in Section 7.3.

Competing removal mechanisms:

Mechanisms which compete with volatilization/ventilation as VOC loss pathways include adsorption both aerobic and anaerobic biodegradation. Each was studied using the CORAL model. Biodegradation rate constants were not available for raw wastewater. Thus, a wide range of values were tested. Except for the introduction of decay constants, analyses were completed using standard conditions as listed in Table 7-1.

Decay constants of 0.001, 0.01, and 0.1 hr^{-1} were prescribed to account for biodegradation associated with microbes suspended in the bulk liquid. Total removal of PERC from wastewater increased by 1%, 11%, and a factor of 2.2, respectively, in comparison to standard conditions (4.9% removal). However, total emission reductions were < 1%, < 1%, and 3%, respectively, relative to standard conditions. Thus, biological decay in the bulk liquid, for the range of decay constants prescribed, did not significantly affect emissions.

Decay constants of 0.001 and 0.1 $m \cdot hr^{-1}$ were prescribed for anaerobic biodegradation at the fixed slime layer. Total removal of PERC from wastewater was increased to 5.1% and 24%, respectively, compared to standard conditions (4.9% removal). PERC emissions were reduced by < 1% and 11%, respectively, relative to standard conditions.

7.2 PARAMETER ANALYSES - DROPS

The SUDS model was used to study variables associated with VOC emissions from drops. A confined atmosphere above the drop was assumed, e.g. wet well, with standard conditions listed in Table 7-5. A reach length of only 1.0 m was assumed so that VOCs were essentially discharged directly to the top of the drop. The a value was set equal to 1.0, a conservative assumption for raw wastewater. Variations were completed around the standard reach.

Temporal discretization:

Sensitivity to temporal discretization was much greater than for uniform reaches. Depending on drop and discharge conditions, numerical instabilities were observed to occur for time steps as low as ten seconds.

Drop height:

Drop heights of 0.5, 1.0, 2.5, and 5.0 m were prescribed. Corresponding depletion ratios of 1.06, 1.20, 1.61, and 2.30,

Table 7-5. Standard Conditions for Parameter Analyses on Drops

---

Reach length: 1.0 m (one cell)
Diameter: 1.0 m i.d.
Channel slope: 0.001 $m \cdot m^{-1}$
Roughness coefficient: 0.013
Relative depth: 0.5

Wastewater flow rate: 0.38 $m^3 \cdot s^{-1}$
Wastewater mean velocity: 0.97 $m \cdot s^{-1}$

Gas mean velocity: 0.32 $m \cdot s^{-1}$

Drop height: 1.0 m
Tailwater depth: 1.0 m
Gas volume above drop: 10.0 m^3

VOC: PERC at 20 ^{o}C ($H = 0.549$; $\Psi = 0.52$)

Discharge: slug at 1000 $mg \cdot m^{-3}$ from time = 0.0 to 600 s

Depletion ratio: 1.20 (computed)
Normalized discharge: 1360 $m^2 \cdot hr^{-1}$

Mass discharged: 227 grams
Mass emitted: 19.7 grams (computed)
Total removal to atmosphere: 8.7% (computed)

---

respectively, were computed. Total PERC removals were 4.3%, 8.7%, 12.3%, and 13.8%, respectively. Thus, above 2.5 m, removal increased only slightly with drop height, indicating that the confined gas volume was approaching "saturation" conditions.

Tailwater depth:

Tailwater depths of 0.25 to 3.0 m were prescribed. Depletion ratios varied from 1.14 to 1.20, respectively, with no change above 1.0 m. Total removal varied from 7.4% at tailwater depth of 0.25 m, to 8.7% at tailwater depths of 1.0 and 3.0 m. Removal at 0.5 m was 8.3%. Thus, PERC removal from the drop was much less sensitive to tailwater depth than to drop height.

Gas volume:

Gas volume was varied from 1.0 to 100 m^3, with negligible effect on PERC removal.

Temperature:

Increasing wastewater temperature from 20 ^{o}C to 40 ^{o}C increased Henry's law constant for PERC from 0.55 to 1.50. The depletion ratio r_i was increased slightly from 1.20 to 1.27. Total removal from wastewater increased from a standard value of 8.7% to 15.0%. The difference was almost entirely due to a Henry's law constant, as opposed to higher depletion ratio.

Compound:

In addition to PERC, TCM was studied. Thus, Henry's law constant was decreased to 0.115, the diffusivity parameter was increased to 0.57, and the depletion ratio was increased to 1.22. Overall VOC removal decreased from a value of 8.7% for PERC to only 3.2% for TCM.

Continuous discharge:

In addition to a standard slug discharge, a continuous discharge of PERC was also tested. Initial gas concentration was set equal to 0.0 $mg \cdot m^{-3}$. Steady-state conditions were achieved within three minutes, with a gas concentration of 260 $mg \cdot m^{-3}$, liquid concentration at drop bottom of 913 $mg \cdot m^{-3}$, and a removal from wastewater of 8.7%. Total removal was identical to that for a slug discharge.

Ventilation:

In addition to setting gas velocity equal to 0.33 times liquid velocity, factors of 0.1, 10, and 100 times liquid velocity were also studied. Tetrachloroethene emissions of 4.1, 16.0, and 16.4%, respectively, were predicted. Thus, because infinite ventilation conditions were approached, a 1000-fold increase in gas velocity increased VOC removal by only a factor of four.

Discharge:

Wastewater discharge was varied by changing standard slope and relative depth. For each modification, gas velocity was adjusted to equal 0.33 times wastewater mean velocity. Normalized discharges (wastewater flow divided by surface width), depletion ratios, and predicted removal of PERC are summarized in Table 7-6. Relative removal was obviously sensitive to wastewater discharge. Percent removal increased with discharge at low discharge. However, the opposite was true for discharges above 95 $m^2 \cdot hr^{-1}$. Nakasone (1986) described this in terms of a culmination point at 235 $m^2 \cdot hr^{-1}$, but provided no physical explanation. Variations in discharge should change the relative importance of losses during fall versus losses which occur as a result of entrained air bubbles and splashing in tailwater.

Table 7-6. Removal of PERC from Drops with Varying Wastewater Discharge

Normalized Discharge [m^2 hr^{-1}]	Depletion Ratio [-]	Removal [%]
30	1.17	13.8
95	1.29	21.0
432	1.31	18.2
1360	1.20	8.7
2870	1.15	3.3
9090	1.09	2.9

7.3 HYPOTHETICAL SCENARIOS

A series of hypothetical scenarios were used to assess the relative importance of drops and reaches. All scenarios were simplified, but were intended to represent commonly occurring segments of wastewater collection systems. They included small and large sewers discharging to pump station wet wells, building laterals discharging to street sewers, and drop manholes connecting two sewer channels of different elevations. For each scenario a standard case was defined based upon typical sewer characteristics, and model variations were completed around the standard case. Mass transfer along uniform reaches was computed based on the Parkhurst-Pomeroy model (Equation 3-29) for mass transfer coefficients. No adjustments were made for water quality, since the Parkhurst-Pomeroy model was developed from experimental data associated with raw wastewater. Mass transfer to and from drops was computed using Nakasone's model (Equation 3-39). Results described for drops are believed to overestimate emissions from drops, as "a" was set equal to 1.0.

Small Interceptor Discharging to Wet Well

The first hypothetical scenario was intended to represent a small interceptor at average channel slope discharging to a pump station wet well, either along a collection reach or at the headworks of a small wastewater treatment plant. Standard conditions are listed at the bottom of Table 7-7. Pipe diameter was 1.0 m with a reach length of 5000 m, channel slope of 0.001 m m^{-1}, and total drop of 5 m along the entire reach. Wastewater was assumed to flow at a relative depth of 0.5, which yielded a wastewater flow rate of 0.38 $m^3 \cdot s^{-1}$ and mean wastewater velocity of 0.97 $m \cdot s^{-1}$. Mean gas velocity was assumed to equal 0.33 times liquid velocity, or 0.32 $m \cdot s^{-1}$, and gas flow was ultimately emitted from an exhaust vent or manhole cover above the wet well. For simplicity, the receiving wet well was assumed to be an ideal cylinder with a depth of 10.0 m and diameter of 2.0 m.

Wastewater drop height and tailwater depth (depth of wastewater in well) were assumed to be 1.0 and 4.0 m, respectively. The corresponding 18.8 m^3 of gas volume comprising the wet well atmosphere was assumed to be well-mixed. Tetrachloroethene (PERC) was chosen as a reference VOC at 20 ^oC. A 10-minute slug discharge of 1000 $mg \cdot m^{-3}$ was assumed at the upstream boundary of the collection reach.

To obtain estimates of total removal from the hypothetical system, SUDS was executed for a length of time necessary to observe complete passage of VOC from the system (in both gas and liquid phases). Therefore, at completion of execution, concentrations of PERC in both the wet well atmosphere and influent wastewater were equal to zero.

Results for the standard scenario are provided in Table 7-7. The mass transfer coefficient associated with the uniform reach was a relatively low 0.039 hr^{-1}. The depletion ratio r_i was equal to 1.20 for the drop. A total removal (loss to ambient atmosphere) of 12.7% was predicted for the system. Only 28% of the total emissions were attributed to desorption from the drop, with 72% accounted for along the uniform interceptor reach.

The standard condition was varied to reduce relative depth of wastewater from 0.5 to 0.25. Although depth was reduced, so was wastewater velocity, with a corresponding reduction in mass transfer coefficient to 0.034 hr^{-1}. However, mean PERC transport time along the interceptor increased from 1.4 to 2.3 hours. Normalized (by width) discharge decreased from a standard value of 1360 m^2 hr^{-1} to 432 m^2 hr^{-1}, and r_i increased from 1.20 to 1.31. Actual wastewater flow rate decreased to 0.104 m^3 s^{-1}. A significantly higher removal of PERC was observed during low flow conditions, consistent with findings reported in Section 7.1. Total removal from the system increased from a standard value of 12.7% to 32.8%, with relative contribution from the drop decreasing slightly to 23%.

Table 7-7. Model Conditions and Results for Small Interceptor Discharging to Wet Well

Variation from Standard	Fractional Removal Reach	Drop	Total	Drop/Total
Standard	0.092	0.036	0.127	0.28
Channel relative depth = 0.25	0.254	0.074	0.328	0.23
Tailwater depth = 2 m;				
Drop height = 3 m;				
Gas volume = 25.1 m^3	0.092	0.055	0.146	0.37
Gas velocity = 0.1 times liquid velocity	0.048	0.003	0.051	0.06
Gas velocity = liquid velocity	0.116	0.085	0.201	0.43
TCM ($H = 0.115$; $\Psi = 0.57$)	0.036	0.001	0.037	0.02
VC ($H = 0.907$; $\Psi = 0.72$)	0.131	0.055	0.186	0.30

Standard Conditions

Reach length: 5000 m (25 cells at 200 m $cell^{-1}$)

Pipe: 1.0 m inside diameter; channel slope of 0.001 m m^{-1}

Wastewater flow: 1/2 full; flow = 0.379 m^3 s^{-1}; mean velocity = 0.97 m s^{-1}

Gas flow: mean velocity = 0.32 m s^{-1} (1/3 wastewater velocity)

Wet well: ideal cylinder with 10 m depth and 2 m diameter;
fall height = 1 m;
tailwater depth = 4 m;
gas volume = 18.8 m^3

VOC: PERC at 20 ^oC ($H = 0.549$; $\Psi = 0.52$)

Discharge: slug at 1000 mg m^{-3} from time = 0 - 600 seconds

Effects of modifying wet well pumping conditions were assessed by decreasing tailwater depth from 4.0 to 2.0 m, with a corresponding increase in drop height from 1.0 to 3.0 m, and an increase in gas volume from 18.8 to 25.1 m^3. This led to r_i equal to 1.98. Removal from the reach was unchanged from the standard case. Removal contribution of losses for the drop increased to 37%.

Effects of sewer ventilation were studied by changing gas velocities from 0.33 times wastewater mean velocity to 0.1 (low ventilation) and 1.0 (high ventilation) of the wastewater velocity. At low ventilation, total removal from the system dropped to 5.1%. Percent of total removal attributed to the drop was only 6% resulting from rapid PERC accumulation in Ψ and slow removal from, the wet well atmosphere, and re-partitioning to wastewater following slug passage in the aqueous phase. Conversely, at high ventilation, total PERC removal increased to 20.1% with 43% of total removal attributed to desorption from the drop.

To evaluate losses of compounds other than PERC, TCM (low volatility VOC) and VC (high volatility VOC) were tested under the same standard conditions as PERC. For TCM, total removal was only 3.7% with only 0.1% accounted for by desorption at the drop. Thus, rapid saturation of the wet well atmosphere was observed for a lower volatility VOC. Conversely, total removal of VC was 18.6%, with a 30% relative contribution from the drop (slightly higher than for PERC).

Based on the modeling effort described above, two general statements can be made regarding VOC emissions from small interceptors which discharge to wet wells:

1. Removal of VOCs is expected to be low except for well-ventilated systems, highly volatile compounds, and/or conditions of relatively low depth of flow and long transport times.

2. Relative removal from drops are likely to be smaller than from uniform reaches, with effects of drops being very small for conditions of low ventilation and/or for lower volatility compounds such as TCM.

Large Interceptor Discharging to Wet Well

The second hypothetical scenario was similar to the first, but with a larger interceptor and wet well. Standard conditions are listed at the bottom of Table 7-8. The interceptor pipe diameter was 2.5 m, with a reach length of 10 km, channel slope of 0.005 $m \cdot m^{-1}$, and total drop of 5 m along the entire reach. Wastewater was assumed to flow at a relative depth of 0.5, which yielded a wastewater flow rate of 3.09 $m^3 \cdot s^{-1}$, and mean velocity of 1.26 $m \cdot s^{-1}$. Gas mean velocity was assumed equal to 0.33 times liquid velocity, or 0.42 $m \cdot s^{-1}$. The wet well was again assumed to be an ideal cylinder.

Dimensions were 13.0 m depth and 3.0 m diameter. Drop height and tailwater depth were assumed to be 1.0 m and 7.0 m, respectively, with gas volume of the wet well atmosphere equal to 42.4 m^3. Again, PERC was the standard VOC at a temperature of 20 ^oC. A 10-minute slug discharge of 1000 $mg \cdot m^{-3}$ was used.

Results are summarized in Table 7-8, with variations from standard conditions similar to those described for small interceptors. The following results are apparent:

1. Removal of VOCs was lower than predicted for smaller interceptors, primarily because of deeper wastewater flows and lower removal from the interceptor.

2. There was a greater relative contribution by drops to total losses than exhibited in smaller interceptors. This is consistent with discussions in Chapter 3 in which it was argued that relative importance of drops and other areas of unusual turbulent mixing increase with size of an interceptor. For the two cases of high fall height and high ventilation, losses attributed to the hypothetical drop actually exceeded those from the uniform reach.

Table 7-8. Model Conditions and Results for Large Interceptor Discharging to Wet Well

Variation from Standard	Fractional Removal Reach	Drop	Total	Drop/Total
Standard	0.058	0.043	0.101	0.43
Channel relative depth = 0.25	0.160	0.085	0.245	0.34
Tailwater depth = 4 m;				
Drop height = 4 m;				
Gas volume = 63.6 m^3	0.058	0.082	0.140	0.59
Gas velocity = 0.1 times liquid velocity	0.039	0.009	0.048	0.19
Gas velocity = liquid velocity	0.066	0.075	0.141	0.53
TCM (H = 0.115; Ψ = 0.57)	0.033	0.004	0.036	0.10
VC (H = 0.907; Ψ = 0.72)	0.082	0.066	0.147	0.44

Standard Conditions

Reach length: 10000 m (50 cells at 200 m $cell^{-1}$)
Pipe: 2.5 m inside diameter; channel slope of 0.0005 m m^{-1}
Wastewater flow: 1/2 full; flow = 3.09 m^3 s^{-1}; mean velocity = 1.26 m s^{-1}
Gas flow: mean velocity = 0.42 m s^{-1} (1/3 wastewater velocity)
Wet well: ideal cylinder with 13 m depth and 3 m diameter;
fall height = 1 m;
tailwater depth = 7 m;
gas volume = 42.4 m^3
VOC: PERC at 20 ^oC (H = 0.549; Ψ = 0.52)
Discharge: slug at 1000 mg m^{-3} from time = 0 - 600 seconds

3. For lower volatility VOCs, losses attributed to desorption along the relatively long hypothetical interceptor were nearly an order of magnitude greater than those attributed to the drop.

Building Connections Discharging to Street Sewers

In most collection systems, the largest contribution of wastewater is discharged from residential dwellings and commercial establishments which connect to street sewers by small building laterals. From households, TCM is discharged to the sewer in drinking water, and other VOCs are discharged as slugs through use or decant of household cleaners. As a general rule, building connections are of steep slope (> 0.025 $m \cdot m^{-1}$) and connect to the upper portion of the street sewer. Thus, potential for VOC loss exists along building laterals and at connections with street sewers. The third hypothetical scenario was completed to assess potential for such losses. The SUDS model was again employed.

Standard conditions for a hypothetical building connection are listed at the bottom of Table 7-9. Building laterals were assumed to be 0.10 m (4 inches) in diameter, with a length of 50 m and slope of 0.05 $m \cdot m^{-1}$. Laterals were assumed to discharge at the top of a 0.30 m (12 inch) diameter street sewer flowing at relative depth of 0.5. Tailwater depth in the street sewer was assumed to be mean hydraulic depth (0.12 m), and drop height was 0.15 m. Wastewater discharge through the building lateral was assumed to be 0.0004 $m^3 \cdot s^{-1}$ (6 $gal \cdot min^{-1}$) with a relative depth of flow of 0.125, and wastewater mean velocity of 0.69 $m \cdot s^{-1}$. Gas mean velocity was assumed to be 0.23 $m \cdot s^{-1}$. Unlike confined wet well atmospheres, receiving street sewers appear axially unconfined and gaseous conditions above lateral drops are a function of gaseous conditions in both laterals and street sewers. If a street sewer is characterized by a high concentration of VOC in the gaseous head space, desorption of that VOC from a drop connection is likely to be small, and absorption may even occur. Conversely, if gas flows in a street sewer are high and a VOC concentration is low, removal from a drop connection will be maximized. For the purpose of this hypothetical scenario, gas concentrations of VOCs in the street sewer were assumed to be zero, and gas flow was due entirely to entry from building connections. Since easily defined gas control volumes, e.g. wet well atmospheres, do not exist above drops in street sewers, effective well-mixed gas control volumes were applied and assumed to influence the atmosphere which interacts with the falling wastewater stream. Effects of variation in effective gas volume were insignificant for volumes ranging from 0.1 to 100 m^3.

The standard VOC used in the analysis was TCM at 20 ^oC. Discharge concentration was 50 $mg \cdot m^{-3}$ (1/2 the federal drinking water standard) during a five minute discharge. Results summarized in Table 7-9 indicate that even for TCM, losses along steep building laterals can be significant (28% for standard case). Although mean VOC transport time along the hypothetical building lateral was only 1.2 minutes, removal was attributed to a relatively high mass transfer coefficient of 0.30 hr^{-1}, and low depth of flow. Less than one percent of total relative removal from the building connection was attributed to loss from the connecting drop. Low wastewater discharge, small drop height, and shallow tailwater depth led to a depletion ratio of only 1.01.

In Chapter 4 it was suggested that ventilation rates in residential sewers are expected to be higher than for isolated interceptors due to a wealth of openings to the ambient atmosphere, and ventilation mechanisms such as wind eduction through house vents and buoyancy flows driven by discharge of hot water. When gas velocity was increased to 10 times wastewater mean velocity (approaching infinite dilution) in building laterals, total TCM removal increased to 48.2%. Building laterals remained as the major component for desorption.

Table 7-9. Model Conditions and Results for House Connection Discharging to Street Sewer

Variation from Standard	Fractional Removal Reach	Drop	Total	Drop/Total
Standard	0.280	0.001	0.281	0.004
Gas velocity = 10 times Liq velocity	0.479	0.003	0.482	0.007
TCM at 40 ^{o}C (H = 0.115; Ψ = 0.57)	0.459	0.001	0.460	0.003
VC (H = 0.907; Ψ = 0.72)	0.516	0.003	0.519	0.006

Standard Conditions

Reach length: 50 m (10 cells at 5 m $cell^{-1}$)

Pipe: 0.101 m inside diameter; channel slope of 0.05 m m^{-1}

Wastewater flow: 1/8 full; flow = 0.0004 m^3 s^{-1}; mean velocity = 0.69 m s^{-1}

Gas flow: mean velocity = 0.23 m s^{-1} (1/3 wastewater velocity)

Receiving sewer: 0.305 m inside diameter; depth at 1/2 full; drop height = 0.15 m; tailwater depth = 0.12 m (hydraulic depth); gas volume = 0.1 - 10 m^3

VOC: TCM at 20 ^{o}C (H = 0.115; Ψ = 0.57)

Discharge: slug at 50 mg m^{-3} from time = 0 - 300 seconds

Many wastewater discharges are of elevated temperature, e.g. from dishwashers or hot showers. Thus, temperature was increased from 20 ^{o}C to 40 ^{o}C, with a corresponding increase in Henry's law constant from 0.115 to 0.294 for TCM. The mass transfer coefficient increased to 0.46 hr^{-1}, and total TCM removal increased from a standard value of 28% to 46%. Significant removal prior to entering street sewers is consistent with findings summarized in Table 2-6. Assuming an average between 20 ^{o}C and 40 ^{o}C losses, a concentration of 50 $mg \cdot m^{-3}$ (50 $\mu g \cdot L^{-1}$), and a per capita consumption of 0.56 $m^{3} \cdot day^{-1}$ (150 $gal \cdot day^{-1}$), these results suggest a per capita TCM emission rate of 11 $mg \cdot day^{-1}$ (4000 $kg \cdot year^{-1}$ for a population of one million). These results do not reflect additional emissions following discharge to a street sewer, or generation of TCM from chlorine bleach in washing machines or following discharge to sewers.

Finally, although it is not expected to be discharged from residential dwellings, VC was studied as a compound representative of higher volatility VOCs. Total removal at 20 ^{o}C was nearly double that of TCM, with a slightly greater but still relatively small contribution from the connecting drop.

Drop Manholes Connecting Two Sewer Pipes

The connection of two uniform reaches by an unobstructed drop (drop manhole) was also examined. Standard conditions are summarized at the bottom of Table 7-10. The higher elevation (discharging) reach was assumed to be 5000 m in length with a diameter of 0.5 m and channel slope of 0.001 $m \cdot m^{-1}$. Wastewater was assumed to flow at a relative depth of 0.5, with a flow rate of 0.058 $m^{3} \cdot s^{-1}$, and wastewater mean velocity of 0.6 $m^{3} \cdot s^{-1}$. Gas velocity was assumed to be 0.2 $m \cdot s^{-1}$. The standard VOC was PERC at 20 ^{o}C, with an assumed 10-minute slug discharge of 1000 $mg \cdot m^{-3}$ at the upstream boundary of discharging pipe. The lower elevation (receiving pipe) was assumed to have a diameter of 1.0 m, with a relative depth of 0.5 leading to a tailwater depth (mean hydraulic depth) of 0.39 m. Gas velocity in the receiving pipe was assumed to be low (with no PERC present), and gas entering from the discharge pipe was assumed to be exhausted from a manhole cover above the drop. As with building connections, effective gas volume above the drop was varied with little effect on results.

Results are summarized in Table 7-10. For standard conditions, the mass transfer coefficient in the discharging pipe was 0.032 hr^{-1}. The VOC mean transport time in the discharging pipe was 2.3 hours. Normalized (by surface width) discharge was 430 $m^2 \cdot hr^{-1}$, with a depletion ratio r_i of 1.26 for the standard case. These conditions led to a 14.9% PERC removal with only a small contribution from the drop.

Similar to the hypothetical scenarios for small and large interceptors, decreasing relative depth in the discharge channel to 0.25 led to a substantial increase (to 40.4%) in total PERC removal. The mass transfer coefficient decreased from a standard value of 0.032 hr^{-1} to 0.028 hr^{-1}. However, VOC mean transport time increased from 2.3 to 3.3 hours, and losses from the discharging reach nearly tripled to 39%. The depletion ratio r_i increased from a standard value of 1.26 to 1.28. However, desorption from the drop accounted for only 4% of total PERC emissions.

Effects of a larger receiving channel were assessed by increasing the channel diameter from 1.0 to 2.0 m. At a relative depth of 0.5, tailwater depth increased from 0.39 to 0.79 m. The depletion ratio increased slightly to 1.32, but total losses were only slightly greater than for the standard case. The same was true for an increase in drop height to 2.0 m.

Results were very sensitive to degree of ventilation. At low gas velocity (0.1 times wastewater mean velocity) in the discharging pipe, losses from the drop were negligible (< 0.1%), and only 5.2% of PERC was removed from the system.

Table 7-10. Model Conditions and Results for Drop Manhole Connecting Two Reaches

Variation from Standard	Fractional Removal Reach	Drop	Total	Drop/Total
Standard	0.139	0.010	0.149	0.07
Channel relative depth = 0.25 (discharging sewer)	0.386	0.018	0.404	0.04
Tailwater depth = 0.785 m (receiving sewer)	0.139	0.011	0.150	0.07
Drop height = 2 m	0.139	0.013	0.152	0.08
Gas velocity = 0.1 times liquid velocity	0.052	< 0.001	0.052	< 0.01
Gas velocity = liquid velocity	0.228	0.054	0.282	0.19
TCM (H = 0.115; Ψ = 0.57)	0.037	< 0.001	0.037	< 0.01
VC (H = 0.907; Ψ = 0.72)	0.205	0.017	0.222	0.08

Standard Conditions

<u>Discharging reach</u>
Reach length: 5000 m (25 cells at 200 m $cell^{-1}$)
Pipe: 0.5 m inside diameter; channel slope of 0.001 m m^{-1}
Wastewater flow: 1/2 full; flow = 0.0597 m^3 s^{-1}; mean velocity = 0.61 m s^{-1}
Gas flow: mean velocity = 0.20 m s^{-1} (1/3 wastewater velocity)

<u>Receiving reach</u>
pipe: 1 m inside diameter
Wastewater flow: 1/2 full
Drop: 1 m
Tailwater depth: 0.393 m (hydraulic depth)
Gas volume: varied with insignificant impact

VOC: PERC at 20 ^{o}C (H = 0.549; Ψ = 0.52)

Discharge: slug at 1000 mg m^{-3} from time = 0 - 600 s

During high gas velocity (1.0 times mean wastewater velocity), 28.2% was removed from the system, with 5.4% removal (19% of total) attributed to the drop.

For TCM, results were similar to those for interceptors. Less than 4% removal was predicted, with negligible contributions from drops. However, for VC total losses increased to 22.2%, with 8% of total losses attributed to desorption at the drop.

The drop manhole scenario allows comparison of losses along a 0.5 m i.d. sewer with the same length and slope as the 1.0 m i.d. interceptor described in Table 7-7. Although the mass transfer coefficient was greater (0.039 hr^{-1} compared to 0.032 hr^{-1}) in the larger system, absolute depth of flow was smaller and transport time was longer (2.3 hours compared to 1.4 hours) in the smaller system. The net result was slightly greater losses, for all variations, in the smaller system.

7.4 Application to Residential Chloroform Loss

Emissions of VOCs from hypothetical sewer reaches were presented in Section 7.3. The SUDS model was also used to simulate emissions of trichloromethane (TCM) from a multiple reach system depicted in Figure 7.8. The hypothetical network illustrates predictive capabilities of reach-by-reach model applications, and exemplifies the relative importance of emissions in different segments of the same collection reach.

Trichloromethane was assumed to be discharged continuously at a concentration of 100 $\mu g/L$ (upper limit of federal drinking water standard) from a residential dwelling. The building lateral (segment 1) had a diameter of 0.102 m i.d., slope of 0.05 m/m, and length of 20 m. Relative depth of flow within the lateral was 0.25. Wastewater temperature was assumed to be 35 ^{o}C. A high ventilation rate (approaching infinite dilution conditions) was assumed in the lateral, consistent with findings reported in Section 4.2. The building lateral discharged to a street sewer (segment 2) of 0.15 m i.d. and tailwater depth of 0.12 m, i.e. mean hydraulic depth of a street sewer of 0.31 m i.d. flowing at relative depth of 0.5. A factor of 0.22 was assumed for all drops in the example.

Segment 3 was characterized by a slope of 0.002 m/m, length of 200 m, and wastewater temperature of 30 ^{o}C. Upstream boundary conditions were defined by gas and liquid concentrations immediately downstream of segment 2. Flow-through ventilation was assumed in the same direction as wastewater flow, and with gas mean velocity assumed equal to wastewater mean velocity. The street sewer discharged to a larger connecting sewer (0.4 m i.d.) via a drop manhole (segment 4) with a drop height of 0.23 m and tailwater depth of 0.18 m, i.e. mean hydraulic depth of connecting sewer flowing with a relative depth of 0.5.

The connecting sewer (segment 5) was characterized by a slope of 0.002 m/m, length of 1000 m, and a wastewater temperature of 25 ^{o}C. Upstream boundary conditions were defined by gas and liquid concentrations immediately downstream of segment 4. Flow-through ventilation was assumed in the same direction as wastewater flow, and with a gas mean velocity of 0.16 m/s (0.2 times wastewater mean velocity). Sewer segment 5 connected to a 2000 m reach of 0.533 m i.d. pipe (segment 7). Segment 7 was characterized by a channel slope of 0.002 m/m, and flow-through ventilation with a gas mean velocity of only 0.045 m/s (0.05 times wastewater mean velocity). Gas concentration at the upstream boundary was set equal to zero, as gases transported through segment 5 were assumed to be fully ventilated at a junction box (segment 6) used to connect segments 5 and 7. The junction box was characterized by a drop height of 2.0 m, tailwater depth of 4.0 m, and effective gas volume of 65 m^3. Sewer segment 7 discharged to a large interceptor (segment 9) via a drop manhole (segment 8).

Segment 8 defined upstream boundary conditions for sewer segment 9. A drop manhole was assumed with a drop height of 2.0 m and tailwater depth of 0.96 m. Segment 9 was characterized by a diameter of 2.44 m i.d., channel slope of 0.0008 m/m, length of 5000 m, relative depth of 0.5, and flow-through ventilation with a gas mean velocity of 0.045 m/s (0.03 times wastewater mean velocity). It discharged to an interceptor (segment 11) of equal diameter, relative depth, and length, via a lift station (segment 10) through which all ventilation flow in segment 9 was passed. The drop manhole was characterized by a drop height of 2.0 m, tailwater depth of 4.0 m, and gas volume of 65 m^3.

The final interceptor (segment 11) was assumed to be force-ventilated by blowers near the headworks of a downstream treatment facility. Flow-through ventilation was assumed with a gas mean velocity of 0.75 m/s (0.5 times wastewater mean velocity). The interceptor discharged to a wet well at the plant headworks. A drop height of 1.0 m, tailwater depth of 5.0 m, and effective gas volume of 65 m^3 were assumed.

Model results are illustrated in Figure 7.9. Total removal of trichloromethane from residential dwelling to treatment facility was 23.4 %. Over half of that removal (57%) was attributed to losses along segment 1, i.e. first 20 m of 13220 m of pipe. Very little removal was predicted at drops or along interceptors characterized by relatively deep flows. These predictions are consistent with previous results discussed in Section 7.1.

Table 7-11. Concentrations of TCM at End of Segments of Sewer Model

Segment	TCM Concentration - [μg/L] Liquid	Gas
0	100.0	0.0
1	86.6	1.1
2	86.4	1.2
3	83.3	1.8
4	82.6	2.0
5	80.7	11.5
6	80.7	11.7
7	80.1	11.8
8	80.1	11.8
9	80.1	11.8
10	80.1	11.8
11	77.4	5.6
12	76.6	7.2

Segment Key

1	building lateral
2	drop at connection of two pipes
3	street sewer
4	drop at connection of two pipes
5	connecting sewer
6	junction box
7	connecting sewer
8	drop manhole
9	main interceptor
10	pump station
11	final interceptor
12	pump station

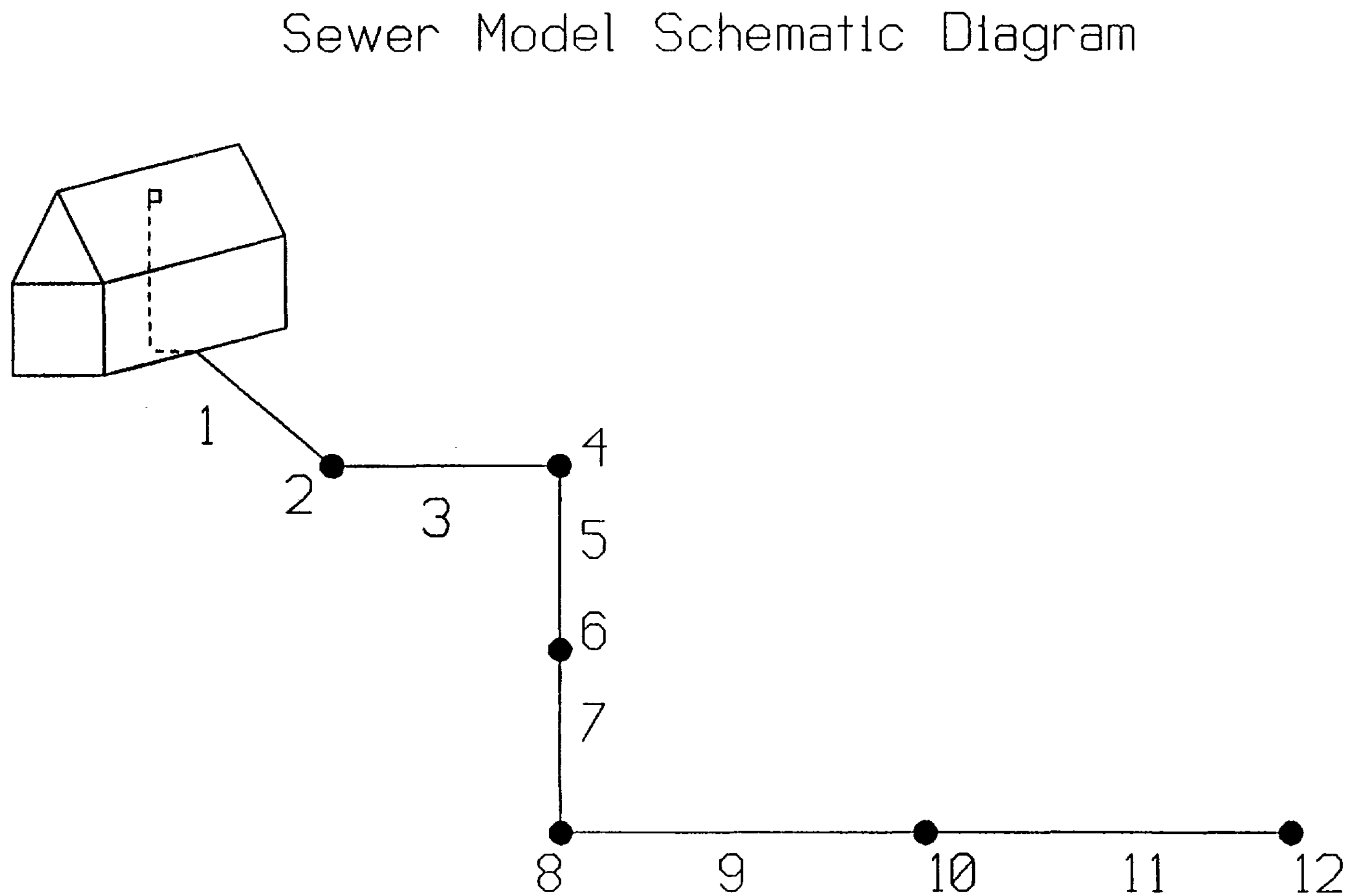

Figure 7-8. Schematic Diagram of Collection System Emission Scenario from Residence to Wastewater Treatment Plant

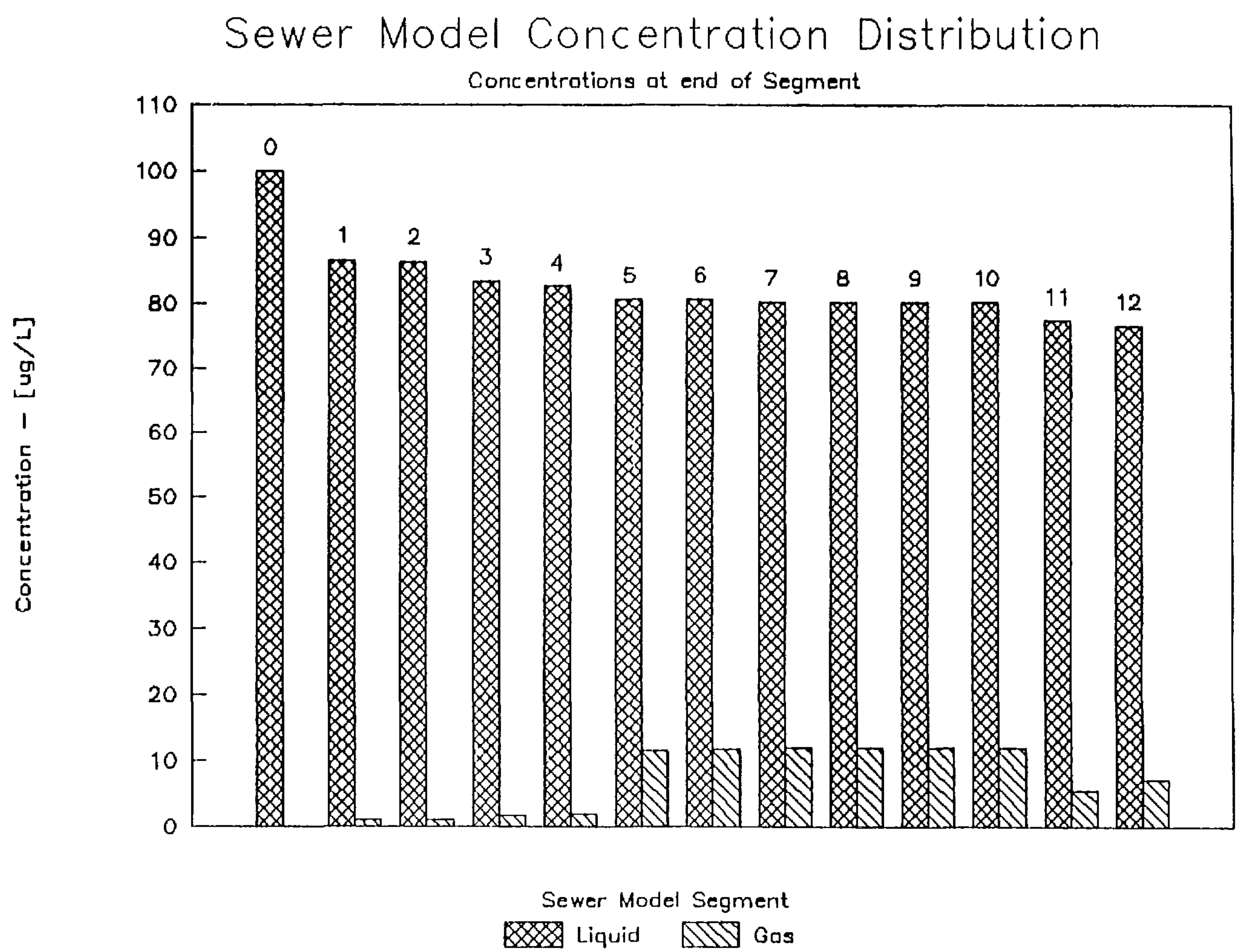

Figure 7-9. Sewer Model Predicted

8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 SUMMARY

A study was completed to assess volatile organic compound emissions, and factors affecting those emissions, from wastewater collection systems. Major components of the study included a literature review of previous studies and theoretical developments, quantitative assessments of factors causing natural ventilation of sewers, field studies to obtain data for evaluating partitioning of VOCs between raw wastewater and overlying gases, and development and application of computational models to evaluate factors affecting VOC emissions from sewers.

A literature review indicated a lack of detailed studies devoted to VOCs in raw wastewater. Previous studies focussed on VOC emissions during wastewater treatment. Limited data indicated the occurrence of several VOCs, often at elevated concentrations, in municipal wastewater and sewer atmospheres. However, little was known about discharge of VOCs to sewers, interfacial partitioning, or ventilation. Mass transfer theory and transfer coefficient models were observed to be dominated by applications involving oxygen absorption to clean water (reaeration). Methods to extrapolate such theories to VOC transfer to/from raw wastewater were examined in Chapter 3. Factors that affect interfacial partitioning were also reviewed. Several transfer coefficient models were described. Only those which included some degree of dimensional argument or theoretical basis were included.

Mass transfer coefficient models were evaluated following a series of tracer studies involving release and measurement of deuterated TCM in small and large operating interceptors. Data confirmed the appropriateness of a model developed from oxygen measurements in operating sewers in Los Angeles County.

Convective transport of VOCs out of collection systems (ventilation) by natural mechanisms was reviewed. Previous estimates of gas flows to/from sewers and relative importance of mechanisms inducing such flows were observed to be less than satisfactory. Ventilation factors were reviewed in Chapter 4. As part of this study, calculations were completed to assess several ventilation mechanisms. It was concluded that no one mechanism dominates all situations, and that actual ventilation rates and dominant mechanisms depend on a complicated interaction of wastewater flow and fluid characteristics, environmental conditions, and physical characteristics of a collection system.

Three computer models were developed to assess VOC emissions from uniformly flowing sewer reaches and drops. In most cases, VOC removal due to drops was small compared to losses along reaches feeding into those drops. One exception was large interceptors with high depths of flow. However, relative removal along large interceptors was low. In contrast, VOCs discharged to steep building laterals were predicted to have high relative removals. Computational models allowed insight to the importance of relative magnitude of emissions and spatial variations in ventilation, wastewater fluid and flow conditions, physico-chemical properties of VOCs, and competing removal mechanisms such as anaerobic biodegradation.

8.2 CONCLUSIONS

Conclusions regarding VOC emissions from collection systems were derived from existing knowledge reported in the literature (Chapters 2 and 3), a quantitative assessment of sewer ventilation mechanisms (Chapter 4), field studies to evaluate models to predict mass transfer coefficients in raw wastewater (Chapter 6), and application of computational models to study hypothetical sewer reaches and to evaluate several factors associated with VOC emissions from sewers (Chapters 5 and 7). Conclusions are separated below into those regarding general concepts of VOC emissions from sewers, those related to interphase partitioning, and those associated with ventilation of wastewater collection systems.

General

1. A comparison of relative VOC emissions between wastewater collection and treatment systems must be made on a system-by-system basis. Results are dependent on size and physical characteristics of a collection system, and location of major dischargers relative to an associated treatment facility.

2. For large interceptors flowing at relative depths of greater than 0.5 and with small channel slopes, VOC removal for discharges that occur within 10 kilometers of a treatment plant are likely to be small relative to emissions at the plant. For such systems, emissions are enhanced at shallower depths of flow or high ventilation rates, e.g., caused by blowers at headworks of a treatment plant. However, even at infinite ventilation, relative losses are likely to be low for VOCs with Henry's law constant less than 0.5.

3. Discharge of VOCs to smaller interceptors located five kilometers or more from a treatment plant can lead to emissions comparable to those at the treatment facility. This is particularly true during periods of low wastewater flow, high ventilation flow rates, or for VOCs with high Henry's law constant.

4 High gas flows in combined sanitary/storm sewers should approach infinite ventilation conditions, and much higher relative emissions result than would be expected in highly confined, separate sanitary sewers.

5. If VOCs are discharged well upstream of wastewater treatment facilities and must traverse building laterals and many smaller reaches with steep channel slopes prior to reaching an interceptor, cumulative emissions of VOCs are likely to be higher than those which occur at an associated treatment facility. This is true even for lower volatility compounds such as chloroform, and is particularly true for VOCs which can be degraded during secondary wastewater treatment, e.g., benzene.

6. Extensive <u>relative</u> removal (greater than 50%) can occur following VOC discharge to building laterals leading to street sewers. An example of <u>total</u> TCM loss from a "typical" residential discharge and through to a

treatment plant is illustrated in Section 7.4. Total losses of about 25% were predicted.

7. Relative removal from short reaches of sewer, i.e., < two kilometers, with moderate to low channel slopes, i.e., < 0.005 $m\text{-}m^{-1}$, should not exceed 50% unless absolute depth of flow is very low, i.e., < 0.2 m.

8. Rapid VOC accumulation in sewer atmospheres leads to low VOC losses from drops, unless high ventilation rates are present, e.g., forced ventilation. Increased desorption, but still relatively low removal (< 20%), can occur under conditions of high ventilation rates, elevated drop heights, elevated temperature, and/or low wastewater discharge. Removal from drops is insensitive to tailwater depth for typical drops and flows in sewers.

9. For a given mass discharge of VOC, total emissions can be substantially higher during periods of low flow in comparison to periods of high flow. Thus, to control emissions from collection systems, discharges from known sources of VOCs should be limited during periods of low flow.

10. Elevated wastewater temperature (e.g., 40 °C as opposed to 20 °C) significantly increases VOC emissions (by up to a factor of nearly two) by increasing VOC diffusivity and hence mass transfer coefficient, Henry's law constant, and buoyancy-driven ventilation.

11. Little is known regarding competing removal mechanisms in sewers. A wide range of first-order decay constants were applied for aerobic and anaerobic biodegradation. Results indicated small reductions (< 14%) in VOC emissions over a hypothetical two kilometer sewer reach.

Partitioning

1. Application of deuterated tracers to study mass transfer characteristics in specific sewer reaches appears promising.

2. Existing theories regarding oxygen transfer to either clean water or wastewater can be adjusted to predict mass transfer coefficients for VOCs in raw wastewater. One model, Parkhurst-Pomeroy, was found to be particularly applicable based on its development from data in operating sewers, and evaluation using VOC tracer data collected as part of this study.

3. Based on oxygen and sulfur hexafluoride measurements at several vertical locations above wastewater, sewer head spaces in interceptors flowing with relative depths of greater than 0.25 appear to be well mixed. Thus, low gas phase resistance can be assumed for most VOCs.

4. The physico-chemical properties of VOCs can have an important impact on partitioning and emissions. At high ventilation rates, sensitivity of emissions to VOC characteristics is minimized and dominated by liquid-phase diffusivity. The opposite is true at lower ventilation rates.

Ventilation

1. Prior to this study, reported estimates of sewer ventilation were sparse. Consideration of ventilation during design of collection systems has developed into something of an "art-within-engineering".

2. Given the complexity of most collection systems it is impossible to accurately calculate actual ventilation rates and gas flow patterns for any given system. For a specific sewer reach, release of an inert tracer can be used to estimate gas flow rates. Reasonable ranges of gas flow rate can be estimated for individual reaches based on examination of individual ventilation mechanisms.

3. Eduction by wind, temperature differences between sewer and ambient atmospheres, and rise and fall of wastewater may act to distribute emissions along a sewer reach. If those factors are not significant, emissions are likely to occur along a reach ending, e.g., pump station wet well. Computational modeling suggested that exact distribution of ventilation may not be significant in terms of total VOC emissions.

4. Liquid drag is the one ventilation mechanism that acts continuously, and causes gas flow in the same direction as wastewater flow.

5. Under conditions of low resistance to ambient air inflow and sewer gas exhaust, liquid drag can induce maximum gas mean velocities of up to 0.2 $m \cdot s^{-1}$. Actual velocities in sanitary sewers are expected to be on the order of 0.01-0.1 $m \cdot s^{-1}$ for small pipes, e.g. 0.25 m i.d., 0.001-0.01 $m \cdot s^{-1}$ for mid-size pipes, e.g. 1.0 m i.d., and 0.0001-0.001 $m \cdot s^{-1}$ for large pipes, e.g. 2.5 m i.d..

6. Barometric pressure gradients on the order of 0.1 $mb \cdot km^{-1}$ can induce gas flows of the same order of magnitude as those caused by liquid drag. Barometric pressure gradients can act to increase or decrease effects of liquid drag depending on direction of the pressure gradient.

7. Rise and fall of wastewater contributes to sewer ventilation. Based on typical depth changes in collection systems, rise and fall of wastewater establishes something of a lower bound on ventilation rates when other factors are not important. It can induce gas velocities on the same order of magnitude as liquid drag for larger pipes, and approximately an order of magnitude lower than liquid drag for smaller pipes.

8. Two factors which may contribute significantly to exhaust of sewer gases are eduction by wind and temperature differences between sewer and ambient atmospheres. However, each requires appropriate environmental conditions. In terms of gas movement along the axis of a sewer, each factor may act to enforce or counteract effects of liquid drag and barometric pressure gradients. Like rise and fall of wastewater, they should act to distribute VOC emissions along a sewer system in contrast to complete exhaust at a reach ending. Under normal environmental conditions, temperature differences and eduction by wind should induce gas velocities on the same order of magnitude as those caused by liquid drag.

9. Barometric pumping is insignificant as a ventilation mechanism.

10. An assumption of infinite ventilation can significantly overestimate VOC emissions under conditions of low ventilation and/or for VOCs with low Henry's law constants. However, such an assumption may be valid and lead to a reduction of modeling complexity for compounds with high Henry's law constants and/or conditions of high ventilation. The latter condition should exist for combined sanitary/storm sewers, or in residential areas or small collectors with many openings between sewer and ambient atmospheres. Even given appropriate environmental conditions, infinite ventilation is not a valid assumption for mid-to-large interceptors characterized by few openings, or connections to smaller collectors.

8.3 RECOMMENDATIONS

Accurate estimates of VOC emissions from multiple collection reaches will require information not available at the time of this writing. For accurate system-specific emission estimates, data regarding mass loadings from all major dischargers, time profiles of wastewater flows in various segments of the system, detailed information on physical characteristics of the system, and information regarding wastewater temperatures would all be required. Even then, a lack of information or ability to reliably estimate ventilation flow rates in various portions of a system could negate the accuracy of such a data-intensive effort. Thus, it may be more appropriate for POTWs to concentrate on evaluation of a few major dischargers and associated reach-by-reach emissions estimates, and/or analysis of potential emission hot spots, e.g., sewer gas exhaust at an opening with flow-through ventilation in an industrialized sewer, or at a location of forced ventilation..

Regulations limiting emissions of airborne toxicants are still in developmental stages. Should VOC emissions from sewers become an area of increasing concern, the following recommendations are made:

1. POTWs should concentrate on identifying major dischargers of VOCs, and on quantifying mass release of speciated VOCs from those dischargers.

2. To reduce VOC emissions from collection systems, POTWs should develop discharge limitations, particularly during periods of low flow.

3. Field studies, possibly introducing volatile tracers in the liquid phase, should be completed to evaluate the importance of areas of agitated flows not addressed in this dissertation. Two areas of particular interest are transitional junctions of two reaches, and areas of changing slope, particularly from steep to lower channel slope.

4. Field experiments should be completed to evaluate drop models and to confirm results reported in this report. A single volatile tracer could be introduced in

wastewater upstream of a wet well, with an inert tracer such as sulfur hexafluoride introduced in the sewer head space. Gas-phase concentrations in the wet well could then be used to ascertain ventilation rates, VOC release and accumulation, and evaluation of drop models.

5. Laboratory and field experiments should be completed to improve knowledge regarding aerobic and anaerobic biodegradation and production of VOCs in sewers. A dual tracer approach using degradable and non-degradable deuterated VOCs could be used for such studies. Comparison of relative removal and physico-chemical properties could provide information regarding effects of biodegradation on VOCs.

6. Theoretical considerations, computational modeling, and field sampling and experiments should be completed to assess VOC losses when gas-phase resistance to mass transfer is important (possibly in wet wells). This might include conditions associated with a poorly mixed sewer head space and/or desorption of lesser volatility organic compounds.

7. The possibility of employing routine oxygen (gas phase) measurements to estimate transfer coefficients and ventilation flows for individual sewer reaches should be studied. The accuracy of inferred ventilation rates could be verified by gas-phase tracer releases to determine average velocities in isolated reaches.

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APPENDIX A: SOURCE CODE FOR MODELS

CORAL (Collection System Organic Release Algorithm)

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C     CORAL2 (Collection system Organic Release ALgorithm - II)
C
C     LIQUID AND GAS MASS TRANSPORT MODEL FOR SEWERS
C
C     DEVELOPED BY RICHARD L. CORSI
C     UNIVERSITY OF CALIFORNIA, DAVIS              8-23-1989
C
      REAL LENGTH, KBIO, CG(2,0:250), CL(2,0:250), FLOLIQ(2),
     1FLOGAS(2), VOLGAS(2), EMIT(250), QMAN(2,250), TOMASS(250),
     1A(8), B(8), PSI(10), KMASS, KMOIST, KWALL
C
C-----------------------------------------------------------------
C     REAL ARRAYS
C
C     A(I) - B(I): REGRESSION PARAMETERS TO CALCULATE HENRY'S LAW
C                  CONSTANT AS A FUNCTION OF TEMPERATURE FOR VOC I
C     CG(I,J): GAS CONCENTRATION  (MILLIGRAMS/CUBIC METER)
C     CL(I,J): LIQUID CONCENTRATION  (MILLIGRAMS/CUBIC METER)
C        I = 1 INDICATES PREVIOUS TIME STEP (N)
C        I = 2 INDICATES CURRENT TIME STEP (N+1)
C        J = CELL NUMBER
C     EMIT(I): EMISSIONS TO ATMOSPHERE AT CELL I (GRAMS)
C     FLOGAS(I): GAS FLOWRATE (CUBIC METERS/SECOND)
C        I = 1 INDICATES INTO CELL
C        I = 2 INDICATES OUT OF THE CELL
C     FLOLIQ(I): LIQUID FLOW (CUBIC METERS/SECOND)
C        I = 1 INDICATES INTO CELL
C        I = 2 INDICATES OUT OF CELL
C     PSI(I): RATIO OF DIFFUSIVITY OF VOC I TO OXYGEN
C     QMAN(J,I): GAS EXCHANGE RATE FOR CELL I (CMS)
C        J=1 (INFLOW);    J=2 (OUTFLOW)
C     TOMASS(I): TOTAL MASS THAT HAS REACHED CELL I (MILLIGRAMS)
C     VOLGAS(I): VOLUME OF GAS/CELL
C        I = 1 INDICATES PREVIOUS TIME STEP
C        I = 2 INDICATES CURRENT TIME STEP
C-----------------------------------------------------------------
C
C
C     INTEGER ARRAYS
C
C     IFEX(I): ARRAY THAT STORES FLAG INDICATING VENTILATION AT
C              CELL I  (IF SO, IFEX(I)=1;  OTHERWISE IFEX(I)=0)
C     ISTORE(I): ARRAY TO STORE INFLOW AND OUTFLOW CELL NUMBERS
C                FOR VENTILATION
C-----------------------------------------------------------------
C
C
C     REAL VARIABLES
C
C     AGAS: X-SECTIONAL AREA OF GAS (SQ. METERS)
C     ALIQ: X-SECTIONAL AREA OF LIQUID (SQ. METERS)
C     ALPHA: VALUE USED IN MANNING'S CALCULATIONS OF FLOW
C     APH: RATIO OF CONTAMINATED TO CLEAN WATER MASS TRANSFER
C          COEFFICIENTS
C     ATOT: TOTAL X-SECTIONAL AREA OF PIPE (SQ. METERS)
C     CAMB: AMBIENT CONCENTRATION (mg/m3)
C     CLOCK: TIME CONVERTED FROM SECONDS TO MINUTES
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```
C      CLSLUG: SLUG CONCENTRATION (mg/m3)
C      CONG: INITIAL GASEOUS CONCENTRATION (mg/m3)
C      CONL: INITIAL AQUEOUS CONCENTRATION (mg/m3)
C      DCG: GAS-PHASE DISPERSION COEFFICIENT (m2/s)
C      DEPTH: WASTEWATER DEPTH FROM SURFACE TO INVERT (METERS)
C      DIST1,DIST2,DIST3: DISTANCES TO MIDPOINTS OF THE 3 CELLS
C                         SPECIFIED FOR OUTPUT (METERS)
C      DIAM: SEWER PIPE DIAMETER (METERS)
C      DT: TIME STEP INCREMENT (SECONDS)
C      DX: SPATIAL STEP INCREMENT (CELL SIZE) IN (METERS)
C      EXFACT: ESCAPE COEFFICIENT USED IN TSIVOGLOU MASS TRANSFER
C              MODEL (1/M)
C      FR: FROUDE NUMBER (USED IN PARKHURST AND POMEROY MASS
C          TRANSFER MODEL
C      GAMMA: TEMPERATURE CORRECTION FACTOR USED IN PARKHURST
C             AND POMEROY MASS TRANSFER MODEL
C      H: HENRY'S LAW CONSTANT (DIMENSIONLESS)
C      HYDEP: MEAN HYDRAULIC DEPTH (METERS)
C      HYRAD: HYDRAULIC RADIUS (METERS)
C      KBIO: FIRST-ORDER BIO-OXIDATION RATE (1/HR)
C      KMASS: MASS TRANSFER RATE COEFFICIENT (1/HR)
C      KMOIST: SORPTION LOSS COEFFICIENT FOR REMOVAL AT MOIST WALLS
C              (M/HR)
C      KWALL: BIODECAY CONSTANT FOR ANAEROBIC DEGRADATION AT WETTED
C             WALL (M/HR)
C      LENGTH: TOTAL LENGTH OF SYSTEM (METERS)
C      PERM:  WETTED PERIMETER (METERS)
C      QEXIT: FLOW EXITING FROM CELL BY VENTILATION (m3/s)
C      QINTO: FLOW ENTERING CELL BY VENTILATION (m3/s)
C      QMIT: INFLOW AND OUTFLOW FOR CELLS UNDER UNIFORM
C            VENTILATION (m3/s)
C      RADIUS: SEWER PIPE RADIUS (METERS)
C      REM1,REM2,REM3: TOTAL MASS REMOVAL BY OUTPUT CELLS 1-3
C      ROUGH: ROUGHNESS COEFFICIENT IN MANNING'S EQUATION
C      SBEGIN: START TIME FOR SLUG DISCHARGE (SECONDS)
C      SEND: END TIME FOR SLUG DISCHARGE (SECONDS)
C      SLOPE: SEWER CHANNEL SLOPE (METERS PER METER)
C      TEMP: TEMPERATURE OF WASTEWATER (INPUT IN C AND
C            CONVERTED TO K)
C      TIME: CUMULATIVE RUN TIME FOR SIMULATION (SECONDS)
C      TOEMIT: TOTAL EMISSIONS FROM SYSTEM (mg CONVERTED TO g)
C      TOTIN: TOTAL MASS DISCHARGED TO SYSTEM (mg)
C      TRPORT: AVERAGE TOTAL RESIDENCE TIME IN SYSTEM (HOURS)
C      TTIME: TOTAL TIME OF SIMULATION (SECONDS)
C      VELOC: AVERAGE VELOCITY OF WASTEWATER (m/s)
C      VOLCEL: TOTAL VOLUME OF ONE CELL (m3)
C      VOLLIQ: VOLUME OF LIQUID/CELL (m3)
C      VOLOLD: VOLLIQ FROM PREVIOUS TIME STEP (m3)
C      VOLSYS: VOLUME OF ENTIRE SYSTEM (m3)
C      VRATE: VENTILATION RATE FOR SYSTEM (turnovers/day)
C      WIDTH: WIDTH OF LIQUID SURFACE IN CHANNEL (METERS)
C      SAREA: INTERFACIAL SURFACE AREA ASSOCIATED WITH A CELL (M2)
C      XLONG: CUMULATIVE DISTANCE TO EACH CELL (METERS)
C
C      ------------------------------------------------------------
C
C
C      INTEGER VARIABLES
```

```
C
C     IBC: FLAG FOR INLET BOUNDARY CONDITION VARIATION W/ TIME
C       1=CONSTANT WITH TIME
C     INCT: TIME INCREMENT COUNTER
C     INDIL: FLAG FOR INFINITE DILUTION ASSUMPTION (1=ID)
C     IRUN: FLAG FOR ANOTHER RUN (1=COMPLETE ANOTHER RUN)
C     IVENT: FLAG FOR VENTILATION TYPE
C       1=UNIFORM VENTILATION
C       2=CELL-SPECIFIC VENTILATION
C     KMODEL: FLAG INDICATING CHOICE OF PARTITIONING MODEL
C     LOXY: FLAG FOR OXYGEN CONSUMPTION (1=RAPID O2 LOSS IN H20)
C     NCELLS: NUMBER OF CELLS
C     NOUT1,NOUT2,NOUT3:  NUMBERS OF 3 CELLS TO OUTPUT RESULTS AT
C     NTIME: NUMBER OF TIME STEPS
C     NTIMER: TIME COUNTER THAT ACCUMULATES UP TO EACH NTOUT, AT
C             WHICH TIME OUTPUT OCCURS AND NTIMER SET EQUAL 0
C     NTOUT:  NUMBER OF TIME STEPS BETWEEN EACH OUTPUT SUMMARY
C     NVOC: CODE NUMBER OF VOC CHOSEN FOR ANALYSIS
C
C     --------------------------------------------------------------
C
      INTEGER IFEX(250), ISTORE(250)
C
      CHARACTER NAME(10)*25,DATE*25,NOTE*50
C
C     OPEN INPUT AND OUTPUT FILES
C        INGAS2.DAT STORES SYSTEM PARAMETER INPUTS
C        OUTGAS.DAT IS A SUMMARY OF MODEL RESULTS AT THREE CELLS
C        VIEWER.DAT IS AN OUTPUT FILE TO BE USED FOR GRAPHING
C        STREET.DAT IS AN OUTPUT FILE OF EMISSIONS
C
      OPEN(UNIT=2, FILE='OUTGAS.DAT', STATUS='NEW')
      OPEN(UNIT=3, FILE='VIEWER.DAT', STATUS='NEW')
      OPEN(UNIT=5, FILE='STREET.DAT',STATUS='NEW')
      OPEN(UNIT=6, FILE='INGAS2.DAT',STATUS='OLD')
C
      NAME(1)='CARBON TETRACHLORIDE'
      NAME(2)='CHLOROFORM'
      NAME(3)='1,1-DICHLOROETHYLENE'
      NAME(4)='METHYLENE CHLORIDE'
      NAME(5)='PERCHLOROETHYLENE'
      NAME(6)='TRICHLOROETHYLENE'
      NAME(7)='1,1,1-TRICHLOROETHANE'
      NAME(8)='VINYL CHLORIDE'
      NAME(9)='GOOD OLD OXYGEN'
      NAME(10)='OTHER; SPECIFY H AND PSI'
      A(1)=11.29
      A(2)=9.843
      A(3)=8.845
      A(4)=6.653
      A(5)=12.45
      A(6)=11.37
      A(7)=9.777
      A(8)=7.385
      B(1)=4411.0
      B(2)=4612.0
      B(3)=3729.0
      B(4)=3817.0
```

```
      B(5)=4918.0
      B(6)=4780.00
      B(7)=4133.0
      B(8)=3286.0
      PSI(1)=0.63
      PSI(2)=0.57
      PSI(3)=0.62
      PSI(4)=0.61
      PSI(5)=0.52
      PSI(6)=0.57
      PSI(7)=0.49
      PSI(8)=0.72
      PSI(9)=1.0
C
C     INITIALIZE FLAGS AND CONCENTRATIONS
C
      DO 10 I=1,250,1
         IFEX(I)=0
         CL(1,I)=0.0
         CL(2,I)=0.0
         CG(1,I)=0.0
         CG(2,I)=0.0
         ISTORE(I)=0
         EMIT(I)=0.0
         QMAN(1,I)=0.0
         QMAN(2,I)=0.0
         TOMASS(I)=0.0
10    CONTINUE
      CL(1,0)=0.0
      CG(1,0)=0.0
      CL(2,0)=0.0
      CG(2,0)=0.0
C
C     SPECIFY THE DATE OF THE MODELING ANALYSIS
C
      PRINT *,'ENTER TODAYS DATE (25 CHARACTERS MAX.)'
      READ(*,900)DATE
C
C     SPECIFY A MODELING NOTE (IF DESIRED)
C
      PRINT *,'ENTER A MODELING RUN NOTE (50 CHARACTERS MAX.)'
      READ(*,950)NOTE
C
C     SPECIFY THE VOC TO BE ANALYZED
C
      WRITE(*,1000)
      DO 15 I=1,10,1
        WRITE(*,1050)I,NAME(I)
15    CONTINUE
      READ *,NVOC
      IF(NVOC .EQ. 9)THEN
        PRINT *,'ENTER A 1 IF OXYGEN CONSUMED RAPIDLY IN WW'
        READ *,LOXY
      END IF
C
      READ(6,*)DX,NCELLS
      READ(6,*)DT,NTIME
      READ(6,*)NOUT1,NOUT2,NOUT3
```

```
      READ(6,*)NTOUT
      LENGTH=DX*REAL(NCELLS)
      TTIME=DT*REAL(NTIME)
C
      READ(6,*)TEMP
      TEMP=TEMP+273.15
      IF(NVOC .LE. 8)THEN
        H=EXP(A(NVOC)-B(NVOC)/TEMP)/(TEMP*8.21E-5)
      ELSE IF(NVOC .EQ. 9)THEN
        PRINT *,' '
        PRINT *,' ENTER H(DIMENSIONLESS) FOR OXYGEN'
        PRINT *,' H=32.0 AT 25 C'
        READ *,H
      ELSE
        PRINT *,' '
        PRINT *,'OTHER COMPOUND'
        PRINT *,' ENTER H (DIMENSIONLESS)'
        READ *,H
        PRINT *,'ENTER RATIO OF COMPOUND TO OXYGEN DIFFUSIVITY'
        PRINT *,' PSI'
        READ *,PSI(10)
      END IF
C
      READ(6,*)KMODEL,APH
      IF(KMODEL .EQ. 1)THEN
        PRINT *,' '
        PRINT *,' ENTER THE ESCAPE COEFFICIENT (1/M)'
        READ *,EXFACT
      END IF
C
      READ(6,*)KBIO,KWALL,KMOIST,FABS
      READ(6,*)DCG
      KBIO=KBIO/3600.0
      KWALL=KWALL/3600.0
      KMOIST=KMOIST/3600.0
C
      READ(6,*)DIAM,ROUGH,SLOPE
      READ(6,*)DEPTH
      RADIUS=DIAM/2.0
      ATOT=3.14159*RADIUS**2
C
      READ(6,*)CONG,CONL
C
      DO 50 I=1,NCELLS,1
        CG(1,I)=CONG
        CL(1,I)=CONL
50    CONTINUE
C
C     READ IN FLAGS INDICATING TYPE OF TIME VARIATION FOR BC
C
      READ(6,*)IBC
C
C     SET SLUG DISCHARGE PARAMETERS IF IBC NOT 1
C
      IF(IBC .NE. 1)THEN
       READ(6,*)SBEGIN,SEND
       READ(6,*)CLSLUG
       READ(6,*)CG(2,0)
```

```
      ELSE
       READ(6,*)CL(2,0),CG(2,0)
       CL(2,0)=CL(2,0)*FABS
      END IF
C
C     INDICATE WHETHER INFINITE DILUTION (GAS) ASSUMED
C
      READ(6,*)INDIL
C
C     SET VENTILATION PARAMETERS
C
      READ(6,*)IVENT
      READ(6,*)VRATE
      VOLSYS=ATOT*LENGTH
      VOLCEL=VOLSYS/REAL(NCELLS)
      IF(IVENT .EQ. 1)THEN
        QMIT=(VOLCEL/8.64E4)*VRATE
        DO 60 I=1,NCELLS,1
          IFEX(I)=1
          QMAN(1,I)=QMIT
          QMAN(2,I)=QMIT
60      CONTINUE
      ELSE
        READ(6,*)NFLAG,(ISTORE(I),I=1,NFLAG,1)
        DO 63 I=1,NFLAG,1
          IFEX(ISTORE(I))=1
          QMAN(1,ISTORE(I))=(VOLSYS*VRATE)/
     1     (REAL(NFLAG)*8.64E4)
63      CONTINUE
        READ(6,*)NFLAG,(ISTORE(I),I=1,NFLAG,1)
        DO 65 I=1,NFLAG,1
          IFEX(ISTORE(I))=1
          QMAN(2,ISTORE(I))=(VOLSYS*VRATE)/(REAL(NFLAG)*
     1                          8.64E4)
65      CONTINUE
      END IF
C
      READ(6,*)CAMB
C
C     OUTPUT CONSTANT VALUES
C
      WRITE(2,1100)NAME(NVOC),DATE,NOTE,DX,DT,LENGTH,TTIME
      IF(IVENT .EQ. 1)THEN
        WRITE(2,1130)VRATE
      ELSE
        WRITE(2,1140)VRATE
      END IF
      WRITE(2,1200)DIAM,ROUGH,SLOPE
      WRITE(2,1250)EXFACT,DCG,TEMP
      WRITE(2,1255)H,PSI(NVOC)
      WRITE(2,1257)KBIO*3600.0,KWALL*3600.0,KMOIST*3600.0,FABS
C
C     OUTPUT TABLE HEADINGS
C
      DIST1=REAL(NOUT1)*DX-DX/2.0
      DIST2=REAL(NOUT2)*DX-DX/2.0
      DIST3=REAL(NOUT3)*DX-DX/2.0
      WRITE(2,1275)NOUT1,NOUT2,NOUT3,NOUT1,NOUT2,NOUT3,DIST1,DIST2,
```

```
     1DIST3,DIST1,DIST2,DIST3
C
C     INITIALIZE TOTIN (TOTAL MASS INPUT AT INLET OF THE SYSTEM)
C
      TOTIN=0.0
      TOEMIT=0.0
C
C     BEGIN TIME INCREMENTS
C
C     INCT: TIME INCREMENT COUNTER (STOP WHEN INCT = NTIME)
C
      TIME=0.0
      INCT=0
      NTIMER=0
9999  CONTINUE
      TIME=TIME+DT
      INCT=INCT+1
      NTIMER=NTIMER+1
C
C     INPUT THE INLET CONCENTRATION BOUNDARY CONDITIONS
C
      IF(IBC .NE. 1)THEN
         IF(TIME .GE. SBEGIN .AND. TIME .LE. SEND)THEN
           CL(2,0)=CLSLUG*FABS
         ELSE
           CL(2,0)=0.0
         END IF
      END IF
C
C     COMPUTE FLOWS, VOLUMES, AREAS (METERS AND SECONDS)
C
      ALPHA=ACOS((RADIUS-DEPTH)/RADIUS)
      ALIQ=ALPHA*RADIUS**2-(RADIUS-DEPTH)*SQRT(2.0*RADIUS*DEPTH-
     1DEPTH**2)
      PERM=2.0*RADIUS*ALPHA
      AWALL=PERM*DX
      AMOIST=(2.0*3.14159*RADIUS-PERM)*DX
      WIDTH=2.0*SQRT(2.0*RADIUS*DEPTH-DEPTH**2)
      SAREA=WIDTH*DX
      HYDEP=ALIQ/WIDTH
      HYRAD=ALIQ/PERM
      FLOLIQ(1)=ALIQ/ROUGH*(HYRAD**(2.0/3.0))*SQRT(SLOPE)
      VELOC=FLOLIQ(1)/ALIQ
      VOLLIQ=ALIQ*DX
      IF(INCT .EQ. 1)THEN
        VOLOLD=VOLLIQ
      END IF
      AGAS=ATOT-ALIQ
      VOLGAS(2)=AGAS*DX
      IF(INCT .EQ. 1)THEN
        VOLGAS(1)=VOLGAS(2)
      END IF
C
C     COMPUTE LIQUID-GAS MASS TRANSFER COEFFICIENTS
C       KMODEL = 1: TSIVOGLOU
C       KMODEL = 2: O'CONNOR AND DOBBINS
C       KMODEL = 3: PARKHURST AND POMEROY
C       KMODEL = 4: DOBBINS
```

```
C        KMODEL = 5: LAU
C        KMODEL = 6: USER-SPECIFIED
C
      GAMMA=1.0212**((TEMP-273.15)-20.0)
      IF(KMODEL .EQ. 1)THEN
        KMASS=APH*PSI(NVOC)*EXFACT*SLOPE*VELOC*GAMMA
      ELSE IF(KMODEL .EQ. 2)THEN
        KMASS=APH*PSI(NVOC)*0.175*SQRT(VELOC)/(HYDEP**1.5)/3600.0
     1          *GAMMA
      ELSE IF(KMODEL .EQ. 3)THEN
        FR=VELOC/SQRT(9.81*HYDEP)
        KMASS=0.96*(1.0+0.17*FR**2)*GAMMA*(SLOPE*VELOC)**0.375/
     1          HYDEP/3600.0*PSI(NVOC)*APH
      ELSE IF(KMODEL .EQ. 4)THEN
        E=30.0*SLOPE*VELOC
        FR=VELOC/SQRT(9.81*HYDEP)
        ATERM=9.68+0.054*((TEMP-273.15)-20.0)
        BTERM=0.976+0.0137*(30.0-(273.15-TEMP))**1.5
        C4=0.9+FR
        CA=1.0+FR**2
        ANUM=0.12*CA*ATERM*E**0.375/TANH((BTERM*E**0.125)/SQRT(C4))
        DENOM=(C4**1.5)*HYDEP
        KMASS=ANUM/DENOM/3600.0
      ELSE IF(KMODEL .EQ. 5)THEN
        USTAR=SQRT(9.81*HYRAD*SLOPE)
        KMASS=(0.0126*(USTAR**3)/VELOC**2)*GAMMA
      ELSE
        IF(TIME .EQ. DT)THEN
         PRINT *,' ENTER KMASS (1/HR)'
         READ *,KMASS
         KMASS=KMASS/3600.0
        END IF
      END IF
      IF(KMODEL .LE. 4)THEN
        KMASS=KMASS*HYDEP
      END IF
C
      TOTIN=TOTIN+CL(2,0)*FLOLIQ(1)*DT
C
C     SKIP LIQUID PHASE IF ANALYSIS IS FOR RAPIDLY CONSUMED OXYGEN
C
      IF(NVOC .EQ. 9 .AND. LOXY .EQ. 1)THEN
        DO 67 I=1,NCELLS,1
          CL(1,I)=0.0
          CL(2,I)=0.0
 67     CONTINUE
        GO TO 777
      END IF
C
C     SPATIAL STEPS IN THE LIQUID PHASE
C
      DO 70 I=1,NCELLS,1
        FLOLIQ(2)=FLOLIQ(1)
        TERM1=FLOLIQ(1)*CL(2,I-1)
        TERM2=KMASS/H*CG(1,I)*SAREA
        TERM3=CL(1,I)*VOLOLD/DT
        ANUM=TERM1+TERM2+TERM3
        TERM1=VOLLIQ/DT
```

```
         TERM2=FLOLIQ(2)
         TERM3=KMASS*SAREA+KBIO*VOLLIQ+KWALL*AWALL
         DENOM=TERM1+TERM2+TERM3
         CL(2,I)=ANUM/DENOM
         TOMASS(I)=TOMASS(I)+(FLOLIQ(1)+FLOLIQ(2))/2.0*DT*
     1   (CL(2,I)+CL(1,I))/2.0
         CL(1,I)=CL(2,I)
         FLOLIQ(1)=FLOLIQ(2)
70     CONTINUE
C
777    CONTINUE
C
C      PASS UP THE SPATIAL STEPS IN GAS IF DILUTION INFINITE
C
       IF(INDIL .EQ. 1)THEN
         DO 75 I=1,NCELLS,1
           CG(2,I)=0.0
           CG(1,I)=0.0
75       CONTINUE
         GO TO 888
       END IF
C
C      SPATIAL STEPS IN THE GAS PHASE
C
       DO 80 I=1,NCELLS,1
         IF(IFEX(I) .EQ. 1)THEN
           QEXIT=QMAN(2,I)
           QINTO=QMAN(1,I)
         ELSE
           QEXIT=0.0
           QINTO=0.0
         END IF
         FLOGAS(2)=FLOGAS(1)+QINTO-QEXIT
          TERM1=(VOLGAS(1)/DT-KMASS*SAREA/H)*CG(1,I)
          TERM2=(FLOGAS(1)+DCG*AGAS/DX)*CG(2,I-1)
          TERM3=DCG*AGAS/DX*CG(1,I+1)
          TERM4=KMASS*CL(2,I)*SAREA
          TERM5=QINTO*CAMB
          ANUM=TERM1+TERM2+TERM3+TERM4+TERM5
          TERM1=VOLGAS(2)/DT
          TERM2=FLOGAS(2)
          TERM3=2.0*DCG*AGAS/DX
          TERM4=KMOIST*AMOIST
          DENOM=TERM1+TERM2+TERM3+TERM4+QEXIT
         CG(2,I)=ANUM/DENOM
         EMIT(I)=EMIT(I)+CG(2,I)*QEXIT*DT/1000.0
         CG(1,I)=CG(2,I)
         FLOGAS(1)=FLOGAS(2)
80     CONTINUE
888    CONTINUE
       VOLGAS(1)=VOLGAS(2)
       IF(INCT .LE. NTIME)THEN
         VOLOLD=VOLLIQ
         WRITE(3,1285)TIME/60.0,CL(2,NOUT3),CG(2,NOUT3),TOTIN,
     1   TOMASS(NOUT3)
         IF(NTIMER .EQ. NTOUT)THEN
           NTIMER=0
           CLOCK=TIME/60.0
```

```
          WRITE(2,1300)CLOCK,CL(2,NOUT1),CL(2,NOUT2),CL(2,NOUT3),
     1    CG(2,NOUT1),CG(2,NOUT2),CG(2,NOUT3)
        END IF
        GO TO 9999
      END IF
C
C     CALCULATE AND OUTPUT THE REMOVAL AT EACH OF THE THREE TARGET
C     CELLS
C
      IF(TOTIN .GT. 0.0)THEN
        REM1=1.0-TOMASS(NOUT1)/TOTIN
        REM2=1.0-TOMASS(NOUT2)/TOTIN
        REM3=1.0-TOMASS(NOUT3)/TOTIN
        WRITE(2,1400)REM1,REM2,REM3
      END IF
C
      WRITE(2,1450)FLOLIQ(2)
C
C     CALCULATE AND OUTPUT THE TRANSPORT TIME IN THE SYSTEM
C
      TRPORT=(LENGTH/VELOC)/3600.0
      VTOT=3.14159*RADIUS**2*DX*REAL(NCELLS)
      QFLO=VTOT*VRATE/(3600.0*24.0)
      VELGAS=QFLO/AGAS
      WRITE(2,1475)VELOC,TRPORT,VELGAS
C
      DO 85 I=1,NCELLS,1
        XLONG=DX*REAL(I)-DX/2.0
        WRITE(5,1500)XLONG,EMIT(I)
        TOEMIT=TOEMIT+EMIT(I)
85    CONTINUE
      WRITE(2,1600)TOEMIT
C
      WRITE(2,1800)KMASS*3600.0
      PRINT *,' AGAS = ',AGAS
      PRINT *,' WIDTH = ',WIDTH
      PRINT *,' GAS HYDRAULIC RADIUS = ',AGAS/WIDTH
      PRINT *,' LIQUID HYDRAULIC DEPTH =',HYDEP
C
C     FORMAT BLOCK
C
900   FORMAT(A25)
950   FORMAT(A50)
1000  FORMAT(1X,'ENTER THE # OF THE VOC TO ANALYZE: ',//)
1050  FORMAT(5X,I2,5X,A25)
1100  FORMAT(' COMPOUND: ',A25,5X,'DATE: ',A25,//,A50,//,' DX(m): ',
     1E10.3,/,' DT (s): ',E10.3,/,' TOTAL REACH LENGTH (m): ',E10.3,
     1/,' TOTAL ANALYSIS TIME (sec): ',E10.3,/)
1130  FORMAT(1X,'UNIFORM VENTILATION: VRATE = ',F6.2,/)
1140  FORMAT(1X,'CELL-SPECIFIC VENTILATION: VRATE = ',F6.2)
1200  FORMAT(' DIAMETER (m):',E10.3,/,' ROUGHNESS COEFFICIENT: ',
     1E10.3,/,' SLOPE (m/m): ',E10.3,/)
1250  FORMAT(' EXFACT (1/m): ',F5.3,/,
     1' DCG (m2/sec): ',E10.3,/,' TEMP (K): ',F6.2)
1255  FORMAT(1X,'H(DIM): ',F6.3,10X,'PSI: ',F5.3)
1257  FORMAT(//,1X,'DECAY CONSTANTS:',//,2X,'AEROBIC (1/HR): ',
     1E10.3,/,2X,'ANAEROBIC (M/HR): ',E10.3,/,2X,
     1'MOIST WALL (M/HR): ',E10.3,/,2X,'SOLIDS SORPTION FRACTION: '
```

```
     1,E10.3)
1275  FORMAT(//,23X,'LIQUID',27X,'GASEOUS',//,12X,6('CELL ',I3,3X),
     1//,2X,'MIN',6X,6(F7.1,1X,'m',2X),/,75('-'))
1285  FORMAT(E10.3,4(2X,E10.3))
1300  FORMAT(1X,F7.2,2X,6(1X,E10.3))
1400  FORMAT(/,9X,3(1X,E10.3))
1450  FORMAT(/,2X,'FINAL FLOWRATE (M3/S): ',E10.3)
1475  FORMAT(1X,'VELOCITY (M/S): ',E10.3,5X,
     1'TRANSPORT TIME (HRS): ',F7.2,7X,'GAS VEL (M/S): ',E10.3)
1500  FORMAT(2(2X,E10.3))
1600  FORMAT(/,1X,'TOTAL EMISSIONS (GRAMS):',E10.3,/,1X,60('-'))
1800  FORMAT(/,1X,'KMASS (1/HR): ',E10.3,/)
C
      CLOSE(UNIT=2)
      CLOSE(UNIT=3)
      STOP
      END
```

MATES (Multi-Parameter Assessment of Toxic Emissions from Sewers)

```
C     PROGRAM MATES3.FOR: Multivariable Assessment of Toxic Emissions
C                         from Sewers (Version 3) - 25 Nov, 1988
C
C                         DEVELOPED BY: RICHARD L CORSI
C                         DEPARTMENT OF CIVIL ENGINEERING
C                         UNIVERSITY OF CALIFORNIA, DAVIS
C
C     THIS PROGRAM TAKES A SET OF VALUES FOR SEWER DIAMETER, DEPTH
C     TO DIAMETER RATIO, SLOPE, VENTILATION RATE, AND HENRY'S LAW
C     CONSTANT, AND COMPUTES VOC REMOVAL FOR EACH PARAMETER COMBINATION.
C     A SPECIFIC CRITERIA OF 50% REMOVAL IS USED.  A COUNTER IS UTILIZED
C     TO KEEP TRACK OF THOSE COMBINATIONS THAT MEET THE SPECIFIC
C     CRITERIA.  THE RESULTS ARE OUTPUT IN MATRIX FORM SHOWING EACH
C     PARAMETER VERSUS EACH OTHER PARAMETER.  THE MATRIX CELLS
C     INDICATE THE FRACTION OF TIME THAT EACH PARAMETER COMBINATION
C     LED TO A 50% REMOVAL OVER A 10 MILE REACH.
C
C     -----------------------------------------------------------------
C
C     DESCRIPTION OF INTEGER VARIABLES AND ARRAYS
C
C
C     IBC       DECISION VARIABLE FOR TYPE OF DISCHARGE CONDITION
C                 IBC=1 : CONTINUOUS DISCHARGE
C                 IBC=2 : SLUG DISCHARGE
C
C     KMODEL    DECISION VARIABLE DENOTING SPECIFIC PARTITIONING MODEL
C                 KMODEL=1 : O'CONNOR-DOBBINS (ISOTROPIC TURBULENCE)
C                 KMODEL=2 : O'CONNOR-DOBBINS (NON-ISOTROPIC TURBULENCE)
C                 KMODEL=3 : DOBBINS
C                 KMODEL=4 : KRENKEL-ORLOB
C                 KMODEL=5 : PARKHURST-POMEROY
C                 KMODEL=6 : TSIVOGLOU-NEAL
C
C     MDF(I,J,K) COUNTING ARRAY FOR DIAMETER AND FRACTIONAL DEPTH
C                   I=SPECIFIC TO DIAM(I)
C                   J=SPECIFIC TO FDEP(J)
C                   K=1 FOR COUNTING NUMBER OF VIOLATIONS FOR I,J COMBO
C                    =2 FOR COUNTING NUMBER OF COMBINATIONS FOR I,J
C                     WITH ALL OTHER PARAMETERS VARIED THROUGH ALL VALUES
C
C     MDH(I,J,K) COUNTING ARRAY FOR DIAMETER AND HENRY'S LAW CONSTANT
C                   I=SPECIFIC TO DIAM(I)
C                   J=SPECIFIC TO H(J)
C                   K (SEE MDF)
C
C     MDS(I,J,K) COUNTING ARRAY FOR DIAMETER AND CHANNEL SLOPE
C                   I=SPECIFIC TO DIAM(I)
C                   J=SPECIFIC TO SLOPE(J)
C                   K (SEE MDF)
C
C     MDV(I,J,K) COUNTING ARRAY FOR DIAMETER AND VENTILATION RATE
C                   I=SPECIFIC TO DIAM(I)
C                   J=SPECIFIC TO VRATE(J)
C                   K (SEE MDF)
C
C   MFH (I,J,K) COUNTING ARRAY FOR FRACTIONAL DEPTH AND HENRY'S CONSTANT
C                   I=SPECIFIC FDEP(I)
```

```
C                   J=SPECIFIC TO H(J)
C                   K (SEE MDF)
C
C      MFS(I,J,K) COUNTING ARRAY FOR FRACTIONAL DEPTH AND SLOPE
C                   I=SPECIFIC TO FDEP(I)
C                   J=SPECIFIC TO SLOPE(J)
C                   K (SEE MDF)
C
C      MFV(I,J,K) COUNTING ARRAY FOR FRACTIONAL DEPTH AND VENTILATION
C                   I=SPECIFIC TO FDEP(I)
C                   J=SPECIFIC TO VRATE(J)
C                   K (SEE MDF)
C
C      MSH(I,J,K) COUNTING ARRAY FOR SLOPE AND HENRY'S LAW CONSTANT
C                   I=SPECIFIC TO SLOPE(I)
C                   J=SPECIFIC TO H(J)
C                   K (SEE MDF)
C
C      MSV(I,J,K) COUNTING ARRAY FOR SLOPE AND VENTILATION RATE
C                   I=SPECIFIC TO SLOPE(I)
C                   J=SPECIFIC TO VRATE(J)
C                   K (SEE MDF)
C
C      MVH(I,J,K) COUNTING ARRAY FOR VENTILATION AND HENRY'S CONSTANT
C                   I=SPECIFIC TO VRATE(I)
C                   J=SPECIFIC TO H(J)
C                   K (SEE MDF)
C
C      NCELLS     NUMBER OF CELLS (SPATIAL)
C
C      NDIAM      NUMBER OF DIAMETERS TO ANALYZE
C
C      NFDEP      NUMBER OF FRACTIONAL DEPTHS TO ANALYZE
C
C      NH         NUMBER OF HENRY'S LAW CONSTANTS TO ANALYZE
C
C      NSLOPE     NUMBER OF CHANNEL SLOPES TO ANALYZE
C
C      NTIMER     COUNTER FOR NUMBER OF TIME STEPS PER COMBINATION
C
C      NUMCOM     COUNTER FOR NUMBER OF COMBINATIONS
C
C      NUMMET     COUNTER FOR NUMBER OF COMBOS MEETING CRITERIA (FCRIT)
C
C      NVRATE     COUNTER FOR NUMBER OF VENTILATION RATES TO ANALYZE
C
C      ----------------------------------------------------------------
C
C
C      DESCRIPTION OF REAL VARIABLES AND ARRAYS
C
C
C
C      AGAS       CROSS-SECTIONAL AREA OF GAS (m2))
C
C      ALIQ       CROSS-SECTIONAL AREA OF WASTEWATER (m2)
C
C      APH        CONTAMINATED FROM TAP WATER CONVERSION -  ALPHA
```

```
C
C     ATOT         TOTAL CROSS-SECTIONAL AREA OF PIPE (m2)
C
C     CAMB         AMBIENT CONCENTRATION (mg/m3)
C
C     CG(I,J)      GASEOUS CONCENTRATION ARRAY (mg/m3)
C                    I=TIME SUBSCRIPT (1=PREVIOUS STEP; 2=CURRENT)
C                    J=CELL SUBSCRIPT (0=FOR INLET)
C
C     CGIN         INLET GASEOUS CONCENTRATION (mg/m3)
C
C     CL(I,J)      AQUEOUS CONCENTRATION ARRAY (mg/m3)
C                    I=TIME SUBSCRIPT (1=PREVIOUS STEP; 2=CURRENT)
C                    J=CELL SUBSCRIPT (0 FOR INLET)
C
C     CLIN         INLET AQUEOUS CONCENTRATION FOR CONTINUOUS DISCHARGE
C                  (mg/m3)
C
C     CLSLUG       INLET AQUEOUS CONCENTRATION FOR SLUG DISCHARGE (mg/m3)
C
C     COEFF        RATIO OF GAS VELOCITY TO LIQUID VELOCITY
C                  SHOULD SET=0 FOR CASE OF UNIFORM VENTILATION
C
C     CONG         INITIAL GASEOUS CONCENTRATION IN ALL CELLS (mg/m3)
C
C     CONL         INITIAL AQUEOUS CONCENTRATION IN ALL CELLS (mg/m3)
C
C     CRIT         CRITERIA VARIABLE TO INDICATE WHEN SYSTEM HAS REACHED
C                  STEADY-STATE
C
C     DEPTH       PEPENDICULAR DISTANCE FROM PIPE INVERT TO LIQUID SURFACE
C                  (M)
C
C     DIAM(I)      DIAMETER VALUE I (m)
C
C     DT           TIME STEP (sec) - COMPUTED AS 1/3 OF ADVECTION TIME FOR
C                  ONE CELL
C
C     DX           SPATIAL DISTANCE BETWEEN CELL CENTERS (m)
C
C     FCRIT        REMOVAL CRITERIA FOR GIVEN COMBINATION.  IF FRACTIONAL
C                  REMOVAL AT DISTANCE=LENGTH > FCRIT, THEN RECORD AS
C                  MEETING REMOVAL CRITERIA IN APPROPRIATE COUNTING ARRAYS
C
C     FDEP(I)      FRACTIONAL DEPTH VALUE I (-)
C
C     FLOGAS       GAS FLOW ALONG LENGTH OF CHANNEL (m3/s).  SHOULD BE
C                  ZERO FOR UNIFORM VENTILATION
C
C     FLOLIQ     LIQUID FLOWRATE (m3/s) - COMPUTED FROM MANNING'S EQUATION
C
C     FR           FROUDE NUMBER
C
C     H            DIMENSIONLESS HENRY'S LAW CONSTANT (-) RATIO OF GAS-TO-
C                  AQUEOUS CONCENTRATIONS AT EQUILIBRIUM.
C
C     HYDEP        HYDRAULIC DEPTH (m)
C
```

```
C      HYRAD       HYDRAULIC RADIUS (m)
C
C      KMASS       LIQUID-PHASE MASS TRANFER COEFFICIENT FOR OXYGEN (1/hr)
C
C      LENGTH      TOTAL REACH LENGTH (m)
C
C      PERM        WETTED PERIMETER (m)
C
C      PSI         RATIO OF VOC MASS TRANSFER COEFFICIENT TO KMASS (-)
C
C      QMIT        UNIFORM VENTILATING FLOWRATE (m3/s). ASSUMMED TO BE THE
C                  SAME FOR ALL CELLS.
C
C      RADIUS      PIPE RADIUS (m)
C
C      REMOVE      FRACTIONAL REMOVAL AT DISTANCE=LENGTH (END OF PIPE)
C
C      ROUGH       ROUGHNESS COEFFICIENT IN MANNING'S EQUATION (-)
C
C      SBEGIN      START TIME FOR SLUG DISCHARGE (sec)
C
C      SEND        ENDING TIME FOR SLUG DISCHARGE (sec)
C
C      SLOPE(I)    CHANNEL SLOPE VALUE I (m/m)
C
C      TEMP        WASTEWATER TEMPERATURE (celcius)
C
C      TIME        CUMULATIVE RUN TIME (sec)
C
C      TOTIN       TOTAL MASS INPUT AT INLET FOR A GIVEN COMBINATION
C                  OF PARAMETERS (mg)
C
C      TOX         TOTAL MASS REACHING END OF PIPE FOR A GIVEN
C                  COMBINATION OF PARAMETERS (mg)
C
C      TRANS       MEAN HYDRAULIC RESIDENCE TIME FOR THE ENTIRE PIPE
C                  REACH (sec)
C
C      VELOC       MEAN VELOCITY OF WASTEWATER (m/s)
C
C      VOLCEL      TOTAL VOLUME FOR ONE CELL (m3)
C
C      VOLGAS      GAS VOLUME FOR ONE CELL (m3)
C
C      VOLLIQ      LIQUID VOLUME FOR ONE CELL (m3)
C
C      VOLSYS      TOTAL VOLUME OF ENTIRE SYSTEM (m3)
C
C      VRATE(I)    VENTILATION RATE VALUE I (turnovers/day)
C                  VOLUME TURNOVER BASED UPON ENTIRE PIPE VOLUME
C
C      WIDTH       SURFACE WIDTH OF WASTEWATER (m)
C
C      ---------------------------------------------------------------
C
C
C
       REAL KMASS,LENGTH,CL(2,0:100),CG(2,0:100),DIAM(10),FDEP(10),
```

```
     1     SLOPE(10),VRATE(10),H(10),FRACT(10,10)
      INTEGER MDF(10,10,2),MDS(10,10,2),MDV(10,10,2),MDH(10,10,2),
     1MFS(10,10,2),MFV(10,10,2),MFH(10,10,2),MSV(10,10,2),MSH(10,10,2),
     1MVH(10,10,2)
      CHARACTER PARA(5)*30
C
      OPEN(UNIT=2, FILE='PARIN.DAT', STATUS='OLD')
      OPEN(UNIT=5, FILE='MATRIX.DAT', STATUS='NEW')
C
      PARA(1)='                 DIAMETER (M)'
      PARA(2)='DEPTH-TO-DIAMETER RATIO (-)'
      PARA(3)='  CHANNEL SLOPE (M/M)'
      PARA(4)='VENTILATION RATE (TuPD)'
      PARA(5)='HENRYS LAW CONSTANT (-)'
C
C
C     READ VALUES FROM PARIN.DAT
C
      READ(2,*)NDIAM, (DIAM(N),N=1,NDIAM)
      READ(2,*)NFDEP, (FDEP(N),N=1,NFDEP)
      READ(2,*)NSLOPE, (SLOPE(N),N=1,NSLOPE)
      READ(2,*)NVRATE, (VRATE(N),N=1,NVRATE)
      READ(2,*)NH, (H(N),N=1,NH)
      READ(2,*)ROUGH
      READ(2,*)PSI
      READ(2,*)COEFF
      READ(2,*)DX,NCELLS
      READ(2,*)TEMP
      READ(2,*)CONG,CONL
      READ(2,*)CAMB
      READ(2,*)KMODEL,APH
      READ(2,*)IBC
C
C
C     INPUT INLET VALUES FOR CONTINUOUS OR SLUG DISCHARGE
C
      IF(IBC .EQ. 1)THEN
       READ(2,*)CLIN,CGIN
      ELSE
       READ(2,*)SBEGIN,SEND,CLSLUG,CGIN
      END IF
C
      READ(2,*)FCRIT
C
C
C     INITIALIZATIONS
C
      DO 10 I=1,NCELLS,1
       CL(1,I)=0.0
       CL(2,I)=0.0
       CG(1,I)=0.0
       CG(2,1)=0.0
10    CONTINUE
      CL(1,0)=0.0
      CL(2,0)=0.0
      CG(1,0)=0.0
      CG(2,0)=0.0
      DO 11 I=1,10,1
```

```
        DO 12 J=1,10,1
         DO 13 K=1,2,1
          MDF(I,J,K)=0
          MDS(I,J,K)=0
          MDV(I,J,K)=0
          MDH(I,J,K)=0
          MFS(I,J,K)=0
          MFV(I,J,K)=0
          MFH(I,J,K)=0
          MSV(I,J,K)=0
          MSH(I,J,K)=0
          MVH(I,J,K)=0
13       CONTINUE
12      CONTINUE
11     CONTINUE
C
       LENGTH=DX*REAL(NCELLS)
C
C
C      LOOP - LOOP - LOOP ....... DIAMETER
C
       NUMCOM=0
       NUMMET=0
       DO 15 ID=1,NDIAM
        RADIUS=DIAM(ID)/2.0
        ATOT=3.14159*RADIUS**2
        VOLSYS=ATOT*LENGTH
        VOLCEL=VOLSYS/REAL(NCELLS)
C
C
C      LOOP - LOOP - LOOP ....... DEPTH/DIAMETER FACTOR
C
        DO 20 IFD=1,NFDEP
         DEPTH=DIAM(ID)*FDEP(IFD)
         ALPHA=ACOS((RADIUS-DEPTH)/RADIUS)
         ALIQ=ALPHA*RADIUS**2-(RADIUS-DEPTH)*SQRT(2.0*RADIUS*DEPTH
     1   - DEPTH**2)
         PERM=2.0*RADIUS*ALPHA
         WIDTH=2.0*SQRT(2.0*RADIUS*DEPTH-DEPTH**2)
         HYDEP=ALIQ/WIDTH
         HYRAD=ALIQ/PERM
         AGAS=ATOT-ALIQ
         VOLGAS=AGAS*DX
         VOLLIQ=ALIQ*DX
C
C
C      LOOP - LOOP - LOOP ....... SLOPE
C
         DO 25 IS=1,NSLOPE
          FLOLIQ=ALIQ/ROUGH*(HYRAD**(2.0/3.0))*SQRT(SLOPE(IS))
          VELOC=FLOLIQ/ALIQ
          TRANS=LENGTH/VELOC
          DT=TRANS/(3.0*REAL(NCELLS))
C
C
C       KMODEL = 1 :  O'CONNO-DOBBINS (ISOTROPIC TURBULENCE)
C
          IF(KMODEL .EQ. 1)THEN
```

```
            KMASS=0.175*SQRT(VELOC)/HYDEP**(1.5)
C
C      KMODEL = 2 :  O'CONNOR-DOBBINS (NON-ISOTROPIC TURBULENCE)
C
          ELSE IF (KMODEL .EQ. 2)THEN
           DOX=9.2E-5
           CS=SLOPE(IS)*1000.0
           CH1=HYDEP/0.3048
           KMASS=480.0*SQRT(DOX)*(CS**0.25)/(CH1**(-1.25))/24.0
C
C
C      KMODEL = 3 :  DOBBINS
C
          ELSE IF(KMODEL .EQ. 3)THEN
           FR=VELOC/SQRT(9.81*HYDEP)
           TERM1=(1.0+FR**2)/((0.9+FR)**1.5)
           TERM2=((VELOC*SLOPE(IS))**0.375)/HYDEP
           TERM3=(4.75*(VELOC*SLOPE(IS))**0.125)/SQRT(0.9+FR)
           TERM4=1.0/TANH(TERM3)
           KMASS=2.60*TERM1*TERM2*TERM4
C
C      KMODEL = 4 :  KRENKEL-ORLOB
C
          ELSE IF(KMODEL .EQ. 4)THEN
           KMASS=8.15*(VELOC*SLOPE(IS))**0.408*HYDEP**(-0.66)
C
C      KMODEL = 5 :  PARKHURST-POMEROY
C
          ELSE IF(KMODEL .EQ. 5)THEN
           GAMMA=1.0212**(TEMP-20.0)
           FR=VELOC/SQRT(9.81*HYDEP)
           KMASS=0.96*(1.0+0.17*FR**2)*GAMMA*(SLOPE(IS)*VELOC)**0.375/
     1           HYDEP
C
C
C      KMODEL = 6 :  TSIVOGLOU-NEAL
C
          ELSE IF(KMODEL .EQ. 6)THEN
           KMASS=0.177*VELOC*SLOPE(IS)*3600.0
          END IF
          KMASS=KMASS*APH*PSI/3600.0
C
          FLOGAS=COEFF*AGAS/ALIQ*FLOLIQ
C
C
C     LOOP - LOOP - LOOP ....... VENTILATION RATE
C
          IHTOT=1
          DO 30 IV=NVRATE,1,-1
           QMIT=VOLCEL/86400.0*VRATE(IV)
           IF(IHTOT .EQ. 0)THEN
            DO 31 II=1,IV,1
             DO 32 JJ=1,IH,1
              CALL COUNT(MDF,MDS,MDV,MDH,MFS,MFV,MFH,MSV,MSH,MVH,
     1                    ID,IFD,IS,II,JJ,2)
              NUMCOM=NUMCOM+1
32           CONTINUE
31          CONTINUE
```

```
           GO TO 25
          END IF
C
C
C     LOOP - LOOP - LOOP ........ HENRY'S LAW CONSTANT
          IHTOT=0
          DO 35 IH=NH,1,-1
           NUMCOM=NUMCOM+1
           DO 40 IIN=1,NCELLS,1
            CG(1,IIN)=CONG
            CG(2,IIN)=0.0
            CL(1,IIN)=CONL
            CL(2,IIN)=0.0
40         CONTINUE
           CALL COUNT(MDF,MDS,MDV,MDH,MFS,MFV,MFH,MSV,MSH,MVH,ID,
     1                IFD,IS,IV,IH,2)
C
           TIME=0.0
           NTIMER=0
           IF(IBC .EQ. 2)THEN
            TOTIN=0.0
            TOX=0.0
           END IF
C
9999       CONTINUE
           TIME=TIME+DT
           NTIMER=NTIMER+1
C
           IF(IBC .EQ. 1)THEN
            CL(2,0)=CLIN
            CG(2,0)=CGIN
           ELSE IF(IBC .NE. 1)THEN
            IF(TIME .GE. SBEGIN .AND. TIME .LE. SEND)THEN
             CL(2,0)=CLSLUG
            ELSE
             CL(2,0)=0.0
            END IF
            CG(2,0)=CGIN
            TOTIN=TOTIN+FLOLIQ*CL(2,0)*DT
           END IF
           IF(NTIMER .GT. 1)THEN
            DO 42 IT=1,NCELLS,1
             CG(1,IT)=CG(2,IT)
             CL(1,IT)=CL(2,IT)
42          CONTINUE
           END IF
C
C
C     LIQUID PHASE ---- SPATIAL STEPS .......
C
           DO 45 ILIQ=1,NCELLS,1
            T1=FLOLIQ*CL(2,ILIQ-1)
            T2=KMASS/H(IH)*CG(1,ILIQ)*VOLLIQ
            T3=CL(1,ILIQ)*VOLLIQ/DT
            ANUM=T1+T2+T3
            CL(2,ILIQ)=ANUM/(VOLLIQ/DT+FLOLIQ+KMASS*VOLLIQ)
45         CONTINUE
           IF(IBC .EQ. 2)THEN
```

```
            TOX=TOX+FLOLIQ*CL(2,NCELLS)*DT
           END IF
C
C
C     GASEOUS PHASE ---- SPATIAL STEPS
C
           DO 50 IG=1,NCELLS,1
            T1=(VOLGAS/DT-KMASS*VOLLIQ/H(IH))*CG(1,IG)
            T2=FLOGAS*CG(2,IG-1)
            T4=KMASS*CL(2,IG)*VOLLIQ
            T5=QMIT*CAMB
            ANUM=T1+T2+T4+T5
            T1=VOLGAS/DT
            T2=FLOGAS
            DENOM=T1+T2+QMIT
            CG(2,IG)=ANUM/DENOM
50         CONTINUE
           IF(TIME .GE. 3.0*TRANS)THEN
            IF(IBC .EQ. 1)THEN
             IF(CL(2,NCELLS) .GT. 0.0)THEN
              CRIT=ABS((CL(2,NCELLS)-CL(1,NCELLS))/CL(2,NCELLS))*
     1             100.0*3600.0/DT
              IF(CRIT .LE. 0.1)THEN
               REMOVE=1.0-CL(2,NCELLS)/CLIN
               GO TO 3999
              ELSE
               GO TO 9999
              END IF
             END IF
            ELSE
             IF(CL(2,NCELLS) .LT. 0.01)THEN
              REMOVE=1.0-TOX/TOTIN
              GO TO 3999
             ELSE
              GO TO 9999
             END IF
            END IF
           ELSE
            GO TO 9999
           END IF
3999       IF(REMOVE .GE. FCRIT)THEN
            CALL COUNT(MDF,MDS,MDV,MDH,MFS,MFV,MFH,MSV,MSH,MVH,ID,
     1                IFD,IS,IV,IH,1)
            NUMMET=NUMMET+1
            IHTOT=IHTOT+1
C            WRITE(5,1000)DIAM(ID),FDEP(IFD),SLOPE(IS),VRATE(IV),H(IH),
C     1                    VELOC,TRANS/3600.0,KMASS*3600.0,REMOVE
           ELSE
            IF(IH .GT. 1)THEN
             DO 80 III=IH-1,1,-1
              CALL COUNT(MDF,MDS,MDV,MDH,MFS,MFV,MFH,MSV,MSH,MVH,
     1                ID,IFD,IS,IV,III,2)
              NUMCOM=NUMCOM+1
80           CONTINUE
             GO TO 30
            END IF
           END IF
35        CONTINUE
```

```
30          CONTINUE
25         CONTINUE
20        CONTINUE
15       CONTINUE
         WRITE(5,1200)
         CALL DIVIDE(FRACT,MDF,NDIAM,NFDEP)
         CALL OUTPUT(FRACT,MDF,NDIAM,NFDEP,PARA(1),PARA(2),DIAM,FDEP)
         CALL DIVIDE(FRACT,MDS,NDIAM,NSLOPE)
         CALL OUTPUT(FRACT,MDS,NDIAM,NSLOPE,PARA(1),PARA(3),DIAM,SLOPE)
         CALL DIVIDE(FRACT,MDV,NDIAM,NVRATE)
         CALL OUTPUT(FRACT,MDV,NDIAM,NVRATE,PARA(1),PARA(4),DIAM,VRATE)
         CALL DIVIDE(FRACT,MDH,NDIAM,NH)
         CALL OUTPUT(FRACT,MDH,NDIAM,NH,PARA(1),PARA(5),DIAM,H)
         CALL DIVIDE(FRACT,MFS,NFDEP,NSLOPE)
         CALL OUTPUT(FRACT,MFS,NFDEP,NSLOPE,PARA(2),PARA(3),FDEP,SLOPE)
         CALL DIVIDE(FRACT,MFV,NFDEP,NVRATE)
         CALL OUTPUT(FRACT,MFV,NFDEP,NVRATE,PARA(2),PARA(4),FDEP,VRATE)
         CALL DIVIDE(FRACT,MFH,NFDEP,NH)
         CALL OUTPUT(FRACT,MFH,NFDEP,NH,PARA(2),PARA(5),FDEP,H)
         CALL DIVIDE(FRACT,MSV,NSLOPE,NVRATE)
         CALL OUTPUT(FRACT,MSV,NSLOPE,NVRATE,PARA(3),PARA(4),SLOPE,VRATE)
         CALL DIVIDE(FRACT,MSH,NSLOPE,NH)
         CALL OUTPUT(FRACT,MSH,NSLOPE,NH,PARA(3),PARA(5),SLOPE,H)
         CALL DIVIDE(FRACT,MVH,NVRATE,NH)
         CALL OUTPUT(FRACT,MVH,NVRATE,NH,PARA(4),PARA(5),VRATE,H)
C
         WRITE(5,1100)NUMCOM,NUMMET
C
C1000     FORMAT(1X,2(F4.2,3X),3X,F6.4,3(3X,F5.2),3X,F7.2,3X,F6.3,6X,F6.3)
1100     FORMAT(6(///),1X,'TOTAL COMBINATIONS: ',I6,/,1X,
        1'TOTAL EXCEEDING 50% REMOVAL: ',I6)
1200     FORMAT('1')
         END
C
C
         SUBROUTINE COUNT(MDF,MDS,MDV,MDH,MFS,MFV,MFH,MSV,MSH,MVH,ID,
        1IFD,IS,IV,IH,J)
C
         INTEGER MDF(10,10,2),MDS(10,10,2),MDV(10,10,2),MDH(10,10,2),
        1MFS(10,10,2),MFV(10,10,2),MFH(10,10,2),MSV(10,10,2),MSH(10,10,2),
        1MVH(10,10,2)
C
         MDF(ID,IFD,J)=MDF(ID,IFD,J)+1
         MDS(ID,IS,J)=MDS(ID,IS,J)+1
         MDV(ID,IV,J)=MDV(ID,IV,J)+1
         MDH(ID,IH,J)=MDH(ID,IH,J)+1
         MFS(IFD,IS,J)=MFS(IFD,IS,J)+1
         MFV(IFD,IV,J)=MFV(IFD,IV,J)+1
         MFH(IFD,IH,J)=MFH(IFD,IH,J)+1
         MSV(IS,IV,J)=MSV(IS,IV,J)+1
         MSH(IS,IH,J)=MSH(IS,IH,J)+1
         MVH(IV,IH,J)=MVH(IV,IH,J)+1
C
         RETURN
         END
C
C
         SUBROUTINE DIVIDE(FRACT,MTOTAL,NSUB1,NSUB2)
```

```
      REAL FRACT(10,10)
      INTEGER MTOTAL(10,10,2)
      DO 10 I=1,NSUB1
       DO 20 J=1,NSUB2
        FRACT(I,J)=REAL(MTOTAL(I,J,1))/REAL(MTOTAL(I,J,2))
20     CONTINUE
10    CONTINUE
      RETURN
      END
C
C
      SUBROUTINE OUTPUT(FRACT,MTOTAL,NSUB1,NSUB2,NAME1,NAME2,PAR1,PAR2)
      REAL FRACT(10,10),PAR1(10),PAR2(10)
      INTEGER MTOTAL(10,10,2)
      CHARACTER NAME1*30,NAME2*30
      WRITE(5,1000)
      WRITE(5,1100)NAME1,NAME2,(PAR2(I),I=1,NSUB2)
      WRITE(5,1150)
      DO 10 I=1,NSUB1
       WRITE(5,1200)PAR1(I),(FRACT(I,J),J=1,NSUB2)
10    CONTINUE
1000  FORMAT(10(/))
1100  FORMAT(5X,A30,2X,'VS',2X,A30,4(/),7X,8(2X,F5.2))
1150  FORMAT(4X,65('-'),/)
1200  FORMAT(1X,F5.3,1X,8(2X,F5.2),/)
      RETURN
      END
```

SUDS (Sewer Uniform Reach with Drop Solution)

```
C     SUDS (Sewer Uniform reach with Drop Solution)
C
C     LIQUID AND GAS MASS TRANSPORT MODEL FOR SEWERS
C
C     DEVELOPED BY RICHARD L. CORSI
C     UNIVERSITY OF CALIFORNIA, DAVIS          9-2-1989
C
      REAL LENGTH, KBIO, CG(2,0:250), CL(2,0:250), FLOLIQ(2),
     1VOLGAS(2), TOMASS(250),
     1A(8), B(8), PSI(10), KMASS, KMOIST, KWALL, CGAS(2)
C
C-----------------------------------------------------------------
C     REAL ARRAYS
C
C     A(I) - B(I): REGRESSION PARAMETERS TO CALCULATE HENRY'S LAW
C                  CONSTANT AS A FUNCTION OF TEMPERATURE FOR VOC I
C     CG(I,J): GAS CONCENTRATION  (MILLIGRAMS/CUBIC METER)
C     CL(I,J): LIQUID CONCENTRATION  (MILLIGRAMS/CUBIC METER)
C        I = 1 INDICATES PREVIOUS TIME STEP (N)
C        I = 2 INDICATES CURRENT TIME STEP (N+1)
C        J = CELL NUMBER
C     FLOLIQ(I): LIQUID FLOW (CUBIC METERS/SECOND)
C        I = 1 INDICATES INTO CELL
C        I = 2 INDICATES OUT OF CELL
C     PSI(I): RATIO OF DIFFUSIVITY OF VOC I TO OXYGEN
C     TOMASS(I): TOTAL MASS THAT HAS REACHED CELL I (MILLIGRAMS)
C     VOLGAS(I): VOLUME OF GAS/CELL
C        I = 1 INDICATES PREVIOUS TIME STEP
C        I = 2 INDICATES CURRENT TIME STEP
C---------------------------------------------------------------
C
C
C     REAL VARIABLES
C
C     AGAS: X-SECTIONAL AREA OF GAS (SQ. METERS)
C     ALIQ: X-SECTIONAL AREA OF LIQUID (SQ. METERS)
C     ALPHA: VALUE USED IN MANNING'S CALCULATIONS OF FLOW
C     APH: RATIO OF CONTAMINATED TO CLEAN WATER MASS TRANSFER
C          COEFFICIENTS
C     ATOT: TOTAL X-SECTIONAL AREA OF PIPE (SQ. METERS)
C     CAMB: AMBIENT CONCENTRATION (mg/m3)
C     CLOCK: TIME CONVERTED FROM SECONDS TO MINUTES
C     CLSLUG: SLUG CONCENTRATION (mg/m3)
C     CONG: INITIAL GASEOUS CONCENTRATION (mg/m3)
C     CONL: INITIAL AQUEOUS CONCENTRATION (mg/m3)
C     DCG: GAS-PHASE DISPERSION COEFFICIENT (m2/s)
C     DEPTH: WASTEWATER DEPTH FROM SURFACE TO INVERT (METERS)
C     DIST1,DIST2,DIST3: DISTANCES TO MIDPOINTS OF THE 3 CELLS
C                        SPECIFIED FOR OUTPUT (METERS)
C     DIAM: SEWER PIPE DIAMETER (METERS)
C     DT: TIME STEP INCREMENT (SECONDS)
C     DX: SPATIAL STEP INCREMENT (CELL SIZE) IN (METERS)
C     EXFACT: ESCAPE COEFFICIENT USED IN TSIVOGLOU MASS TRANSFER
C             MODEL (1/M)
C     FR: FROUDE NUMBER (USED IN PARKHURST AND POMEROY MASS
C         TRANSFER MODEL
C     GAMMA: TEMPERATURE CORRECTION FACTOR USED IN PARKHURST
```

```
C             AND POMEROY MASS TRANSFER MODEL
C       H: HENRY'S LAW CONSTANT (DIMENSIONLESS)
C       HYDEP: MEAN HYDRAULIC DEPTH (METERS)
C       HYRAD: HYDRAULIC RADIUS (METERS)
C       KBIO: FIRST-ORDER BIO-OXIDATION RATE (1/HR)
C       KMASS: MASS TRANSFER RATE COEFFICIENT (1/HR)
C       KMOIST: SORPTION LOSS COEFFICIENT FOR REMOVAL AT MOIST WALLS
C               (M/HR)
C       KWALL: BIODECAY CONSTANT FOR ANAEROBIC DEGRADATION AT WETTED
C              WALL (M/HR)
C       LENGTH: TOTAL LENGTH OF SYSTEM (METERS)
C       PERM:  WETTED PERIMETER (METERS)
C       QEXIT: FLOW EXITING FROM CELL BY VENTILATION (m3/s)
C       QINTO: FLOW ENTERING CELL BY VENTILATION (m3/s)
C       QMIT: INFLOW AND OUTFLOW FOR CELLS UNDER UNIFORM
C             VENTILATION (m3/s)
C       RADIUS: SEWER PIPE RADIUS (METERS)
C       REM1,REM2,REM3: TOTAL MASS REMOVAL BY OUTPUT CELLS 1-3
C       ROUGH: ROUGHNESS COEFFICIENT IN MANNING'S EQUATION
C       SBEGIN: START TIME FOR SLUG DISCHARGE (SECONDS)
C       SEND: END TIME FOR SLUG DISCHARGE (SECONDS)
C       SLOPE: SEWER CHANNEL SLOPE (METERS PER METER)
C       TEMP: TEMPERATURE OF WASTEWATER (INPUT IN C AND
C             CONVERTED TO K)
C       TIME: CUMULATIVE RUN TIME FOR SIMULATION (SECONDS)
C       TOEMIT: TOTAL EMISSIONS FROM SYSTEM (mg CONVERTED TO g)
C       TOTIN: TOTAL MASS DISCHARGED TO SYSTEM (mg)
C       TRPORT: AVERAGE TOTAL RESIDENCE TIME IN SYSTEM (HOURS)
C       TTIME: TOTAL TIME OF SIMULATION (SECONDS)
C       VELOC: AVERAGE VELOCITY OF WASTEWATER (m/s)
C       VOLCEL: TOTAL VOLUME OF ONE CELL (m3)
C       VOLLIQ: VOLUME OF LIQUID/CELL (m3)
C       VOLOLD: VOLLIQ FROM PREVIOUS TIME STEP (m3)
C       VOLSYS: VOLUME OF ENTIRE SYSTEM (m3)
C       WIDTH: WIDTH OF LIQUID SURFACE IN CHANNEL (METERS)
C       SAREA: INTERFACIAL SURFACE AREA ASSOCIATED WITH A CELL (M2)
C       XLONG: CUMULATIVE DISTANCE TO EACH CELL (METERS)
C
C       ------------------------------------------------------------
C
C
C       INTEGER VARIABLES
C
C       IBC: FLAG FOR INLET BOUNDARY CONDITION VARIATION W/ TIME
C         1=CONSTANT WITH TIME
C       INCT: TIME INCREMENT COUNTER
C       INDIL: FLAG FOR INFINITE DILUTION ASSUMPTION (1=ID)
C       IRUN: FLAG FOR ANOTHER RUN (1=COMPLETE ANOTHER RUN)
C       IVENT: FLAG FOR VENTILATION TYPE
C         1=UNIFORM VENTILATION
C         2=CELL-SPECIFIC VENTILATION
C       KMODEL: FLAG INDICATING CHOICE OF PARTITIONING MODEL
C       LOXY: FLAG FOR OXYGEN CONSUMPTION (1=RAPID O2 LOSS IN H20)
C       NCELLS: NUMBER OF CELLS
C       NOUT1,NOUT2,NOUT3:  NUMBERS OF 3 CELLS TO OUTPUT RESULTS AT
C       NTIME: NUMBER OF TIME STEPS
C       NTIMER: TIME COUNTER THAT ACCUMULATES UP TO EACH NTOUT, AT
C               WHICH TIME OUTPUT OCCURS AND NTIMER SET EQUAL 0
```

```
C     NTOUT:  NUMBER OF TIME STEPS BETWEEN EACH OUTPUT SUMMARY
C     NVOC: CODE NUMBER OF VOC CHOSEN FOR ANALYSIS
C
C     ---------------------------------------------------------------
C
C
      CHARACTER NAME(10)*25,DATE*25,NOTE*50
C
C     OPEN INPUT AND OUTPUT FILES
C        INGAS2.DAT STORES SYSTEM PARAMETER INPUTS
C        OUTGAS.DAT IS A SUMMARY OF MODEL RESULTS AT THREE CELLS
C        DROP.DAT IS A SUMMARY OF LOSSES AT SPECIFIED DROP
C
      OPEN(UNIT=2, FILE='OUTGAS.DAT', STATUS='NEW')
      OPEN(UNIT=6, FILE='DRGAS.DAT',STATUS='OLD')
      OPEN(UNIT=7, FILE='DROP.DAT',STATUS='NEW')
C
      NAME(1)='CARBON TETRACHLORIDE'
      NAME(2)='CHLOROFORM'
      NAME(3)='1,1-DICHLOROETHYLENE'
      NAME(4)='METHYLENE CHLORIDE'
      NAME(5)='PERCHLOROETHYLENE'
      NAME(6)='TRICHLOROETHYLENE'
      NAME(7)='1,1,1-TRICHLOROETHANE'
      NAME(8)='VINYL CHLORIDE'
      NAME(9)='GOOD OLD OXYGEN'
      NAME(10)='OTHER; SPECIFY H AND PSI'
      A(1)=11.29
      A(2)=9.843
      A(3)=8.845
      A(4)=6.653
      A(5)=12.45
      A(6)=11.37
      A(7)=9.777
      A(8)=7.385
      B(1)=4411.0
      B(2)=4612.0
      B(3)=3729.0
      B(4)=3817.0
      B(5)=4918.0
      B(6)=4780.00
      B(7)=4133.0
      B(8)=3286.0
      PSI(1)=0.63
      PSI(2)=0.57
      PSI(3)=0.62
      PSI(4)=0.61
      PSI(5)=0.52
      PSI(6)=0.57
      PSI(7)=0.49
      PSI(8)=0.72
      PSI(9)=1.0
C
C     INITIALIZE FLAGS AND CONCENTRATIONS
C
      DO 10 I=1,250,1
         CL(1,I)=0.0
         CL(2,I)=0.0
```

```
        CG(1,I)=0.0
        CG(2,I)=0.0
        TOMASS(I)=0.0
10    CONTINUE
      CL(1,0)=0.0
      CG(1,0)=0.0
      CL(2,0)=0.0
      CG(2,0)=0.0
C
C     SPECIFY THE DATE OF THE MODELING ANALYSIS
C
      PRINT *,'ENTER TODAYS DATE (25 CHARACTERS MAX.)'
      READ(*,900)DATE
C
C     SPECIFY A MODELING NOTE (IF DESIRED)
C
      PRINT *,'ENTER A MODELING RUN NOTE (50 CHARACTERS MAX.)'
      READ(*,950)NOTE
C
C     SPECIFY THE VOC TO BE ANALYZED
C
      WRITE(*,1000)
      DO 15 I=1,10,1
        WRITE(*,1050)I,NAME(I)
15    CONTINUE
      READ *,NVOC
      IF(NVOC .EQ. 9)THEN
        PRINT *,'ENTER A 1 IF OXYGEN CONSUMED RAPIDLY IN WW'
        READ *,LOXY
      END IF
C
C     SET PARAMETERS FOR DROP ANALYSIS - IF DROP AT END OF REACH
C
      PRINT *,' DROP AT END OF REACH (1=YES)'
      READ *,IDROP
      IF(IDROP .EQ. 1)THEN
       PRINT *,' ENTER THE GAS VOLUME OF DROP CHAMBER (M3)'
       READ *,VGASES
       PRINT *,' ENTER THE FALL HEIGHT (M)'
       READ *,FH
       PRINT *,' ENTER THE TAILWATER DEPTH (M)'
       READ *,TWD
       IF(TWD .GT. 0.67*FH)THEN
        TWD=0.67*FH
       END IF
       CGAS(1)=0.0
       DEMIT=0.0
      END IF
C
      READ(6,*)DX,NCELLS
      READ(6,*)DT,NTIME
      READ(6,*)NOUT1,NOUT2,NOUT3
      READ(6,*)NTOUT
      LENGTH=DX*REAL(NCELLS)
      TTIME=DT*REAL(NTIME)
C
      READ(6,*)TEMP
      TEMP=TEMP+273.15
```

```
      IF(NVOC .LE. 8)THEN
        H=EXP(A(NVOC)-B(NVOC)/TEMP)/(TEMP*8.21E-5)
      ELSE IF(NVOC .EQ. 9)THEN
        PRINT *,' '
        PRINT *,' ENTER H(DIMENSIONLESS) FOR OXYGEN'
        PRINT *,' H=32.0 AT 25 C'
        READ *,H
      ELSE
        PRINT *,' '
        PRINT *,'OTHER COMPOUND'
        PRINT *,' ENTER H (DIMENSIONLESS)'
        READ *,H
        PRINT *,'ENTER RATIO OF COMPOUND TO OXYGEN DIFFUSIVITY'
        PRINT *,' PSI'
        READ *,PSI(10)
      END IF
C
      READ(6,*)KMODEL,APH
      IF(KMODEL .EQ. 1)THEN
        PRINT *,' '
        PRINT *,' ENTER THE ESCAPE COEFFICIENT (1/M)'
        READ *,EXFACT
      END IF
C
      READ(6,*)KBIO,KWALL,KMOIST,FABS
      READ(6,*)DCG
      KBIO=KBIO/3600.0
      KWALL=KWALL/3600.0
      KMOIST=KMOIST/3600.0
C
      READ(6,*)DIAM,ROUGH,SLOPE
      READ(6,*)DEPTH
      RADIUS=DIAM/2.0
      ATOT=3.14159*RADIUS**2
C
      READ(6,*)CONG,CONL
C
      DO 50 I=1,NCELLS,1
        CG(1,I)=CONG
        CL(1,I)=CONL
50    CONTINUE
C
C     READ IN FLAGS INDICATING TYPE OF TIME VARIATION FOR BC
C
      READ(6,*)IBC
C
C     SET SLUG DISCHARGE PARAMETERS IF IBC NOT 1
C
      IF(IBC .NE. 1)THEN
       READ(6,*)SBEGIN,SEND
       READ(6,*)CLSLUG
       READ(6,*)CG(2,0)
      ELSE
       READ(6,*)CL(2,0),CG(2,0)
       CL(2,0)=CL(2,0)*FABS
      END IF
C
C     INDICATE WHETHER INFINITE DILUTION (GAS) ASSUMED
```

```
C
      READ(6,*)INDIL
C
      READ(6,*)VELGAS
      VOLSYS=ATOT*LENGTH
      VOLCEL=VOLSYS/REAL(NCELLS)
C
      READ(6,*)CAMB
C
C     OUTPUT CONSTANT VALUES
C
      WRITE(2,1100)NAME(NVOC),DATE,NOTE,DX,DT,LENGTH,TTIME
      WRITE(7,1100)NAME(NVOC),DATE,NOTE,DX,DT,LENGTH,TTIME
      WRITE(2,1200)DIAM,ROUGH,SLOPE
      WRITE(7,1200)DIAM,ROUGH,SLOPE
      WRITE(2,1250)EXFACT,DCG,TEMP
      WRITE(2,1255)H,PSI(NVOC)
      WRITE(7,1255)H,PSI(NVOC)
      WRITE(2,1257)KBIO*3600.0,KWALL*3600.0,KMOIST*3600.0,FABS
C
C     OUTPUT TABLE HEADINGS
C
      DIST1=REAL(NOUT1)*DX-DX/2.0
      DIST2=REAL(NOUT2)*DX-DX/2.0
      DIST3=REAL(NOUT3)*DX-DX/2.0
      WRITE(2,1275)NOUT1,NOUT2,NOUT3,NOUT1,NOUT2,NOUT3,DIST1,DIST2,
     1DIST3,DIST1,DIST2,DIST3
C
C     INITIALIZE TOTIN (TOTAL MASS INPUT AT INLET OF THE SYSTEM)
C
      TOTIN=0.0
      TOEMIT=0.0
C
C     BEGIN TIME INCREMENTS
C
C     INCT: TIME INCREMENT COUNTER (STOP WHEN INCT = NTIME)
C
      TIME=0.0
      INCT=0
      NTIMER=0
9999  CONTINUE
      TIME=TIME+DT
      INCT=INCT+1
      NTIMER=NTIMER+1
C
C     INPUT THE INLET CONCENTRATION BOUNDARY CONDITIONS
C
      IF(IBC .NE. 1)THEN
         IF(TIME .GE. SBEGIN .AND. TIME .LE. SEND)THEN
           CL(2,0)=CLSLUG*FABS
         ELSE
           CL(2,0)=0.0
         END IF
      END IF
C
C     COMPUTE FLOWS, VOLUMES, AREAS (METERS AND SECONDS)
C
      ALPHA=ACOS((RADIUS-DEPTH)/RADIUS)
```

```
      ALIQ=ALPHA*RADIUS**2-(RADIUS-DEPTH)*SQRT(2.0*RADIUS*DEPTH-
     1DEPTH**2)
      PERM=2.0*RADIUS*ALPHA
      AWALL=PERM*DX
      AMOIST=(2.0*3.14159*RADIUS-PERM)*DX
      WIDTH=2.0*SQRT(2.0*RADIUS*DEPTH-DEPTH**2)
      SAREA=WIDTH*DX
      HYDEP=ALIQ/WIDTH
      HYRAD=ALIQ/PERM
      FLOLIQ(1)=ALIQ/ROUGH*(HYRAD**(2.0/3.0))*SQRT(SLOPE)
      VELOC=FLOLIQ(1)/ALIQ
      VOLLIQ=ALIQ*DX
      IF(INCT .EQ. 1)THEN
        VOLOLD=VOLLIQ
      END IF
      AGAS=ATOT-ALIQ
      FLOGAS=VELGAS*AGAS
      VOLGAS(2)=AGAS*DX
      IF(INCT .EQ. 1)THEN
        VOLGAS(1)=VOLGAS(2)
      END IF
C
C     COMPUTE LIQUID-GAS MASS TRANSFER COEFFICIENTS
C       KMODEL = 1: TSIVOGLOU
C       KMODEL = 2: O'CONNOR AND DOBBINS
C       KMODEL = 3: PARKHURST AND POMEROY
C       KMODEL = 4: DOBBINS
C       KMODEL = 5: LAU
C       KMODEL = 6: USER-SPECIFIED
C
      GAMMA=1.0212**((TEMP-273.15)-20.0)
      IF(KMODEL .EQ. 1)THEN
        KMASS=APH*PSI(NVOC)*EXFACT*SLOPE*VELOC*GAMMA
      ELSE IF(KMODEL .EQ. 2)THEN
        KMASS=APH*PSI(NVOC)*0.175*SQRT(VELOC)/(HYDEP**1.5)/3600.0
     1        *GAMMA
      ELSE IF(KMODEL .EQ. 3)THEN
        FR=VELOC/SQRT(9.81*HYDEP)
        KMASS=0.96*(1.0+0.17*FR**2)*GAMMA*(SLOPE*VELOC)**0.375/
     1         HYDEP/3600.0*PSI(NVOC)*APH
      ELSE IF(KMODEL .EQ. 4)THEN
        E=30.0*SLOPE*VELOC
        FR=VELOC/SQRT(9.81*HYDEP)
        ATERM=9.68+0.054*((TEMP-273.15)-20.0)
        BTERM=0.976+0.0137*(30.0-(273.15-TEMP))**1.5
        C4=0.9+FR
        CA=1.0+FR**2
        ANUM=0.12*CA*ATERM*E**0.375/TANH((BTERM*E**0.125)/SQRT(C4))
        DENOM=(C4**1.5)*HYDEP
        KMASS=ANUM/DENOM/3600.0
      ELSE IF(KMODEL .EQ. 5)THEN
        USTAR=SQRT(9.81*HYRAD*SLOPE)
        KMASS=(0.0126*(USTAR**3)/VELOC**2)*GAMMA
      ELSE
        IF(TIME .EQ. DT)THEN
         PRINT *,' ENTER KMASS (1/HR)'
         READ *,KMASS
         KMASS=KMASS/3600.0
```

```
        END IF
      END IF
      IF(KMODEL .LE. 4)THEN
        KMASS=KMASS*HYDEP
      END IF
C
      TOTIN=TOTIN+CL(2,0)*FLOLIQ(1)*DT
C
C     SKIP LIQUID PHASE IF ANALYSIS IS FOR RAPIDLY CONSUMED OXYGEN
C
      IF(NVOC .EQ. 9 .AND. LOXY .EQ. 1)THEN
        DO 67 I=1,NCELLS,1
          CL(1,I)=0.0
          CL(2,I)=0.0
67      CONTINUE
        GO TO 777
      END IF
C
C     SPATIAL STEPS IN THE LIQUID PHASE
C
      DO 70 I=1,NCELLS,1
        FLOLIQ(2)=FLOLIQ(1)
        TERM1=FLOLIQ(1)*CL(2,I-1)
        TERM2=KMASS/H*CG(1,I)*SAREA
        TERM3=CL(1,I)*VOLOLD/DT
        ANUM=TERM1+TERM2+TERM3
        TERM1=VOLLIQ/DT
        TERM2=FLOLIQ(2)
        TERM3=KMASS*SAREA+KBIO*VOLLIQ+KWALL*AWALL
        DENOM=TERM1+TERM2+TERM3
        CL(2,I)=ANUM/DENOM
        TOMASS(I)=TOMASS(I)+(FLOLIQ(1)+FLOLIQ(2))/2.0*DT*
     1  (CL(2,I)+CL(1,I))/2.0
        CL(1,I)=CL(2,I)
        FLOLIQ(1)=FLOLIQ(2)
70    CONTINUE
C
777   CONTINUE
C
C     PASS UP THE SPATIAL STEPS IN GAS IF DILUTION INFINITE
C
      IF(INDIL .EQ. 1)THEN
        DO 75 I=1,NCELLS,1
          CG(2,I)=0.0
          CG(1,I)=0.0
75      CONTINUE
        GO TO 888
      END IF
C
C     SPATIAL STEPS IN THE GAS PHASE
C
      DO 80 I=1,NCELLS,1
         TERM1=(VOLGAS(1)/DT-KMASS*SAREA/H)*CG(1,I)
         TERM2=(FLOGAS+DCG*AGAS/DX)*CG(2,I-1)
         TERM3=DCG*AGAS/DX*CG(1,I+1)
         TERM4=KMASS*CL(2,I)*SAREA
         TERM5=QINTO*CAMB
         ANUM=TERM1+TERM2+TERM3+TERM4+TERM5
```

```
          TERM1=VOLGAS(2)/DT
          TERM2=FLOGAS
          TERM3=2.0*DCG*AGAS/DX
          TERM4=KMOIST*AMOIST
          DENOM=TERM1+TERM2+TERM3+TERM4+QEXIT
         CG(2,I)=ANUM/DENOM
         CG(1,I)=CG(2,I)
80     CONTINUE
888    CONTINUE
       VOLGAS(1)=VOLGAS(2)
       IF(INCT .LE. NTIME)THEN
         VOLOLD=VOLLIQ
         IF(NTIMER .EQ. NTOUT)THEN
           NTIMER=0
           CLOCK=TIME/60.0
           WRITE(2,1300)CLOCK,CL(2,NOUT1),CL(2,NOUT2),CL(2,NOUT3),
     1     CG(2,NOUT1),CG(2,NOUT2),CG(2,NOUT3)
         END IF
C
C      ALGORITHM FOR LOSSES OVER DROPS
C
         IF(IDROP .EQ. 1)THEN
          QN=FLOLIQ(2)/WIDTH*3600.0
          IF((FH .LE. 1.2) .AND. (QN .LE. 235.0))THEN
           CA=0.0785
           ALPS=1.31
           BETA=0.428
          ELSE IF((FH .GT. 1.2) .AND. (QN .LE. 235.0))THEN
           CA=0.0861
           ALPS=0.816
           BETA=0.428
          ELSE IF((FH .LE. 1.2) .AND. (QN .GT. 235.0))THEN
           CA=5.39
           ALPS=1.31
           BETA=-0.363
          ELSE
           CA=5.92
           ALPS=0.816
           BETA=-0.363
          END IF
          RO2=EXP(CA*(FH**ALPS)*(QN**BETA)*(TWD**0.31))
          RO2=RO2**(1.0+0.0168*((TEMP-273.15)-20))
          RI=RO2**PSI(NVOC)
          CB=CL(2,NCELLS)/RI-(CGAS(1)/H)*(1.0/RI-1.0)
          ANUM=FLOLIQ(2)*(CL(2,NCELLS)-CB)+CG(2,NCELLS)*FLOGAS
     1         +CGAS(1)*VGASES/DT
          DENOM=VGASES/DT+FLOGAS
          CGAS(2)=ANUM/DENOM
          cdiff=cl(2,ncells)-cb
          partv=cdiff*floliq(2)*dt
          DEMIT=DEMIT+(CGAS(1)+CGAS(2))/2.0*FLOGAS*DT
          CGAS(1)=CGAS(2)
          parte=cgas(2)*flogas*dt
          IF(NTIMER .EQ. 0)THEN
           WRITE(7,1950)TIME/60.0,CL(2,NCELLS),CB,CG(2,NCELLS),
     1                  CGAS(2),cdiff,partv,parte
          END IF
         END IF
```

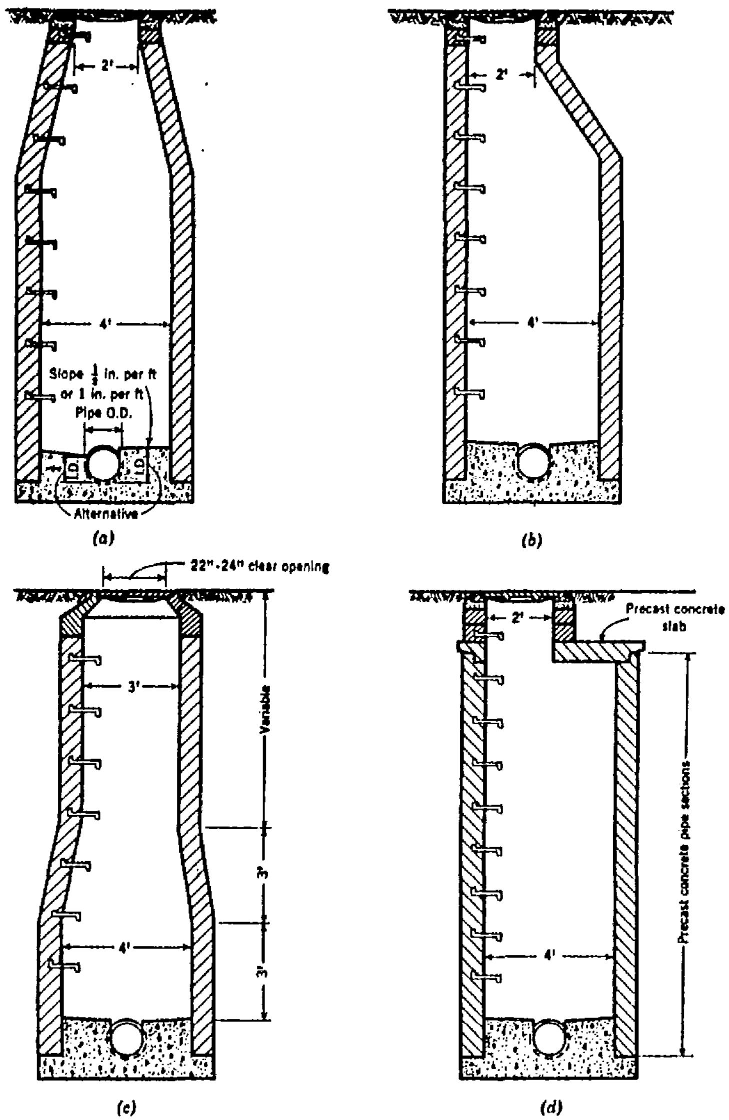
```
        GO TO 9999
       END IF
C
       IF(IDROP .EQ. 1)THEN
        FREM=DEMIT/TOTIN
        WRITE(7,2000)RI,QN,TWD,FH
        WRITE(7,2050)DEMIT/1000.0,TOTIN/1000.0
       END IF
C
C      CALCULATE AND OUTPUT THE REMOVAL AT EACH OF THE THREE TARGET
C      CELLS
C
       IF(TOTIN .GT. 0.0)THEN
         REM1=1.0-TOMASS(NOUT1)/TOTIN
         REM2=1.0-TOMASS(NOUT2)/TOTIN
         REM3=1.0-TOMASS(NOUT3)/TOTIN
         WRITE(2,1400)REM1,REM2,REM3
       END IF
C
       WRITE(7,2100)REM3,FREM,(FREM-REM3)/FREM
       WRITE(2,1450)FLOLIQ(2)
       WRITE(7,1450)FLOLIQ(2)
C
C      CALCULATE AND OUTPUT THE TRANSPORT TIME IN THE SYSTEM
C
       TRPORT=(LENGTH/VELOC)/3600.0
       WRITE(2,1475)VELOC,TRPORT,VELGAS
       WRITE(7,1475)VELOC,TRPORT,VELGAS
C
C
       WRITE(2,1800)KMASS*3600.0
       WRITE(7,1800)KMASS*3600.0
C
C      FORMAT BLOCK
C
900    FORMAT(A25)
950    FORMAT(A50)
1000   FORMAT(1X,'ENTER THE # OF THE VOC TO ANALYZE: ',//)
1050   FORMAT(5X,I2,5X,A25)
1100   FORMAT(' COMPOUND: ',A25,5X,'DATE: ',A25,//,A50,//,' DX(m): ',
      1E10.3,/,' DT (s): ',E10.3,/,' TOTAL REACH LENGTH (m): ',E10.3,
      1/,' TOTAL ANALYSIS TIME (sec): ',E10.3,/)
1200   FORMAT(' DIAMETER (m):',E10.3,/,' ROUGHNESS COEFFICIENT: ',
      1E10.3,/,' SLOPE (m/m): ',E10.3,/)
1250   FORMAT(' EXFACT (1/m): ',F5.3,/,
      1' DCG (m2/sec): ',E10.3,/,' TEMP (K): ',F6.2)
1255   FORMAT(1X,'H(DIM): ',F6.3,10X,'PSI: ',F5.3,//)
1257   FORMAT(//,1X,'DECAY CONSTANTS:',//,2X,'AEROBIC (1/HR): ',
      1E10.3,/,2X,'ANAEROBIC (M/HR): ',E10.3,/,2X,
      1'MOIST WALL (M/HR): ',E10.3,/,2X,'SOLIDS SORPTION FRACTION: '
      1,E10.3)
1275   FORMAT(//,23X,'LIQUID',27X,'GASEOUS',//,12X,6('CELL ',I3,3X),
      1//,2X,'MIN',6X,6(F7.1,1X,'m',2X),/,75('-'))
1300   FORMAT(1X,F7.2,2X,6(1X,E10.3))
1400   FORMAT(/,9X,3(1X,E10.3))
1450   FORMAT(/,2X,'FINAL FLOWRATE (M3/S): ',E10.3)
1475   FORMAT(1X,'VELOCITY (M/S): ',E10.3,5X,
      1'TRANSPORT TIME (HRS): ',F7.2,7X,/,' GAS VEL (M/S): ',E10.3)
```

```
1800  FORMAT(/,1X,'KMASS (1/HR): ',E10.3,/)
1950  FORMAT(2X,F6.1,7(3X,E10.3))
2000  FORMAT(//,5X,'RI, QN, TWD, FH:  ',4(2X,E10.3))
2050  FORMAT(/,5X,'EMITTED MASS (g): ',E10.3,/,5X,
     1'TOTAL MASS INPUT (g): ',E10.3)
2100  FORMAT(//,2X,'REMOVAL FROM REACH (-): ',E10.3,/,2X,
     1'REMOVAL TOTAL (-): ',E10.3,/,2X,
     1'FRACTION OF REMOVAL BY DROP (-): ',E10.3)
C
      CLOSE(UNIT=2)
      CLOSE(UNIT=3)
      STOP
      END
```

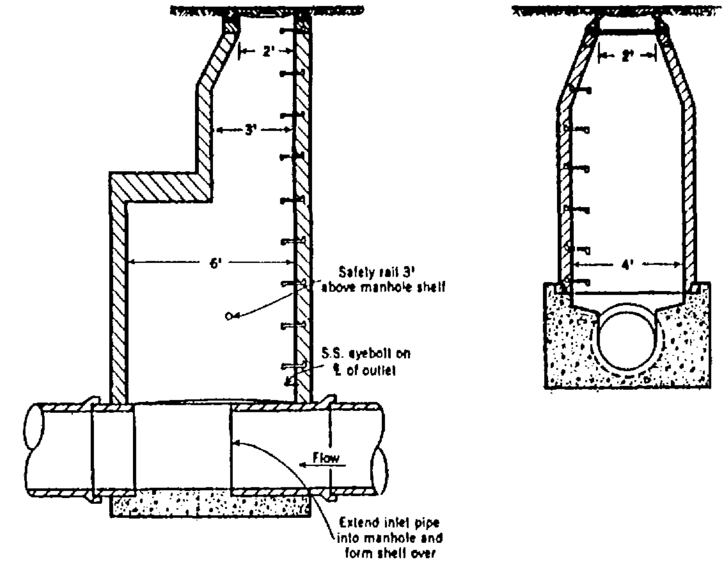
APPENDIX B: SCHEMATICS OF SEWER APPURTENANCES AND STRUCTURES

This appendix contains some schematic diagrams (requested by ARB staff) of types of sewer connections and appurtenances. The figures are not intended to be a complete representation of the types of structures encountered in sanitary sewers, but hopefully will enable the reader to visualize some of the points where turbulence can be generated and emissions occur. The figures have been adapted from an ASCE (1970) publication

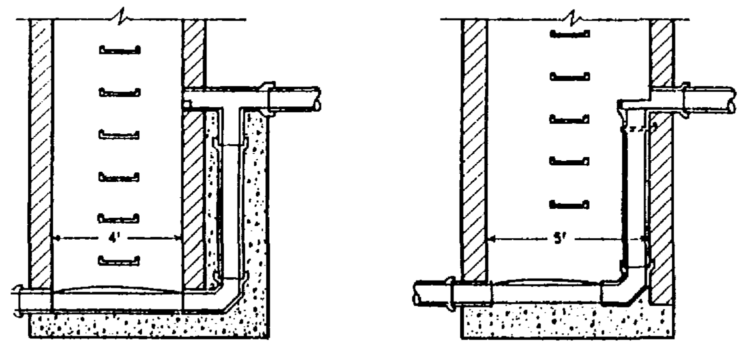
Figures B-1, B-2, and B-3 illustrate typical types of connections to sewer mains, primarily from residences or buildings. Note the relatively steep slopes that impart energy that must be dissipated. Figure B-4 indicates that access holes are often located above or near bends in pipes. The bends lead to increased turbulence and are known to be areas of odor production. Figures B-5 and B-6 illustrate common manhole arrangements for small and intermediate size sewer pipe. Note the sewer pipe "invert" location relative to the bottom of the access hole. Figure B-7 illustrates a "drop" manhole, again an area of high energy dissipation. Figure B-8 illustrates an "inverted siphon" which is used to carry flow below the normal hydraulic grade line of the sewer. Figure B-9 illustrates common "wet well" arrangements at pump stations. Such stations are commonly vented, and breathing losses from changes in the headspace volume occur.



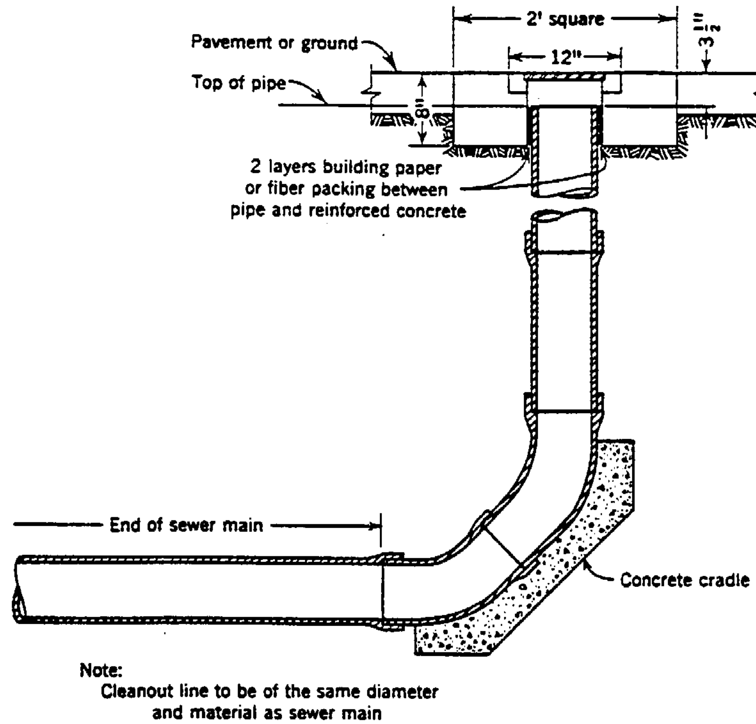
B-1 —Typical manholes for small sewers. (Ft × 0.3 = m; in. × 2.54 = cm.)



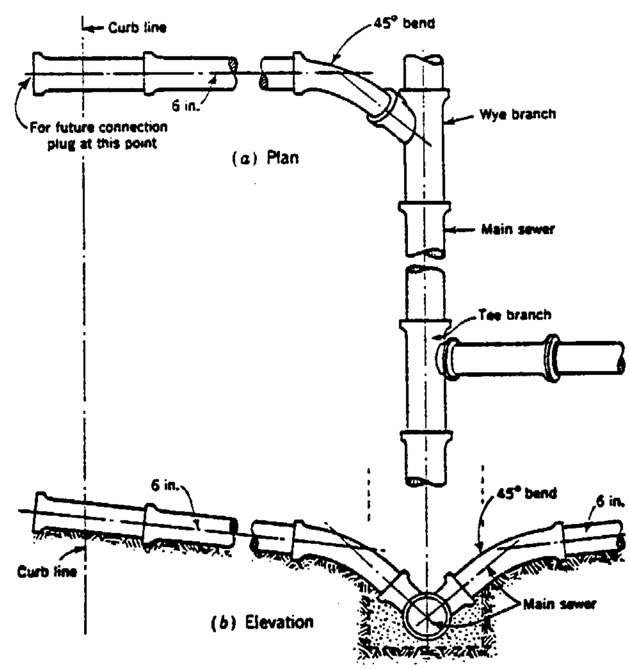
B-2 —Two manholes for intermediate-sized sewers. (Ft × 0.3 =



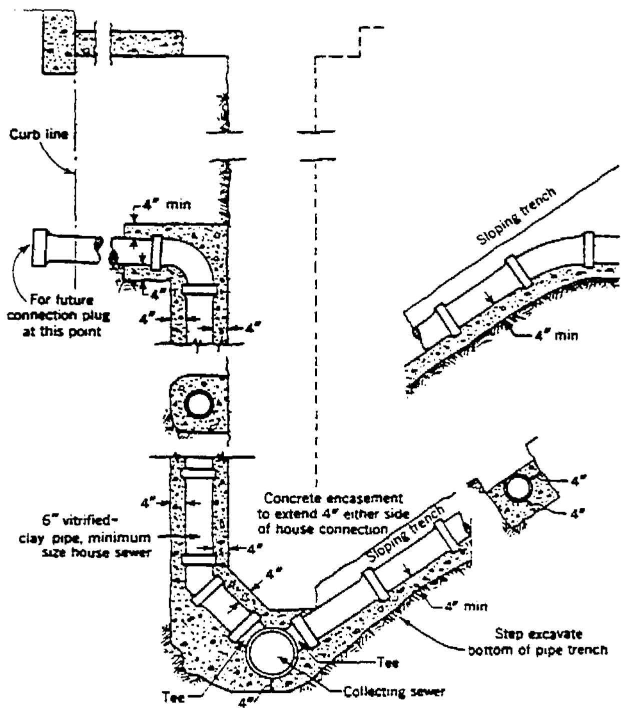
B-3 —Drop manholes. (Ft × 0.3 = m.)



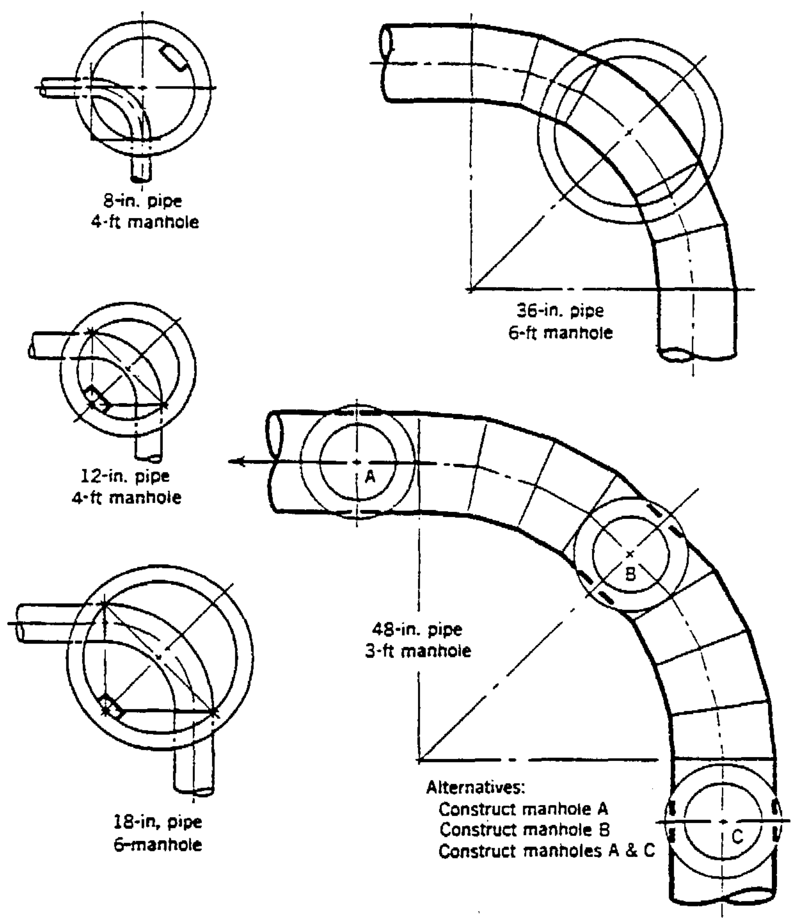
B-4 **—Terminal cleanout. (Ft × 0.3 = m; in. × 2.54 = cm.)**



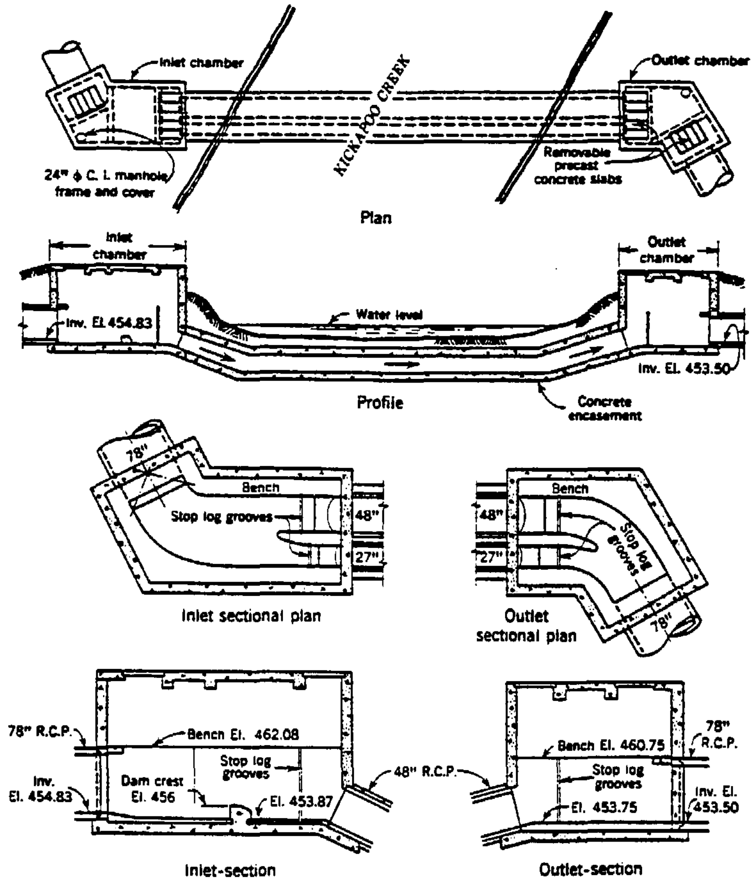
B-5 **—Service connection for shallow sewer. (In. × 2.54 = cm.)**



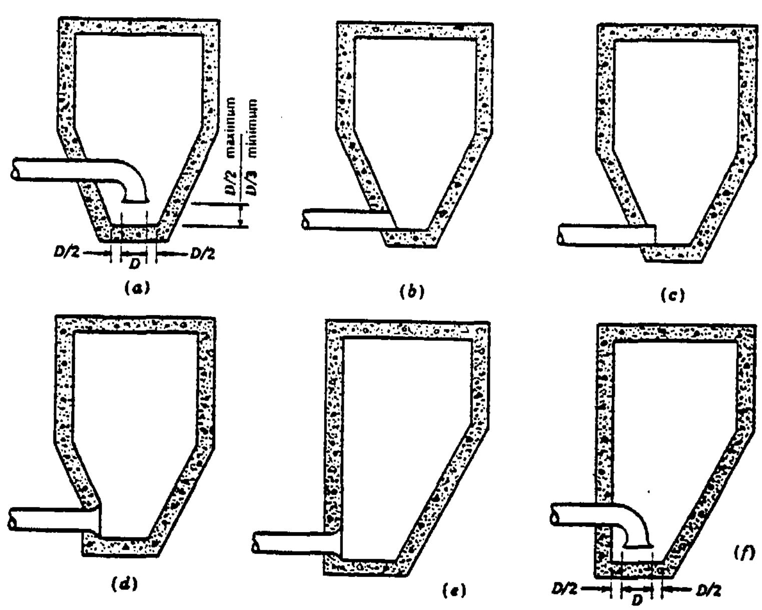
B-6 **—Service connection for deep sewer. (In. × 2.54 = cm.)**



B-7 **—Manhole placement for various types of bends. (Ft × 0.3 = m; in. × 2.54 = cm.)**



B–8 —Twin-barrel siphon. (In. × 2.54 = cm.)



B–9 —Typical suction inlets for sewage pumps.