

## CHAPTER 5.0

# WASTEWATER COLLECTION SYSTEM MODELING

### 5.1 Overview

Modeling wastewater collection system odors and corrosion requires adequately representing multiple biological, chemical, and physical processes, such as the following:

- Liquid phase sulfide generation
- Liquid-to-vapor H<sub>2</sub>S mass transfer
- Natural liquid phase chemical and biological oxidation of sulfides
- Dissolved oxygen (DO) impacts on sulfide generation
- Liquid and vapor phase bulk transport of sulfides and H<sub>2</sub>S, respectively
- Vapor phase H<sub>2</sub>S-induced concrete corrosion

Many of these processes have been studied and reported on over the last several decades. The purpose of this chapter is to provide an overview of the information found in the published literature related to recent advances in modeling wastewater collection system odors and corrosion (rather than to provide a detailed explanation of model development or use).

Published information related to various processes is discussed with the intent to increase the reader's general knowledge of factors, parameters, or issues affecting the understanding of specific mechanisms and how best to quantitatively represent them.

Information obtained and reviewed as part of this literature search was not sufficient to allow for a detailed examination of each individual model described or a detailed comparative assessment.

### 5.2 Models Available

Of all the papers reviewed for this report, 50 related to modeling were identified. Within this subset, six models were cited. The information presented regarding each model varied from a qualitative explanation of the model to a detailed presentation of the algorithms used. A brief description of each model is provided below. Table 5-1 summarizes each model's capabilities as reported in the literature.

### **5.2.1 Wastewater Aerobic–Anaerobic Transformations in Sewers**

This model (or its components) was cited the most often, and thus there is significant information about it available in the public domain. This model was developed in the 1990s as a sewer microbial biochemical oxygen demand (BOD) transformation model (Nielsen et al., 1992; Hvitved-Jacobsen et al., 1998a, b; Tanaka and Hvitved-Jacobsen, 1998).

Yongsiri et al. (2003a, b) presented an overview of the incorporation of a H<sub>2</sub>S liquid-vapor mass transfer component into the wastewater aerobic–anaerobic transformations in sewers (WATs) model. Subsequently, Yongsiri et al. (2004a) presented a two-phase model for predicting gravity flow sewer sulfide generation and release into the overlying sewer headspace. In developing this model, the authors considered only sulfide formation, transfer to the vapor phase, and bulk transport within the liquid and vapor phases; potential removal mechanisms such as biological or chemical oxidation were not included. Consequently, the model is reported to be conservative in predicting liquid phase sulfide and vapor phase H<sub>2</sub>S concentrations.

Nielsen et al. (2005a) built upon this work and described the addition of the sulfur cycle to the WATS model. Sulfur-cycle components added to the model included sulfide generation, precipitation, biological and chemical oxidation, reaeration, transfer to the vapor phase, and corrosion. For each component discussed, algorithms are provided.

### **5.2.2 Septicity Prediction and Control Algorithms (SPACA)**

Boon et al. (1998) provided an overview of an algorithm developed to predict sulfide generation within force mains (rising mains). Their paper presents results from the model and compares predicted sulfide concentrations to field-measured ones but does not provide the actual algorithms used. Instead, Boon et al. referred to previously published papers that contain the algorithms used. Parameters required in modeling sulfide generation include flow rate, temperature, chemical oxygen demand (COD), pH, and initial DO concentrations.

### **5.2.3 East Central Interceptor Sewer (ECIS)**

Michiels and Salgaonkar (1994) presented the development of the ECIS model, a new model for predicting liquid phase sulfide and vapor phase H<sub>2</sub>S concentrations. The authors begin by reviewing two existing sulfide prediction models, SULF.BAS and HS Program, and the limitations associated with each. They report that SULF.BAS is a gravity sewer model that predicts sulfide generation and subsequent liquid phase sulfide concentrations but does not account for liquid-to-vapor mass transfer and does not report headspace H<sub>2</sub>S concentrations. HS Program similarly calculates sulfide generation within gravity sewers using the Parkhurst and Pomeroy equation but also calculates concrete corrosion rates associated with the predicted liquid phase sulfide concentration. The limitation of both of these models, according to Michiels and Salgaonkar, is that neither calculates nor provides sewer headspace H<sub>2</sub>S concentrations. The ECIS model calculates liquid phase sulfide generation, flux to the headspace, and the resultant H<sub>2</sub>S vapor space concentration. Model algorithms and parameter values are provided.

### **5.2.4 AEROSEPT**

Matos and Aires (1995) described the use of a gravity sewer and force main model, AEROSEPT, to predict sulfide concentrations within a collection system in Portugal. Model algorithms were not presented, but information about their sources was provided—for example, use of Pomeroy’s (1959) algorithm for pressure main sulfide generation and Pomeroy and

Parkhurst's (1977) for gravity sewer sulfide formation. Although Matos and Aires did not compare model-predicted values to field-measured ones, they did present model results for a new interceptor system as a means to highlight the value of the model during system design.

### 5.2.5 EPA Sulfide and Corrosion Models

Kienow and Kienow (2004) reviewed the EPA sulfide model developed by Pomeroy and Parkhurst (1977) and presented in an ASCE (1982) manual of practice. They also referred to and reviewed the EPA (1974) corrosion model. To enhance these algorithms, Kienow and Kienow described using a turbulence corrosion factor and a crown corrosion factor to account for system-specific corrosion rates induced by turbulence and system design. These two factors' values are provided for various structures and conditions.

### 5.2.6 INTERCEPTOR Model

Witherspoon et al. (2004) provided an overview of the INTERCEPTOR Model and listed the mechanisms incorporated into it, including sulfide generation, liquid phase and vapor phase bulk transport, oxidation, liquid-vapor mass transfer, and concrete corrosion. The only algorithm presented is related to concrete corrosion (Pomeroy, 1974).

Table 5-1 summarizes which parameters the models' algorithms attempt to address.

Table 5-1. Summary of Models Reviewed

	WATS	INTERCEPTOR	SPACA	ECIS	AEROSEPT	EPA Sulfide and Corrosion
Sulfide generation	Yes	Yes	Yes	Yes	Yes	Yes
Sulfide oxidation/removal	Yes	Yes	Yes	Yes	NR	No
Mass transfer	Yes	Yes	No	Yes	Yes	Yes
pH impacts on liquid phase speciation	Yes	Yes	Yes	Yes	Yes	Yes
DO impacts	Yes	Yes	Initial conc. only	No	NR	Yes
Vapor flow rates	Yes	Yes	NR	Yes	NR	No
Corrosion	Yes	Yes	NR	No	Yes	Yes

NR, not reported.

## 5.3 Compounds

While it is generally understood that there are potentially several odorous compounds present in wastewater, the primary compound of interest in all modeling papers reviewed was H<sub>2</sub>S. Boon et al. (1998), during their discussion of the SPACA model, indicated that other compounds may also be responsible for odors, for example, volatile fatty acids (VFAs) such as acetic, propionic, and butyric acid, and basic compounds such as ammonia, amines, skatole, and indole. However, the authors state that these compounds normally account for less than 5 percent of odors and that H<sub>2</sub>S is considered the predominant compound.

Likewise, H<sub>2</sub>S was the dominant compound discussed in terms of concrete corrosion and is the compound all published algorithms are developed around in terms of predicting corrosion rates. In addition to discussing the mechanisms of H<sub>2</sub>S-induced concrete corrosion, Boehm et al.

(1998) reported that other compounds such as nitrates and nitrides may play a role in concrete corrosion. However, the role or mechanism of these compounds is not discussed. It is likely that these compounds play a minor role in concrete corrosion in municipal wastewater collection systems.

## 5.4 Sulfide Generation

All models reviewed included a term for representing the generation of sulfides within the sewer biofilm. There are two different forms of algorithm used: one for predicting sulfide within gravity flow sewers, where there is a vapor headspace, and another for force or rising mains that have no headspace.

In general terms, sulfide is formed as a result of the anaerobic transformation of biodegradable compounds and the reduction of sulfate. However, as presented by Nielsen et al. (2005b), sulfate is not usually included in sulfide generation equations because it is not rate limiting when it is present in concentrations greater than 5 to 15 mg/L.

Nielsen et al. (1992) provided an overview of four algorithms commonly used to represent force main sulfide generation. Although slightly different in the empirical constants used, the algorithms all utilize temperature and organic material concentration. Some of the equations presented additionally include flow velocity or slope. The form of organic matter concentration used in the various models ranged from soluble COD to BOD. Kienow and Kienow (2004) stated that factors affecting sulfide generation include high temperature, high BOD, flat sewers, and long detention times in fully flowing pipes—for example, force mains, siphons, and surcharged gravity sewers.

Algorithms for gravity flow sewers use similar parameters in describing sulfide generation. However, one important difference is that in gravity flow sewers, there is the potential for reaeration of the wastewater, resulting in the potential to maintain sufficient DO within the wastewater to prevent anaerobic conditions. Therefore, in addition to tracking sulfide, gravity flow sewers must also perform a DO balance. The bulk phase DO concentration required to prevent sulfide generation or accumulation in the liquid phase has been reported to be in the range of 0.2 to 0.5 mg/L (Nielsen et al., 1992; EPA, 1974).

Several published papers provide information about the best parameter to use in characterizing the nutrients available to sulfate-reducing bacteria. For example, Hvitved-Jacobsen et al. (1999) described a model that has been developed to account for aerobic and anaerobic microbial transformations. Instead of just describing sulfide generation as a function of BOD or COD, they suggest that the anaerobic transformation of sulfate to sulfide is accomplished through mainly the use of fermentable substrates and their byproducts, for example, VFAs. Nielsen et al. (1998) discussed the use of acetate or VFAs as a potential indicator of sulfide generation within force mains because this compound is associated with multiple anaerobic metabolic pathways. A sulfide production algorithm is presented and adjusted for site-specific data by use of an empirical constant used to adjust for different wastewater types—for example, industrial, domestic—and a different temperature adjustment factor. However, the algorithm uses soluble COD as the substrate indicator.

Michiels and Salgaonkar (1994) reported on the use of the sulfide generation rate constant ( $M'$ ) developed by Pomeroy (1959) as an initial starting point for estimating sulfide generation in the ECIS model. The authors report that field measurements used during model calibration resulted in the determination that the actual system-specific  $M'$  was six times greater

than the default value developed by Pomeroy. These results suggest that it is important to obtain system-specific data so that an appropriate value of  $M'$  can be used.

## 5.5 Dissolved Oxygen

DO is an important component of the sulfide generation phenomenon because at sufficient concentrations it is capable of maintaining an aerobic environment in which sulfide generation will not occur. However, DO is continually consumed by sewer biomass and must be replaced through a gas-to-liquid mass transfer (reaeration). Much of the research on DO has focused on improving the knowledge base associated with these competing mechanisms.

Nielsen et al. (1992) discussed the importance of DO uptake and used the algorithms developed by Parkhurst and Pomeroy (1997) to represent reaeration in sewers. They reported literature values of oxygen uptake ranging from 2 to 20 mg O<sub>2</sub>/L/hr in gravity sewers and approximately 0.7 mg/m<sup>2</sup>/hr within rising mains.

Tanaka et al. (2000) measured several parameters in an operating pressure sewer in Japan and evaluated the use of air injection as a means to provide sufficient DO to prevent septic conditions. They found that sulfide generation was prevented at DO concentrations greater than 1 mg/L.

Gudjonsson et al. (2002) measured DO concentrations within an operating 3.6-km interceptor over a 2-month period. They then compared the results of this monitoring to modeling results. The authors accounted for biological utilization of DO in both the bulk phase and within the biofilm in addition to the mass transfer component. The comparison of predicted and measured DO concentrations was reported to have yielded good long-term but not short-term averaging results owing to potential fluctuations in wastewater composition that were not captured within modeling input parameter values.

## 5.6 Sulfide Oxidation

One method for removing sulfide from the liquid phase is through oxidation. There are two naturally occurring forms of sulfide oxidation, biological and chemical. Chemical oxidation is primarily mediated through oxygen in the bulk phase whereas biological oxidation is carried out by bacteria within the sewer biofilm.

Nielsen et al. (2005b) compared the relative importance of chemical versus biological oxidation of sulfides. They provide references indicating conflicting information on the relative importance of the two forms of oxidation. For example, the authors present information from ASCE (1989) that states that chemical oxidation is slower than biological oxidation, whereas Wilmot et al. (1988) determined that chemical oxidation makes up 44 to 88 percent of sulfide oxidation. Nielsen et al. presented two algorithms developed to predict chemical and biological sulfide oxidation and state that the chemical oxidation rate is dependent on the form of sulfide present and that H<sub>2</sub>S is oxidized slower than hydrosulfide ion (HS<sup>-</sup>).

Nielsen et al. (2004) reported that chemical oxidation is temperature dependent and doubled with an increase of 12°C.

## 5.7 Mass Transfer

Several papers on the issue of liquid-to-vapor phase mass transfer have been published. Extensive research has been performed in the past on oxygen reaeration of sewers and streams

and much of the current H<sub>2</sub>S-related mass transfer research has been done developing refined oxygen: H<sub>2</sub>S mass transfer correlations.

Nielsen et al. (2005a, b) built upon the oxygen reaeration equation for sewers developed by Parkhurst and Pomeroy (1972) and report that the overall mass transfer coefficient ratio of H<sub>2</sub>S:O<sub>2</sub> is 0.86.

Yongsiri et al. (2004) reported that the H<sub>2</sub>S mass transfer rate (KLA H<sub>2</sub>S) is dependent on pH. They provide an algorithm that predicts KLA H<sub>2</sub>S as a function of pH (range of 4.5–8.0) and oxygen mass transfer (KLA O<sub>2</sub>). For a given pH, the ratio of H<sub>2</sub>S:O<sub>2</sub> mass transfer was 0.86, the same as that reported by Nielsen et al. (2005a, b). Huisman et al. (2004) described a set of experiments and a new algorithm for calculating sewer reaeration. Provided also are a summary of available reaeration equations and methods—direct and indirect—routinely used to measure oxygen transfer. In developing the proposed algorithm, the authors used an inert tracer gas, sulfur hexafluoride (SF<sub>6</sub>). The proposed equation indicates that oxygen mass transfer is related to oxygen solubility, the presence of surfactants and three dimensionless parameters (Froude, Reynolds, and Schmidt numbers). The surfactant adjustment factor, which is the ratio of the wastewater mass transfer rate to the clean water mass transfer rate, was reported to be as low as 0.4 but typically in the range of 0.5–0.9.

Yongsiri et al. (2004b) described research done to determine the impact of temperature on mass transfer. The authors present an expression that follows the form of the Arrhenius equation and discuss the importance of separating the effects of pH and temperature on mass transfer when considering the mass transfer rate on the basis of dissolved sulfides, which includes H<sub>2</sub>S (the component of sulfides that can volatilize) versus the ionized component HS<sup>-</sup>, which cannot volatilize. Their research also indicated that conductivity has little impact on mass transfer.

Lahav et al. (2004) presented a new method for predicting H<sub>2</sub>S emissions from gravity flow sewers. They develop a model using a velocity gradient as the parameter to describe hydraulic conditions within the sewer. This method was compared to the EPA (1985) equation using sulfide concentration data collected from an operating sewer in South Africa. Results indicate that their new method performs better than the EPA method. However, these results should be considered preliminary because other mechanisms such as generation or removal are not included.

Chern and Yang (2004) reported on experimental work developed to better understand oxygen mass transfer across drop structures. The authors describe two zones for mass transfer: the droplet (the zone in which the water is falling and disintegrates into droplets) and the surface (the tailwater surface). The authors varied temperature, drop height, receiving water depth, and flow rate and found that mass transfer rate for both zones increased with drop height and flow rate. Water depth also impacted the surface zone mass transfer but did not impact droplet zone.

## 5.8 Ventilation

For gravity flow sewers, the flow of vapors within the sewer headspace is an important parameter in completing mass balances for the liquid and vapor phases. However, little research has been done on this topic. Previous works include those by Pescod and Price (1981), who published information related to liquid-drag-induced natural ventilation; Quigley and Corsi (1995), who measured natural ventilation rates in a large municipal sewer; and Olsen et al.

(1997a, b), who presented a mechanistic approach to calculating sewer ventilation on the basis of thermodynamic fundamentals.

When possible, it is best to use actual field data to calculate sewer natural ventilation rates. For example, Michiels and Salgaonkar (1994) reported that the ECIS odor model used air and liquid velocity data collected in an operating sewer to develop a method for estimating natural ventilation rates. Field data collected indicated that the air velocity was equal to 0.05 times liquid velocity. This could then be multiplied by the headspace cross-sectional area to obtain a ventilation rate.

When field data are not available, it is necessary to estimate the ventilation rate. This can be done by assuming either a constant air:water flow rate or velocity ratio. Yongsiri et al. (2004a, b) used a constant air:water velocity ratio of 0.2, citing previous works that indicated the range may vary from 0.2 to 0.3.

Edwini-Bonsu and Steffler (2004) presented a computational fluid dynamics–based model developed to calculate air flow in sewers. The model is compared to previously published models and measured ventilation-rate data. Results of this comparison suggest that the previous models may overpredict the air flow rate in sewers. While the data used for the comparison are relatively sparse, the potential for this model to provide an improved method for predicting natural ventilation rates in sewers is significant.

## 5.9 Corrosion

Two notable papers related to H<sub>2</sub>S-induced concrete corrosion were published. Kienow and Kienow (2004) reviewed an ASCE (1989) algorithm that was developed to predict the quantity of concrete thickness necessary to prevent pipe failure and that involves using the crown corrosion and the turbulence corrosion factors. They reviewed factors impacting concrete corrosion rates and pipe life, including the level of turbulence as accounted for by the use of turbulence correction factors, concrete alkalinity, and concrete cover thickness  $z$ , which can be specified by the designer. The primary factor impacting rate of corrosion was stated to be turbulence which impacts the amount of H<sub>2</sub>S stripped from the wastewater. According to the authors, concrete with limestone aggregates has four to five times the alkalinity and resistance to corrosion as granitic aggregate concrete. The authors also discuss the mix factors that may impact corrosion rates including cement types, fly ash addition, and high alumina cement.

Boehm et al. (1998) developed a corrosion model and evaluated relative importance of several variables including: concrete surface pH, concrete alkalinity, dissolution rate of calcium carbonate to calcium sulfate. While the focus of the paper is on H<sub>2</sub>S's role in concrete corrosion, Boehm et al. also pointed out that nitrates and nitrides may cause corrosion. However, the relative importance or the manner in which these compounds cause concrete corrosion is not discussed. Boehm et al. setup a hypothetical example using 5 ppmv H<sub>2</sub>S as the headspace concentration and varied concrete pipe surface pH from 1 to 4, the dissolution rate from 0.0084 to 0.84 cm/day and concrete alkalinity from 0.2 to 10 mol/L. Concrete loss was predicted to range from 0.3 to 27 cm over a 25-year period.

## 5.10 Relationship Between Sewer Headspace H<sub>2</sub>S Concentration and Corrosion

Several models exist that allow for the prediction of liquid phase sulfide generation and transport within sewer systems. Additionally, some of these models attempt to facilitate the

prediction of sewer corrosion through implementation of empirical formulae that are based primarily on liquid phase sulfide concentration data.

Given that corrosion is related to sewer headspace  $H_2S$  concentration, it is recommended that an algorithm(s) be developed to account for this relationship. This would be an improvement over the existing methodology as this new method of prediction of corrosion could be completed using the following steps:

1. Liquid phase sulfide generation
2. Liquid-to-vapor mass transfer of  $H_2S$
3. Vapor phase  $H_2S$  fate modeling

Steps 1 and 2 already exist and account for the generation and fate of sulfide within the liquid phase, including bulk transport downstream, chemical or biological oxidation, and interphase mass transfer.

Step 3, however, requires additional focus. It is recommended that research be completed to allow for the development of algorithms that correlate corrosion to several different factors, such as the sewer unwetted wall area, material of construction, bulk flow of air, and headspace  $H_2S$  concentrations.

A research plan describing this proposed work in more detail is included in Chapter 10.

## 5.11 Summary and Conclusions

Several wastewater collection system models have been developed to facilitate the assessment of sulfide generation and potential release into the sewer headspace atmosphere. While several of the models rely on similar methods for approximating sulfide generation and liquid-to-vapor mass transfer, the methods for predicting ventilation rates and inclusion of concrete corrosion as a  $H_2S$  loss term may not be consistent. Improved understanding of the fundamentals associated with these two areas—natural ventilation of sewers and quantification of vapor phase  $H_2S$  loss associated with concrete corrosion—are therefore considered key areas for future research.