



## Technical note

# Emissions of NO, TVOC, CO<sub>2</sub>, and aerosols from a pilot-scale wastewater treatment plant with intermittent aeration

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## Abstract

Atmospheric emissions from a pilot wastewater treatment plant performing aerobic and anoxic processes were investigated. The experiment was performed by sealing the whole aeration tank with an airtight cover of polyethylene in order to obtain a defined flow rate of the off-gas. By measuring concentrations in the known flux of the off-gas emission rates were determined. Due to the dimensions of the pilot plant and the air and water flows these emission rates represent upper limits. The emission rates were put into relation to CO<sub>2</sub> to obtain normalized data that can be used for emission inventories. Normalized emission rates (g component × g<sup>-1</sup> CO<sub>2</sub>) were 8.9 × 10<sup>-3</sup> for TVOC, 6.6 × 10<sup>-6</sup> for non-methane hydrocarbons C<sub>2</sub>-C<sub>7</sub> (NMHC), 2.1 × 10<sup>-5</sup> for NO and 3.0 × 10<sup>-6</sup> for particulate organic carbon (POC). Emission rates per capita equivalent per year accounted at the most for 244 g C TVOC, 0.18 g C NMHC, 0.58 g NO and 0.08 g C POC on a basis of 27,400 g CO<sub>2</sub> per capita. The non-aeration periods also contributed to the production of NO and TVOC emissions of approximately one-third of the total emissions. From this, we conclude that the implementation of denitrification stages in European wastewater treatment plants according to the EU-directive 91/271/EEC will increase trace gas emissions in Europe. However, according to our estimates, emissions of trace gases and aerosols from wastewater treatment compared to anthropogenic sources will still remain very low. © 2001 Elsevier Science Ltd. All rights reserved.

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## 1. Introduction

The study on the emissions of a wastewater treatment plant (WTP) produced during nitrification and denitrification periods was performed due to the following reasons: No emission rates concerning nitric oxides

(NO, NO<sub>2</sub>) and carbonaceous aerosols are available in literature (McInnes, 1996). Emissions of volatile organic compounds (VOC) from WTPs have been investigated, but emission rates ranged over several orders of magnitudes (Namkung and Rittmann, 1987; Bell et al., 1993; Zhu et al., 1999) and recent laws on solvent use in many states are expected to have an effect also on emissions of VOC from sewage treatment plants.

A new technology has to be accomplished in the European Union (CEC1, 1991) to allow the removal of more than 70% of total nitrogen from the wastewater. By adding the required anoxic denitrification stages to the current systems, the size of the plants must be approximately tripled with a considerable increase of the residence

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time of the anoxic phase. Consequently, it appears likely that trace gas emissions that are connected to the denitrification process (e.g. methane,  $\text{NO}_x$ ) will increase in the near future.

## 2. Experimental

### 2.1. Field site

Investigations were performed at the WTP of the University of Agricultural Sciences, in Vienna, Austria. The facility is an activated sludge pilot plant with a water capacity of  $1.6 \text{ m}^3$ . The aeration tank is a rectangular polyethylene basin fed with fresh wastewater out of the local municipal Viennese sewer line. A time-controlled feed produces an inlet rate of  $1 \text{ m}^3 \text{ d}^{-1}$ . Sludge is pumped back from the settling tank into the activated sludge system at a rate of about  $1.7 \text{ m}^3 \text{ d}^{-1}$ . Paddle mixers are used to stir the content of the aeration tank continuously. Aerobic digestion, nitrification and denitrification are all done in the same aeration tank. The aeration periods last 30 min at an air rate of  $16 \text{ m}^3 \text{ h}^{-1}$  (STP based on  $0^\circ\text{C}$  and 1013 mbar) followed by a non-aeration period of one hour. Rod-shaped diaphragm blowers (10 cm in diameter, Purator) are used for aeration. A schematic diagram of the plant and further descriptions are given in Fuerhacker et al. (2000).

The physical-chemical properties of the wastewater were determined according to the DIN-German Industrial Standards (DEV, 1998). Average values obtained for the influent were  $198 \text{ mg l}^{-1}$  total organic carbon (TOC),  $437 \text{ mg l}^{-1}$  chemical oxygen demand (COD),  $207 \text{ mg l}^{-1}$  biological oxygen demand ( $\text{BOD}_5$ ),  $4.3 \text{ mg l}^{-1}$  phosphate ( $\text{PO}_4\text{-P}$ ),  $6 \text{ mg l}^{-1}$  total phosphorus ( $\text{P}_{\text{total}}$ ),  $150 \text{ mg l}^{-1}$  suspended solids (SS), and  $36 \text{ mg l}^{-1}$  ammonia-nitrogen ( $\text{NH}_4\text{-N}$ ). Effluent values were  $6 \text{ mg l}^{-1}$  TOC,  $0.5 \text{ mg l}^{-1}$   $\text{P}_{\text{total}}$ ,  $1 \text{ mg l}^{-1}$  ammonia-nitrogen ( $\text{NH}_4\text{-N}$ ), and  $4 \text{ mg l}^{-1}$  nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ). Average pH was 7.1 and dissolved oxygen  $1.3 \text{ mg l}^{-1}$ .

### 2.2. Methods

The special feature of this study was that the whole aeration tank was completely sealed with a polyethylene cover. A slight overpressure in the chamber was maintained. Additional air at a flow rate of  $5.5 \text{ m}^3 \text{ h}^{-1}$  (STP) was pumped continuously into the cover to form a chamber volume of  $2 \text{ m}^3$ . A glass manifold was connected to the chamber at a distance of 0.5 m above the water level of the aeration tank. All samples were collected from the outlet of the manifold, which was heated to  $25^\circ\text{C}$  to avoid condensation. In addition, intake air used for aeration was checked several times a day. Concentrations of  $\text{CO}_2$  were determined with a non-dispersive infrared (NDIR) gas analyzer (Maihak UNOR 6N), NO and  $\text{NO}_2$  with

a Nitrogen Oxides Analyzer Model 8840 (Monitor Labs Inc.), and TVOC with a Hydrocarbon-Analyzer Model VE 5 with a Flame-Ionization Detector (FID; Messer, Austria). The FID was calibrated with propane. Methane was included in the results for TVOC, which are given in  $\text{mg C m}^{-3}$ . Data were collected every 20 s. An average of every minute was calculated and used to determine daily minima (lowest values) and maxima (highest values) as well as arithmetic averages of the gaseous components over the aeration and non-aeration periods for the selected time intervals. Samples of NMHC were collected on adsorption tubes filled with Carbosieve SII (60/80 Mesh size, Supelco) and Molecular Sieve  $5 \text{ \AA}$  (60/80 Mesh size, Chrompack) adsorbents. The analysis was carried out on a Gas Chromatograph with FID (HP-5890 Series II). Details are described in Sree et al. (2000).

Aerosols were collected on quartz-fiber filters (TISSUQUARTZ 2500QAT-UP, Pallflex, USA) placed in polycarbonate filter stacks (NILU – Norwegian Institute for Air Research). Sampling rate was about  $2 \text{ m}^3 \text{ h}^{-1}$  (STP). Total carbon was determined by burning an aliquot of the filter at  $1000^\circ\text{C}$  in oxygen. The evolved  $\text{CO}_2$  was measured using an NDIR analyzer (Maihak UNOR 6N). The set up of the above combustion method is described elsewhere (Puxbaum and Rendl, 1983).

Data used to determine the emission rates were taken from the 9 February 1998 until the 13 February 1998. During this period, the plant was controlled intensively. The wastewater temperature was  $18\text{--}19^\circ\text{C}$ .

## 3. Results and discussion

Table 1 contains the concentration data of the determined components. To calculate the daily emission rates ( $E$ ) the following equation is used:

$$E = (c_{\text{ae}} t_{\text{ae}} F_{\text{ae}}) + (c_{\text{nae}} t_{\text{nae}} F_{\text{nae}}), \quad (1)$$

where  $c_{\text{ae}}$  stands for the average concentration of a component minus the concentration of this component in the intake air during the aeration phase, and  $c_{\text{nae}}$  is the average concentration of the component during the non-aeration phase minus the concentration of this component in the additional air that was pumped into the cover (Table 1).  $t_{\text{ae}}$  stands for the duration of the aeration phase ( $8 \text{ h d}^{-1}$ ), respectively,  $t_{\text{nae}}$  for the duration of the non-aeration phase ( $16 \text{ h d}^{-1}$ ),  $F$  represents the gas flow, which was  $21.5 \text{ m}^3 \text{ h}^{-1}$  STP ( $F_{\text{ae}}$ ) in the aeration phase and  $5.5 \text{ m}^3 \text{ h}^{-1}$  STP ( $F_{\text{nae}}$ ) in the non-aeration phase. The concentrations and mixing ratios in the intake air are 2.1 ppb NO,  $1.3 \text{ mg C m}^{-3}$  TVOC and 0.04 vol%  $\text{CO}_2$ . The mixing ratios are converted into concentrations by the conversion factors 1.34 for NO ( $\mu\text{g m}^{-3}$ ) and 19.6 for  $\text{CO}_2$  ( $\text{g m}^{-3}$ ). For POC, which is completely removed

Table 1

Concentrations and mixing ratios of NO, TVOC, CO<sub>2</sub>, and POC in the off-gas emitted by the aeration tank of the pilot wastewater treatment plant in Vienna, estimates of aeration and non-aeration phase contributions; lowest (min) and highest (max) minute means on the respective day and daily averages

Date	NO (ppb)			TVOC (mg m <sup>-3</sup> )			CO <sub>2</sub> (vol%)			POC (μg C m <sup>-3</sup> )
	Min	Max	Average	Min	Max	Average	Min	Max	Average	Average
<i>Aeration phase</i>										
10 Feb	—	—	—	16.0	40.5	23.3	0.08	0.23	0.19	11.3
11 Feb	40.5	86.4	56.1	12.8	43.6	27.1	0.08	0.25	0.20	15.6
12 Feb	32.7	65.4	48.6	18.2	92.3	38.6	0.10	0.34	0.23	18.8
13 Feb	28.3	44.4	38.4	—	—	—	0.10	0.28	0.19	—
<i>c<sub>ae</sub></i> (10–13 Feb)			47.7 ± 18.1			29.7 ± 8.0			0.20 ± 0.02	13.2 ± 3.8
<i>Non-aeration phase</i>										
10 Feb	—	—	—	15.7	26.9	19.9	0.08	0.22	0.14	—
11 Feb	38.6	89.8	55.9	12.7	28.9	22.1	0.09	0.25	0.15	—
12 Feb	29.8	68.9	49.3	18.0	35.4	27.0	0.10	0.34	0.19	—
13 Feb	27.3	44.4	35.8	—	—	—	0.10	0.28	0.19	—
<i>c<sub>nae</sub></i> (10–13 Feb)			47.0 ± 17.9			23.0 ± 3.6			0.17 ± 0.03	—

from the intake air by filtering through the liquid in the aeration tank, no contribution of the intake air is subtracted.

For the calculation of the contribution of the aeration and the non-aeration period to the total emissions a mathematical model was applied considering the carry-over of off-gases from aerobic to anoxic phases and vice versa. The carry-over was calculated assuming an exponential dilution of the gaseous products caused by the additional air pumped into the headspace and by the aeration. Assuming that the concentration  $c$  of a gaseous component in the headspace with the volume  $V$  (m<sup>3</sup>) gets diluted by the airflow  $F$  of the intake air (m<sup>3</sup> min<sup>-1</sup>) with the concentration  $c_{in}$  (mg m<sup>-3</sup>) and with the starting condition  $c(t_0) = c_0$ , we obtain the following equation describing the dilution of the component with time:

$$c(t) = (c_0 - c_{in})e^{-(F/V)(t-t_0)} + c_{in}. \quad (2)$$

Fig. 1 gives the average curve of the measured trace gas concentrations in contrast to the dilution curves, which were obtained by Eq. (2). This figure also clearly illustrates the increase of NO and TVOC concentrations during the non-aeration period, while concentrations of CO<sub>2</sub> decreased during the non-aeration period and increased during the aeration phase of the plant. The contribution of the different periods to the total emissions (Table 2) was calculated by the amount of the component produced during the aeration phase and measured during the aeration phase ( $A_{II}F_{ae}$ ), and the amount of the component produced during the aeration phase but due to the carry-over of the gases measured during the non-aeration phase ( $A_{III}F_{nae}$ ) minus the amount of

the component that originates from the last non-aeration phase ( $A_{II}F_{ae}$ ) minus the intake air (Eq. (3)). The calculation was performed in the same way for the non-aeration period (Eq. (4)):

$$E_{ae} = A_{II}F_{ae} + A_{III}F_{nae} - A_{I}F_{ae}, \quad (3)$$

$$E_{nae} = A_{I}F_{ae} + A_{IV}F_{nae} - A_{III}F_{nae}. \quad (4)$$

$A_I$  and  $A_{III}$  were calculated by the integration of Eq. (2) and  $A_{II}$  and  $A_{IV}$  by Eq. (5) with  $n = 30$  for  $A_{II}$  and  $n = 60$  for  $A_{IV}$

$$A = \sum_{i=1}^n c_{\tau(i-1)}(\tau_i - \tau_{i-1}). \quad (5)$$

The results of the above calculations are included in Table 2. The relative contributions of NO, TVOC and CO<sub>2</sub> emitted during the non-aeration periods are 38, 34, and 17%, respectively. Yearly emissions of TVOC, NMHC, NO and POC per capita equivalent and the emission rates normalized to CO<sub>2</sub> are also given in Table 2. The yearly trace gas emissions were calculated from the normalized emission rates and on a basis of 27,400 g CO<sub>2</sub> per capita equivalent (accounts for wastewater from inhabitants and other sources). This basis is obtained from McInnes (1996).

### 3.1. Nitrogen oxides

Emission rates of NO obtained by the current study are approximately 0.58 g per capita equivalent per year (Table 2). Assuming that the operating conditions have the most important influence on the amount of NO emissions the variation of the emission rates with

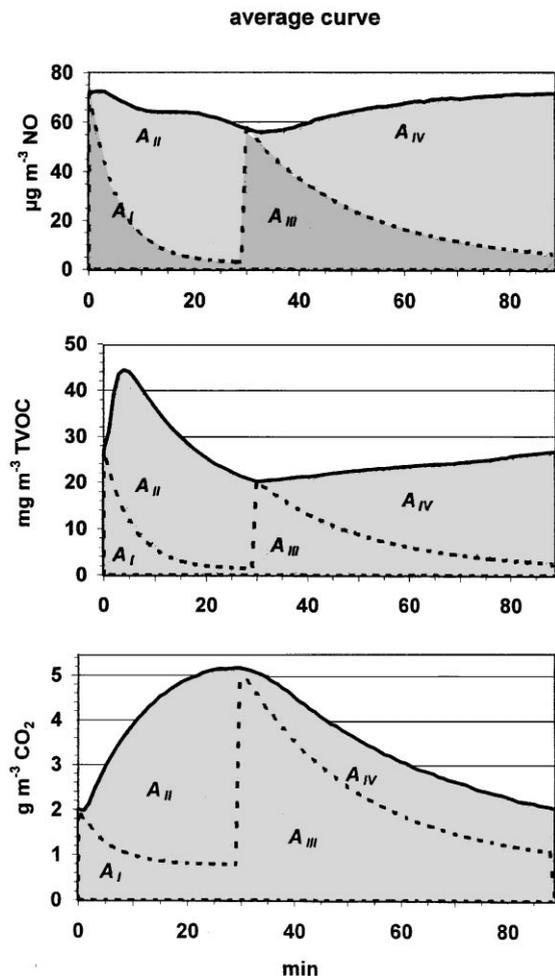


Fig. 1. a–c Average concentration changes of NO, TVOC, and CO<sub>2</sub> over the measuring period (—) and exponential dilution curves (---). A<sub>I</sub> and A<sub>II</sub> represent the whole area under the concentration curve and under the dotted line, respectively, for the aeration period from the beginning of the experiment until the 30th minute. A<sub>III</sub> and A<sub>IV</sub> stand for the whole area under the concentration curve and under the dotted line, respectively, for the non-aeration period, starting with the 30th minute and ending with the 90th minute of the aeration cycle.

different operating conditions was investigated. During a measuring period in January 1998 the WTP was operated under different working conditions (Fuerhacker et al., 2000). To compare the results of the different stages the emissions were put into relation to the inlet by dividing the NO emissions (mg NO d<sup>-1</sup>) by the amount of TOC in the inlet (g TOC d<sup>-1</sup>). The average NO emissions over the four different stages were 0.086 mg NO g<sup>-1</sup> TOC. Slightly higher emissions of 0.131 mg NO g<sup>-1</sup> TOC were obtained for stage I with low load and high aeration (aeration period: two hours, non-aeration

period: 1 h). Stage III operating under overloaded working conditions gave smaller emissions (0.053 mg NO g<sup>-1</sup> TOC). The results of the current study (0.081 mg NO g<sup>-1</sup> TOC) fit well to the emissions of stage II with balanced feed and aeration (0.078 mg NO g<sup>-1</sup> TOC). With a standard deviation of 0.033 a coefficient of variation of 38% is obtained. Even under very different operating conditions of the WTP the NO emissions are of the same order of magnitude 0.1 mg NO g<sup>-1</sup> TOC and an emission rate of  $0.58 \pm 0.22$  g NO per capita equivalent per year is obtained. A remarkable amount of this emission (38%) was produced during the non-aeration periods. This indicates a considerable outgassing during the non-aeration period, simultaneously with methane (Table 2).

### 3.2. Volatile organic compounds

Emissions of TVOC are 244 gC TVOC per capita equivalent per year (Table 2) or  $8.9 \times 10^{-3}$  gC TVOC g<sup>-1</sup> CO<sub>2</sub>. Tentative results showed that methane contributed more than 97% of the TVOCs. These results were obtained by removing the NMVOCs in the off-gas by adsorption on activated charcoal and detecting the remaining methane. Approximately, 66% of the TVOC emissions are produced during the aeration periods (Table 2). The increased emission (34%) during the non-aeration period in relation to CO<sub>2</sub> indicates that active outgassing of TVOC (presumably methane) proceeds during non-aeration.

The emission rate obtained in the present study (approximately 237 g methane per capita per year) corresponds well with the emission factors for emissions to air from WTPs of 300 g methane per capita equivalent (McInnes, 1996). This is in contrast to 39 g per person per year as determined by Czepiel et al. (1993) for a primary and secondary activated sludge treatment process.

Individual non-polar NMHC (C<sub>2</sub>–C<sub>7</sub>) were determined by GC–FID and accounted for 0.1% of emissions of TVOC. Polar organic compounds and higher hydrocarbons, which are supposed to contribute to the TVOC emissions, could not be determined with the applied technique. Converting the NMHC data (Sree et al., 2000) to the units used in Table 2, the WTP in the current study emits 0.18 gC NMHC per capita equivalent per year or  $6.6 \times 10^{-6}$  gC NMHC g<sup>-1</sup> CO<sub>2</sub> (or 0.005 g NMHC m<sup>-3</sup> wastewater). Emissions of aromatic HC, halocarbons and other VOC reported in the literature were much higher. Namkung and Rittmann (1987) estimated emissions of 11 aromatic HC and halocarbons of 0.032–0.036 g m<sup>-3</sup> wastewater, Bell et al. (1993) reported stripping rates of aromatic and halogenated VOCs in the same range (0.036–0.050 g m<sup>-3</sup> wastewater). Zhu et al. (1999) observed even emissions of eight VOCs of 40–100 g m<sup>-3</sup>, which consisted to 75% of acetone. The relatively low NMHC emissions in the present study

Table 2

Normalized emission rates, emissions per capita equivalent per year and contribution of the non-aeration period to the total emissions of the pilot wastewater treatment plant in Vienna

Parameter	Normalized emission	Emissions per capita equivalent	Emitted in non-aeration period (%)
CO <sub>2</sub>	1 g CO <sub>2</sub> g CO <sub>2</sub> <sup>-1</sup>	27400 g CO <sub>2</sub> <sup>a</sup>	17
TVOC	8.9 × 10 <sup>-3</sup> g TVOC g CO <sub>2</sub> <sup>-1</sup>	244 gC	34
C <sub>2</sub> -C <sub>7</sub> NMHC	6.6 × 10 <sup>-6</sup> g NMHC g CO <sub>2</sub> <sup>-1</sup>	0.18 gC	n.d.
NO	2.1 × 10 <sup>-5</sup> g NO g CO <sub>2</sub> <sup>-1</sup>	0.58 g NO	38
POC	3.0 × 10 <sup>-6</sup> gC g CO <sub>2</sub> <sup>-1</sup>	0.08 gC	n.d.

<sup>a</sup>McInnes (1996); TVOC: total gaseous organic carbon determined with FID. C<sub>2</sub>-C<sub>7</sub> NMHC: individual C<sub>2</sub>-C<sub>7</sub> hydrocarbons. n.d.: not determined.

might be explained by the fact that solvent discharge to wastewater is strictly regulated in Austria. Therefore, the NMHC emissions did not contain halogenated hydrocarbons (they were all below the detection limit of the method) and compared to the above studies low emissions of aromatic HC were obtained. More detailed results of the NMHC data of the current project are described elsewhere (Sree et al., 2000).

### 3.3. Particulate organic carbon

Due to the heavy aeration of activated sludge units and the aerosol formation caused by bursting bubbles (Woodcock, 1955), it was expected that sewage treatment plants are an important source of aerosol emissions. Surprisingly, emission rates of POC determined by the present study are quite low below 0.1 gC per capita equivalent per year (Table 2).

## 4. Conclusions

For the calculation of the emission rates it is assumed that mass transfer of the trace gases and aerosols of the pilot plant is comparable to a full-scale WTP. Nevertheless, the air-to-water ratio is much higher in the pilot plant and the surface area is larger and the reactor is more intensively mixed than a standard anoxic zone in a full-scale WTP. Taking these points into consideration would lead to rather smaller emission rates. Therefore, the emission rates determined in the present study (Table 2) have to be taken rather as upper limits for emissions from WTPs.

Applying a dilution model it was found that emissions of NO and TVOC are also produced during the non-aeration periods at approximately one-third of the total emissions. Since denitrification stages in European WTPs will be implemented until 2005 it can be predicted that trace emissions of NO and TVOC will increase in

the next years. Until now no emission rates of NO<sub>x</sub> and carbonaceous aerosols produced by WTPs are available in literature.

However, the contribution of emissions from WTPs to continental emissions, even in combination with denitrification stages, is expected to be very low. In Vienna (1.6 million population) total NO<sub>x</sub>-N emissions in 1995 were approximately 5000 t N (Umweltbundesamt Wien, 1995). The Vienna Main WTP processes an average daily wastewater load (including industry) corresponding to a capita equivalent of 3.4 million (Kainz and Hofstetter, 1996). The NO<sub>x</sub>-N emission from WTPs in Vienna – including the denitrification stages – is thus estimated to be not more than 0.9 ± 0.3 t N yr<sup>-1</sup>, which is < 0.02% of the total NO<sub>x</sub>-N emission.

Emissions of POC in Vienna are estimated to be less than 1 t yr<sup>-1</sup>, which is a very small contribution to the estimated emissions of particulate matter in Vienna of more than 10,000 t yr<sup>-1</sup> (Pucher and Rüdiger, 1997). Emissions of methane produced by WTPs in Vienna are estimated to be not more than 800 ± 300 t C yr<sup>-1</sup>. In Vienna total yearly emissions of methane are 51,200 t (Umweltbundesamt Wien, 1995) resulting in a maximum of 2% emitted by WTPs. Even after the implementation of denitrification stages in European treatment plants emissions of wastewater treatment plants will remain very low.

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## References

- Bell, J., Melcer, H., Monteith, H., Osinga, I., Steel, P., 1993. Stripping of volatile organic compounds at full-scale municipal wastewater treatment plants. *Water Environment Research* 65, 708–716.
- CEC1, 1991. Council Directive 91/271/EEC of 21 May 1991.
- Czepiel, P.M., Crill, P.M., Harriss, R.C., 1993. Methane emissions from municipal wastewater treatment processes. *Environmental Science and Technology* 27, 2472–2477.
- DEV, 1998. Deutsche Einheitsverfahren, Loseblattsammlung. Wiley-VCH, New York, Weinheim (Stand 1998).
- Fuerhacker, M., Bauer, H., Ellinger, R., Sree, U., Schmid, H., Zibuschka, F., Puxbaum, H., 2000. Approach for a novel control strategy for simultaneous nitrification/denitrification in activated sludge reactors. *Water Research* 34, 2499–2506.
- Kainz, H., Hofstetter, H., 1996. Adaption of the main wastewater treatment plant in Vienna to meet Austrian emission regulations. *Water Science and Technology* 33, 65–72.
- McInnes, G., 1996. Wastewater treatment. In: Joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook. European Environment Agency, Copenhagen, Denmark.
- Namkung, E., Rittmann, B.E., 1987. Estimating volatile organic compound emissions from publicly owned treatment works. *Journal of the Water Pollution Control Federation* 59, 670–678.
- Pucher, E., Rüdiger, H.W., 1997. Unsere Luft 1980 bis 2010. Publikation der ÖAMTC AKADEMIE, Österreichischer Automobil-, Motorrad- und Touring Club, Vienna.
- Puxbaum, H., Rendl, J., 1983. Ein automatisches Analysatorsystem zur Bestimmung von Kohlenstoff und Schwefel in luftgetragenen Stäuben. *Mikrochimica Acta* 1983I, 263–272.
- Sree, U., Bauer, H., Fuerhacker, M., Ellinger, R., Schmid, H., Puxbaum, H., 2000. Hydrocarbons emissions from a Municipal wastewater treatment pilot plant in Vienna. *Water, Air and Soil Pollution* 124 (1–2).
- Umweltbundesamt Wien, 1995. Die Bundesländer Luftschadstoff-Inventur. Inventory of Austrian Federal States – BLI 95.
- Woodcock, A.H., 1955. Bursting bubbles and air pollution. *Sewage and Industrial Wastes* 27, 1189–1192.
- Zhu, H., Keener, T.C., Bishop, P.L., Orton, T.L., Wang, M., 1999. Temporal and longitudinal characteristics of volatile organic compound emissions from aeration units of publicly owned treatment works. *Journal of the Air and Waste Management Association* 49, 434–443.