

## Practical Paper

# NDMA and seven other nitrosamines in selected UK drinking water supply systems

Michael R. Templeton and Zhuo Chen

### ABSTRACT

A survey for N-nitrosodimethylamine (NDMA) and seven other nitrosamines in six UK drinking water supply systems was conducted. At the time of the study, there was no NDMA data for UK drinking waters, and the study remains one of few globally to report concentrations of the other seven nitrosamines in water supply systems. Five of the six water supply systems were selected as probable to have elevated nitrosamine concentrations because of the known source water characteristics and/or treatment practices; the sixth supply system had none of the suspected risk factors and was included as a control case. Sampling was conducted in five intervals and included samples collected from the source water, post-filter, post-disinfection and the distribution system. NDMA was measured barely above the method detection limit ( $0.9 \text{ ng l}^{-1}$ ) in a few isolated samples in one distribution system; however, otherwise the majority of samples contained no detectable NDMA or other nitrosamines. An exception was that N-nitrosodibutylamine (NDBA) was consistently detected in one distribution system, up to a maximum concentration of  $6.4 \text{ ng l}^{-1}$ . There were no identifiable relationships to link source water characteristics, the particular treatment processes or distribution system contact time with the observed nitrosamine concentrations.

**Key words** | disinfection by-products, distribution system, nitrosamines, N-nitrosodimethylamine (NDMA)

**Michael R. Templeton** (corresponding author)  
**Zhuo Chen**  
Department of Civil and Environmental  
Engineering,  
Imperial College London,  
South Kensington campus,  
London SW7 2AZ,  
UK  
Tel.: +44(0)2075946099  
Fax: +44(0)2075941511  
E-mail: [m.templeton@imperial.ac.uk](mailto:m.templeton@imperial.ac.uk)

### INTRODUCTION

Disinfection by-products (DBPs) are formed by the reaction of chemical disinfectants (e.g. chlorine) with organic precursor compounds (e.g. natural organic matter). Currently only one class of chlorination DBPs, the trihalomethanes (THMs), must be monitored by UK water companies, with a minimum of four samples collected per water zone per year and the current regulated limit for total THMs in tap water set at  $100 \mu\text{g l}^{-1}$ . Another class of DBPs in drinking water for which there is currently very limited occurrence data globally and in the UK specifically are the nitrosamines. Nitrosamines have been shown to have much higher cancer potencies than the currently regulated

drinking water DBPs (Mitch *et al.* 2003). Due to the demonstrated genotoxic carcinogenicity of NDMA even at very low levels (parts per trillion), regulators have introduced preliminary treatment goals for NDMA and are currently collecting data to set appropriate regulations. In the USA, the state of California has set an action level of  $10 \text{ ng l}^{-1}$  for NDMA (CEPA 2006). The California Department of Health Services had also instituted drinking water notification levels for two other nitrosamine compounds (N-nitrosodiethylamine, N-nitrosodipropylamine) at  $10 \text{ ng l}^{-1}$  (CDHS 2006). The United States Environmental Protection Agency (USEPA) has estimated a  $10^{-6}$  cancer

doi: 10.2166/aqua.2010.077

risk level from NDMA in drinking water at  $0.7 \text{ ng l}^{-1}$  but has not yet established a drinking water maximum contaminant level (USEPA 1997). In Canada, the province of Ontario has set an interim maximum acceptable concentration for NDMA at  $9 \text{ ng l}^{-1}$  (Ontario MOE 2000). At the beginning of this study, there was virtually no information on the occurrence of NDMA or any other nitrosamines in UK drinking waters.

Furthermore, very few studies to date have investigated the occurrence of other nitrosamines besides NDMA, and no regulatory limits or guidelines have been proposed for many of these compounds, despite the fact that other nitrosamines are believed to be of comparable carcinogenicity to NDMA (Ljinsky 1994). Seven nitrosamines (including NDMA) are listed on the USEPA Screen Survey List 2 of unregulated contaminants for which data collection and monitoring is a priority: N-nitrosodimethylamine (NDMA), N-nitrosomethylethylamine (NMEA), N-nitrosodiethylamine (NDEA), N-nitroso-di-n-propylamine (NDPA), N-nitroso-di-n-butylamine (NDBA), N-nitrosopyrrolidine (NPYR), and N-nitrosopiperidine (NPIP) (USEPA 2005). Results from two studies have suggested that the concentrations of the other nitrosamines in drinking water are typically lower than NDMA levels, although the reasons for this are unclear (Charrois *et al.* 2004; Valentine *et al.* 2004).

Certain drinking water treatment processes have been shown to be more likely to form NDMA. Disinfection with monochloramine is generally shown to form higher levels of

NDMA than disinfecting with free chlorine, for a given water matrix (Mitch *et al.* 2003; Valentine *et al.* 2004). Also, the chlorination of waters that have been coagulated with amine-based coagulants (e.g. poly-DADMAC) can form NDMA (Kohut & Andrews 2003; Wilczak *et al.* 2003) and the use of certain cation exchange resins may produce dimethylamine (DMA), which is an NDMA precursor (Najm & Trussell 2001). However, more data and understanding is needed regarding the relative effect of treatment processes and distribution on the formation and occurrence of NDMA and other nitrosamines.

## RESEARCH OBJECTIVES

The primary objective of this study was to select six UK water supply systems, in collaboration with five water company partners, to carry out a sampling and analysis programme for NDMA and seven other nitrosamine compounds—N-nitrosomethylethylamine (NMEA), N-nitrosodiethylamine (NDEA), N-nitroso-di-n-propylamine (NDPA), N-nitroso-di-n-butylamine (NDBA), N-nitrosopyrrolidine (NPYR), N-nitrosopiperidine (NPIP), and N-nitrosomorpholine (NMOR) (Figure 1)—in the source, treated and distributed waters, in order to increase the understanding of the occurrence and formation of NDMA and other nitrosamines in UK water supply systems and to contribute to the still relatively sparse global database of information on nitrosamines in drinking water. Another objective was

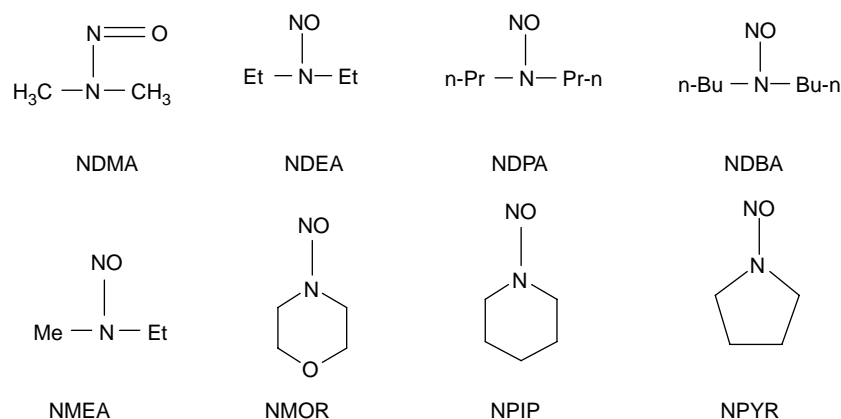


Figure 1 | Chemical structures of the eight nitrosamines analysed in this study.

to attempt to relate the observed nitrosamine concentrations to source water characteristics, treatment practices and/or distribution system contact time, if possible.

## MATERIALS AND METHODS

### Sampling campaign and description of water supply systems

Samples were collected by personnel from water company partners and shipped to London for analysis at Imperial College. Samples were collected from the raw source water (i.e. entering the water treatment plant), pre-disinfection (i.e. after filtration), the final treated water (i.e. post-disinfection, leaving the treatment plant) and distributed water (i.e. collected from multiple points in the distribution system). Samples were collected in amber glass 1-litre bottles containing ascorbic acid to quench any disinfectant residual and therefore prevent further formation of nitrosamines during sample shipment and storage. Samples were shipped in coolers packed with ice packs and received at Imperial College within one day of sampling, where they were refrigerated at 4°C until extraction, which took place within one week of receipt of the samples. Samples were collected and analysed in February 2008, May 2008, September 2008, December 2008 and February 2009.

Representative source water quality characteristics of the six water supply systems (WSS) as measured in one of the sampling periods (May 2008) are given in Table 1. Standard methods for the analysis of these water quality parameters were followed (*Standard Methods 2005*). Historical water quality data from the water company

partners was also collected and was used to inform the site selection process at the beginning of the project.

The treatment processes applied by each water supply system (WSS) are summarised in Table 2, including a description of the risk factors that were suspected to favour nitrosamine formation in each system. WSS F had none of the risk factors and was included as a control site.

### Analytical methods

All nitrosamines were analysed using a solid phase extraction, isotope dilution gas chromatography mass spectrometry method similar to the method described by Taguchi *et al.* (1994). Briefly, 0.5l of water sample was extracted with 125 mg of carbonaceous polymeric beads (Ambersorb 483, Aldrich) by shaking for one hour at 200 rpm. The Ambersorb beads were then vacuum-filtered onto a glass fibre filter. After air drying for 30 minutes, the beads were transferred to a 2-ml amber vial fused with a 400 µl glass insert. Methylene chloride (250 µl) was added to extract the adsorbate. A 5 µl aliquot of methylene chloride extract was injected into a Perkin-Elmer Clarus-500 GC/MS equipped with a programmable large-volume injector and a DB1701 capillary column. *d*<sup>6</sup>-NDMA was used as the internal standard. Quantifications were accomplished using selective ion monitoring based on the characteristic mass peaks of the nitrosamines. The achieved method detection limits (MDLs) were 0.9 ng l<sup>-1</sup> for NDMA, 2.4 ng l<sup>-1</sup> for NDEA, 4.4 ng l<sup>-1</sup> for NDPA, 3.2 ng l<sup>-1</sup> for NDBA, 4.0 ng l<sup>-1</sup> for NMOR, 2.5 ng l<sup>-1</sup> for NPIP, 4.1 ng l<sup>-1</sup> for NPYR, and 2.1 ng l<sup>-1</sup> for NMEA, which were deemed to be acceptable for the purposes of this survey.

**Table 1** | Representative source water quality data for the six water supply systems (WSS) in this study, as measured in May 2008

WSS	Source	pH	DOC (mg/L)	UV <sub>254</sub> (cm <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg/L)	Turbidity (NTU)
A	Peaty lowland river	7.4	8.1	0.20	13.20	3.1
B	Upland reservoir	4.7	9.5	0.17	0.36	5.2
C	Upland reservoir	6.4	17.9	0.30	0.29	8.6
D	Moorland river + reservoir	6.5	18.5	0.27	0.77	6.4
E	Reservoir	7.9	9.5	0.16	37.50	3.2
F	Groundwater	7.1	2.9	0.03	0.11	11.6

**Table 2** | Summary of the treatment processes for the six water supply systems in this study, and the suspected nitrosamine formation risk factors

WSS	Treatment processes	Suspected nitrosamine formation risk factors
A	Coagulation, flocculation, rapid gravity filtration, chlorine gas and ammonia, pH correction with lime slurry	Organic-rich source water, chloramination
B	Coagulation with ferric sulphate, pH correction, dissolved air flotation, primary filtration, ammonia removal by breakpoint chlorination with sodium hypochlorite, secondary filtration, chlorination, phosphate dosing	Organic-rich source water, breakpoint chlorination to remove ammonia
C	Coagulation, pH correction, polyacrylamide addition, clarification, chlorination, rapid gravity filtration, pH correction, chlorination (30 minutes contact time), ammonia addition for chloramination	Organic-rich source water, chloramination
D	Magnetite addition to remove colour and turbidity, coagulation with polyDADMAC, high rate clarification, pH correction, chlorination, rapid gravity filtration, chlorination	Organic-rich source water, polyDADMAC coagulant
E	Coagulation with ferric coagulant, polyacrylamide, and epi-DMA, rapid gravity filtration, granular activated carbon adsorption, chlorination	Organic-rich and nitrogen-rich source water, epi-DMA coagulant
F	Aeration for iron removal, pressurised sand filtration, gas chlorination, fluoridation, orthophosphoric acid dosing	No risk factors

### Quality assurance and quality control

Each water sample was analysed in triplicate, to ensure data quality and reproducibility. Method and analytical blanks and spike and recovery tests were run as quality assurance and quality control measures to rule out intrusive sinks or sources of nitrosamines. Selected samples were also sent to a certified commercial laboratory in the UK for comparison analysis of the measured NDMA concentrations, which closely confirmed the results to within an acceptable difference ( $\pm 1 \text{ ng l}^{-1}$ ) and provided confidence in the analytical methods.

## RESULTS AND DISCUSSION

In the first sampling round in February 2008, NDMA and several other nitrosamines, such as NDPA, NDBA and NMOR, were detected above the MDLs; the maximum NDMA concentration detected in this sampling round was  $26.3 \text{ ng l}^{-1}$ , which was measured at the distant end of the distribution network of WSS A. However, these elevated nitrosamine concentrations were not repeated in subsequent sampling rounds, including another February

sampling in 2009 (e.g. see Table 3). The reason for the abnormally elevated measurements during the February 2008 sampling round compared with subsequent rounds is not known for certain; however, the fact that the nitrosamine levels in the first round were higher for all WSSs, including the control site (WSS F), and that nitrosamines were detected even in the raw water samples, suggests a consistent analytical instrument bias during that sampling round. Therefore, the data for the February 2008 sampling round, while included here for completeness, should be regarded with scepticism.

Neglecting the questionable nitrosamine detections in the first sampling round, NDMA was then detected above the MDL at only one of the six water supply systems in the subsequent four sampling rounds. This NDMA detection was at WSS E at the sampling point at the furthest point of the distribution system, in both September and December 2008, at  $1.0 \text{ ng l}^{-1}$  (Table 3). No NDMA or other nitrosamines were detected at WSS F, the control site, as anticipated.

A surprising finding was that N-nitrosodibutylamine (NDBA) was consistently detected above the MDL in the distribution system of WSS B (Table 4). To our knowledge,

**Table 3** | Quantification of NDMA and other nitrosamines in WSS E in ng l<sup>-1</sup>, February 2008 to February 2009

Sample point	Sample date	NDMA	NDEA	NDPA	NDBA	NMOR	NPIP	NPYR	NMEA
Raw	Feb. 2008	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May 2008	< MDL*	0.0	< MDL	< MDL	< MDL	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Dec. 2008	0.0 <sup>†</sup>	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Feb. 2009	0.0	0.0	0.0	< MDL	< MDL	0.0	0.0	0.0
Pre-chlorination	Feb. 2008	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May 2008	< MDL	0.0	< MDL	< MDL	< MDL	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	< MDL	< MDL	0.0	0.0	0.0
	Dec. 2008	< MDL	0.0	< MDL	< MDL	0.0	0.0	0.0	0.0
	Feb. 2009	< MDL	0.0	< MDL	< MDL	0.0	0.0	0.0	0.0
Final disinfected	Feb. 2008	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May 2008	< MDL	0.0	< MDL	< MDL	< MDL	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	< MDL	< MDL	0.0	0.0	0.0
	Dec. 2008	< MDL	0.0	< MDL	< MDL	< MDL	0.0	0.0	0.0
	Feb. 2009	< MDL	0.0	< MDL	< MDL	0.0	0.0	0.0	0.0
Distribution system near the treatment plant	Feb. 2008	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May 2008	< MDL	0.0	< MDL	< MDL	< MDL	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	< MDL	< MDL	0.0	0.0	0.0
	Dec. 2008	< MDL	0.0	< MDL	< MDL	< MDL	0.0	0.0	0.0
	Feb. 2009	< MDL	0.0	< MDL	< MDL	0.0	0.0	0.0	0.0
Distribution system further from the treatment plant	Feb. 2008	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	May 2008	< MDL	0.0	< MDL	< MDL	< MDL	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	< MDL	< MDL	0.0	0.0	0.0
	Dec. 2008	< MDL	0.0	< MDL	< MDL	< MDL	0.0	0.0	0.0
	Feb. 2009	< MDL	0.0	< MDL	< MDL	0.0	0.0	0.0	0.0
Distribution system furthest from the treatment plant	Feb. 2008	15.6	0.0	0.0	0.0	10.0	0.0	0.0	0.0
	May 2008	< MDL	0.0	< MDL	< MDL	< MDL	< MDL	0.0	0.0
	Sep. 2008	1.0	0.0	0.0	< MDL	< MDL	0.0	0.0	0.0
	Dec. 2008	1.0	0.0	< MDL	< MDL	< MDL	0.0	0.0	0.0
	Feb. 2009	< MDL	0.0	< MDL	< MDL	0.0	0.0	0.0	0.0

\*Discernible peak but below the method detection limit.

†No discernible peak above detector noise.

this is the first reported occurrence of NDBA in drinking water. Unfortunately, the sampling at WSS B had to be discontinued beyond September 2008 because the treatment works was taken out of service for routine maintenance work, but the consistent occurrence of NDBA in this system suggests the presence of NDBA precursors in the source water or possibly resulting from chemicals that are used at the treatment works (e.g. coagulant or polymer solutions). However, the identification of specific NDBA sources was beyond the scope of this survey study.

Since the vast majority of nitrosamine concentrations in this study were zero or less than the MDLs, it was impossible to obtain correlations between nitrosamine concentrations and the source water characteristics or treatment or distribution practices. The reasons for the relatively rare UK occurrence of NDMA, and then only at very low levels, when compared with NDMA occurrence reported in other countries (e.g. USA, Canada) are not known for certain. Differences in disinfection practices may be an explanation. For example, it is more common in the UK to post-ammoniate after a set chlorine contact time

**Table 4** | Quantification of NDMA and other nitrosamines in WSS B in  $\text{ng l}^{-1}$ , February 2008 to September 2008

Sample point	Sample date	NDMA	NDEA	NDPA	NDBA	NMOR	NPIP	NPYR	NMEA
Raw	Feb. 2008	6.0	0.0	0.0	11.6	42.8	0.0	0.0	0.0
	May 2008	< MDL	0.0	0.0	< MDL	0.0	< MDL	0.0	0.0
	Sep. 2008	0.0	0.0	0.0	< MDL	0.0	0.0	0.0	0.0
Pre-chlorination	Feb. 2008	< MDL	0.0	0.0	< MDL	8.0	0.0	0.0	0.0
	May 2008	< MDL	0.0	0.0	3.8	0.0	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	< MDL	0.0	0.0	0.0	0.0
Final disinfected	Feb. 2008	< MDL	0.0	0.0	< MDL	7.4	0.0	0.0	0.0
	May 2008	< MDL	0.0	0.0	< MDL	0.0	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	< MDL	0.0	0.0	0.0	0.0
Distribution system near the treatment plant	Feb. 2008	< MDL	0.0	0.0	10.0	10.9	0.0	0.0	0.0
	May 2008	< MDL	0.0	0.0	4.2	0.0	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	4.0	0.0	0.0	0.0	0.0
Distribution system further from the treatment plant	Feb. 2008	12.7	0.0	0.0	11.9	< MDL	0.0	0.0	0.0
	May 2008	< MDL	0.0	0.0	3.3	0.0	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	4.9	0.0	0.0	0.0	0.0
Distribution system furthest from the treatment plant	Feb. 2008	7.2	0.0	0.0	18.8	6.9	0.0	0.0	0.0
	May 2008	< MDL	0.0	0.0	5.4	0.0	< MDL	0.0	0.0
	Sep. 2008	< MDL	0.0	0.0	6.4	0.0	0.0	0.0	0.0

(often 30 minutes) rather than chloraminating in one step. Also, the disinfectant concentrations in North America (e.g. up to  $4.0 \text{ mg l}^{-1}$  for chloramines) are often higher than those typically applied in the UK (e.g.  $0.5 \text{ mg l}^{-1}$  for chloramines). The fact that none of the source waters of the water supply systems included in this study is directly impacted by wastewater effluents may also have been a factor; it has been shown that wastewater effluents can be significant contributors to NDMA occurrence in downstream water treatment works (Krasner *et al.* 2008).

Given that this study examined nitrosamine levels in water supply systems that were suspected to have higher than normal nitrosamine levels, the overall results suggest that the levels of nitrosamines in most other UK water supply systems that are not directly impacted by wastewater effluents are unlikely to exceed the action levels for NDMA that are recommended by various regulatory agencies (e.g. Ontario MOE 2000; CDHS 2006; WHO 2006) nor the September 2008 Drinking Water Inspectorate (DWI) for England and Wales 'wholesomeness' limit of  $10 \text{ ng l}^{-1}$  for NDMA above which measures must be put in place to reduce the NDMA level (DWI 2008). A broader industry survey for NDMA alone (no other nitrosamines) was

conducted during the same period as this study and detected NDMA in only 3 of 41 water supply systems in England and Wales (Dillon *et al.* 2008); NDMA detections in that study were attributed to a direct source of NDMA contamination coming from a ferric-based coagulant solution that was common to the treatment practice at the affected sites. Therefore, the results of Dillon *et al.* (2008) support the very low and rare NDMA occurrence that was observed at the water supply systems in this study.

## CONCLUSIONS

NDMA was measured barely above the method detection limit ( $0.9 \text{ ng l}^{-1}$ ) at one of the six WSSs (WSS E); however, otherwise the vast majority of samples from the six UK water supply systems contained no detectable nitrosamines. An exception was NDBA, which was consistently detected in distribution in one of the water supply systems (WSS B), up to a maximum concentration of  $6.4 \text{ ng l}^{-1}$ . There were no identifiable relationships to link source water quality characteristics or the particular treatment or distribution practices with the observed nitrosamine concentrations

(or lack thereof). Overall, and taken into consideration alongside the findings of a broader UK survey for NDMA (Dillon *et al.* 2008), the results of this study suggest that nitrosamines are usually not expected to be present at concentrations exceeding the wholesomeness limit of  $10\text{ ng l}^{-1}$  for NDMA as set by the regulator for England and Wales (DWI 2008), with the possible exception of source waters that are directly impacted by wastewater effluents, which was not included in this study.

## ACKNOWLEDGEMENTS

This research was funded by the Engineering and Physical Sciences Research Council (EPSRC). The authors thank their water company partners for providing samples and information regarding their water treatment and distribution practices. The authors also thank Professor Susan Andrews of the University of Toronto for her advice and assistance with the analytical component.

## REFERENCES

- CDHS (California Department of Health Services) 2006 *Drinking Water Notification Levels and Response Levels: An Overview*, 28 June 2006. CDHS, Sacramento, California.
- CEPA (California Environmental Protection Agency) 2006 *Public Health Goal for N-nitrosodimethylamine in Drinking Water: Draft for Review*. Office of Environmental Health Hazard Assessment, Sacramento, California.
- Charrois, J. W., Arend, M. W., Froese, K. L. & Hrudey, S. E. 2004 Detecting N-nitrosamines in drinking water at nanogram per liter levels using ammonia positive chemical ionization. *Environ. Sci. Technol.* **38**(18), 4835–4841.
- Dillon, G., Blake, S., Rumsby, P., Rockett, L., Hall, T., Jackson, P. & Rawlinson, A. 2008 *NDMA: Concentrations in Drinking Water and Factors Affecting its Formation*, Defra Report 7348, March 2008. Defra, London.
- DWI (Drinking Water Inspectorate) 2008 *Guidance on the Water Supply (Water Quality) Regulations 2000 Specific to N-nitrosodimethylamine (NDMA) Concentrations in Drinking Water*. DWI, London.
- Kohut, K. D. & Andrews, S. A. 2003 Polyelectrolyte age and N-nitrosodimethylamine formation in drinking water treatment. *Water Qual. Res. J. Can.* **38**(4), 719–735.
- Krasner, S. W., Scilimenti, M. J., Lee, C. F. T. & Schramm, J. 2008 *Formation of nitrosamines in effluent-impacted drinking waters*. *ACS Symp. Ser.* **995**, 304–318.
- Ljinsky, W. 1994 Chemical structure of nitrosamines related to carcinogenesis. *Nitrosamines and Related N-nitroso Compounds: Chemistry and Biochemistry*. ACS, Washington, DC, pp. 250–266.
- Mitch, W. A., Sharp, J. O., Trussell, R. R., Valentine, R. L., Alvarez-Cohen, L. & Sedlak, D. L. 2003 *N-nitrosodimethylamine (NDMA) as a drinking water contaminant: a review*. *Environ. Eng. Sci.* **20**(5), 389–404.
- Najm, I. & Trussell, R. R. 2001 NDMA formation in water and wastewater. *J. Am. Water Works Assoc.* **93**(2), 92–99.
- Ontario MOE (Ministry of the Environment) 2000 *Regulation made under the Ontario Water Resources Act: drinking water protection—large water works*, 26 August 2000, MOE, Toronto.
- Standard Methods for the Examination of Water and Wastewater* 2005 21st edition, American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC.
- Taguchi, V. Y., Jenkins, S. W. D., Wang, D. T., Palmentier, J. F. P. & Reiner, E. J. 1994 Determination of N-nitrosodimethylamine by isotope dilution, high-resolution mass spectrometry. *Can. J. Appl. Spectrosc.* **39**, 87–93.
- USEPA (United States Environmental Protection Agency) 1997 N-nitrosodimethylamine CASRN 62-75-9, integrated risk information service, substance file. USEPA, Washington, DC.
- USEPA 2005 Unregulated contaminant monitoring regulation for public water systems revisions, proposed rule. *Fed. Regist.* **70**(161), 49094–49138.
- Valentine, R. L., Choi, J., Chen, Z., Barrett, S. E., Hwang, C., Guo, Y., Whener, M., Fitzsimmons, S., Andrews, S. A., Weker, A. G., Brubacher, C. & Kohut, K. 2004 *Factors Affecting the Formation of NDMA in Water and Occurrence*. American Water Works Association Research Foundation, Water Environment Federation, Denver, Colorado, Alexandria, Virginia.
- WHO (World Health Organisation) 2006 *N-nitrosodimethylamine in Drinking Water: Background Document for Development of WHO Guidelines for Drinking Water Quality*. WHO, Geneva.
- Wilczak, A., Assadi-Rad, A., Lai, H. H., Hoover, L. L., Smith, J. F., Berger, R., Rodigari, F., Beland, J. W., Lazzelle, L. J., Kincannon, E. G., Baker, H. & Heaney, C. T. 2003 Formation of NDMA in chloraminated water coagulated with DADMAC cationic polymer. *J. Am. Water Works Assoc.* **95**(9), 94–106.

First received 31 July 2009; accepted in revised form 18 December 2009