DEFRA

# REVIEW OF THE CURRENT TOXICOLOGICAL AND OCCURRENCE INFORMATION AVAILABLE ON IODINATED DISINFECTION BY-PRODUCTS

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# REVIEW OF THE CURRENT TOXICOLOGICAL AND OCCURRENCE INFORMATION AVAILABLE ON IODINATED DISINFECTION BY-PRODUCTS

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# SUMMARY


## I OBJECTIVES

The general objectives of this project were (a) to review existing data on concentrations of iodinated disinfection by-products (DBPs), iodide and bromide in drinking water and its sources in the UK and worldwide, identifying any key factors that give rise to high concentrations of iodinated DBPs; (b) where UK occurrence data are lacking, estimate mean and maximum concentrations of iodinated DBPs likely to occur in UK drinking water, based on knowledge of disinfection and other treatment processes, data on levels of iodide in raw waters, and on levels of chlorinated or brominated DBPs and any other relevant factors; (c) to review existing knowledge of toxicity of the iodinated DBPs identified and if possible conduct a high level risk assessment; (d) to consider the availability of methods of analysis for the iodinated DBPs identified; (e) to devise a priority list of iodinated DBP for future research on occurrence within the UK drinking waters.

## II REASONS

Studies in the USA have identified low levels of iodinated DBPs in drinking water. Concern has been raised that these compounds may be more toxic than chlorinated and brominated DBPs. However, the dataset on the toxicity of these compounds is far from complete. The conditions required for the production of iodinated DBPs are, at present, unknown in the UK and there is thought to be little data on the concentrations of iodinated DBPs in environmental and drinking water.

## III CONCLUSIONS

- **Toxicity** - Concern has arisen that iodinated-DBPs are of greater toxicological concern than their brominated and chlorinated analogues. This view is predominantly based on non-regulatory research *in vitro* cytotoxicity and genotoxicity assays as a dataset of basic toxicological information on the iodinated-DBPs is not available. This lack of basic toxicological data makes any sound assessment of the risk posed by iodinated DBPs in drinking water impossible.

- **Analytical methods** - Although there is increasing interest in iodinated DBPs and more monitoring is likely to be undertaken, at present the analytical methodology is research-based. Sensitive methods may need to be developed for the measurement in water of a number of different iodinated compounds, including iodoacids and iodoform

- **Potential Concentrations in UK drinking water** - There is no evidence that iodide levels are higher in the UK than those detected in the USA. There is evidence that the formation of iodinated DBPs is increased by chloramination and reduced by ozonation and that iodinated-THMs may be removed by GAC to some extent. Chloramination is not common in the UK while ozonation and GAC are widely used. Taking all this information, together with modelling which estimates the formation of iodinated DBPs and limited monitoring data, it appears likely that the levels of iodinated DBPs in England and Wales will be no higher and will probably be lower than the low concentrations detected in the USA. It should be noted that the introduction of a standard for haloacetic acids in England and Wales may lead to an increased use of chloramination and if this occurred, further consideration of the concentration of iodinated DBPs in drinking water would be advisable.

## IV RECOMMENDATIONS

- **Toxicology** - The potential genotoxicity of iodinated DBPs has generated much interest in these compounds and it will be important to expand the dataset on iodinated DBPs using more conventional toxicological methods. Further studies are now being carried out in the USA and it will be important to monitor their progress

- **Monitoring and Analysis** – At present, conditions in the UK indicate that iodinated DBPs are likely to be present at low concentrations. If the use of chloramination in the treatment of drinking water increased, then the formation of iodinated DBPs is also likely to increase. In this case there might be a need for the development of robust methods for the detection of iodinated DBPs. Monitoring in different water conditions and drinking water treatment processes could also then be considered, particularly those which may affect the production of iodinated DBPs such as chloramination, ozonation and GAC.

- It would be useful to have a good study of iodide concentrations in environmental waters, in particular, where there is abstraction for drinking water. This would enable the identification of any area of high iodide where the likelihood of iodinated DBPs production may be increased during drinking water treatment.

- **Prioritisation of iodinated DBPs for future work** - The prioritisation of iodinated DBPs for future study depends considerably on the results of further toxicity testing. It does appear that iodoacids, iodoform and iodate may be of greater toxic potential than iodinated THMs although this remains to be confirmed. It appears that the presence of iodide (a role for bromide, if any, is as yet unclear) in the source water and chloramination in the drinking water treatment process may increase the likelihood of iodinated DBP formation. Unfortunately current surveys of iodide levels in environmental waters have not yielded data that will enable the identification of areas of the UK with higher iodide levels which may be of greater risk for iodinated DBP production. Gathering of this basic information may be the priority before the identification of iodinated DBPs of particular importance for further research.

# 1. INTRODUCTION

It is stated that there are more than 500 disinfection by-products (DBPs) reported in the literature produced from current drinking water disinfection processes i.e. chlorination, ozonation, chlorine dioxide and chloramination, including in combination. Out of these DBPs identified, only a limited number had been quantified in drinking water. In 2002, this led to the completion of a nationwide survey in the USA, of the occurrence of DBPs (Weinberg *et al*., 2002). This study highlighted the occurrence of a number of iodinated DBPs. The five that were identified in finished drinking water were: iodoacetic acid; bromoiodacetic acid; (Z)-3-bromo-3-iodopropenoic acid; (E)-3-bromo-3-iodopropenoic acid; and (E)-2-iodo-3-methylbutenedioic acid. Also, iodinated trihalomethanes (THMs) were identified as DBPs in chlorinated and chloraminated drinking water these were as follows: dichloroiodomethane; bromochloroiodomethane; dibromoiodomethane; chlorodiiodomethane; bromodiiodomethane; and iodoform (Richardson *et al*., 2007).

Concern has arisen due to there being evidence to suggest that these iodinated-DBPs are of greater toxicological concern than their brominated and chlorinated analogues (Richardson *et al*., 2007). This view is predominantly based on non-regulatory research *in vitro* cytotoxicity and genotoxicity assays, as a dataset of basic toxicological information on the iodinated-DBPs is not available at present, and therefore has a relatively weak basis.

It is understood that the production of iodinated DBPs is greatly influenced by the levels of iodide and bromide in the raw source water as well as the disinfection process used. In the 2001-2002 US survey it was reported that in several US cities where the water was chloraminated, iodinated DBPs were detected (Richardson *et al*., 2007). Iodinated-THMs were also found to be formed in drinking water that had been treated with chlorine or chloramines where there was natural iodide present in the source water (Richardson *et al*., 2007). Levels of individual iodinated-acids were almost always below-µg/l levels and typically ng/l and tens ng/l levels, with iodinated-THMs consistently at µg/l and levels as high as 15 µg/l at one location in this specific survey. However, in the US study dichloroiodomethane was the most commonly detected iodinated-THM detected and was found in all states sampled, and it was detected in waters where bromide levels were not high and where consequently iodide concentrations would be expected to be low (Richardson *et al*., 2007).

In the UK as with the rest of the world, there is an increasing demand for water; therefore there could be the need to use raw water sources that have higher iodide levels. This could lead to the increased formation of iodinated DBPs. From research conducted at WRc, iodinated DBPs have been detected in drinking water in particular dichloroiodomethane and bromochloroiodomethane (Fielding *et al*., 1981). However, these results were qualitative rather than quantitative, but they appeared to be present at lower concentration than the chlorinated and brominated THMs. A recent Scottish study has confirmed this observation (Parsons *et al*., 2009).

Iodinated-THMs are associated with causing taste and odour problems at concentration ranges as low as 0.02-0.5 µg/l (Richardson *et al*., 2007). Therefore, it is considered that the presence or absence of unexplained taste and odour effects can be a good indication of the occurrence of iodinated DBPs, in particular iodinated-THMs at or about the threshold concentrations.

To carry out this review, all 26 UK water companies and the Environment Agency have been contacted and information regarding monitoring of iodinated DBPs, levels of iodide and bromide in the raw water, treatment processes used and any taste and odour effects associated with iodinated DBPs has been collected and collated. Also, data from the literature on studies carried out in the UK and worldwide have been located and levels of iodinated DBPs from these has been reported. All these data were used to estimate areas of the UK that might be at risk of having elevated levels of iodinated DBPs. This was then compared to the available toxicological data and a high level risk assessment was carried out using the occurrence of iodinated DBPs and their associated toxicological concern. A priority list has been produced highlighting areas of concern and points for further research.

# 2. EXISTING DATA ON CONCENTRATIONS OF IODINATED DISINFECTION BY-PRODUCTS IN DRINKING WATER IN THE UK AND WORLDWIDE

There has been an increasing amount of work carried out in the US concerning the occurrence of DBPs in drinking water and in particular iodinated DBPs as emerging drinking water contaminants.

Trihalomethanes (THMs) are formed via the reaction between natural organic material in raw water and chlorine used in the drinking water treatment process. Although chlorinated, brominated and mixed chlorobromo-derivatives are the most common DBPs reported, iodinated-THMs are also formed when iodide is present (Cancho *et al*., 2000).

## 2.1 Data from the literature

Iodinated-THMs have been identified in drinking water from around the world. For example, dichloroiodomethane has been reported to be detected in 85 out of 111 USA water supplies and is reportedly more commonly than bromoform (Cancho *et al*., 2000). Several iodinated-DBPs have been detected in recycled water which has been treated with iodine. The practice of adding iodine to water is not considered to be common place and is certainly not used in the UK. However, it can be used in emergency situations, and the military are known to use it as a purification method whilst out in the field and there has been reference to its use on space missions. Therefore, the use of iodine to treat water is not considered as a large scale process. Additionally iodinated substances have been frequently been investigated in marine environments, with methyl iodide being the most abundant compound identified, however other minor compounds such as chloroiodomethane, diiodomethane and alkyl iodides have also been identified (Cancho *et al*., 2000).

### 2.1.1 UK data 1981

Several iodinated DBPs were detected in surveys undertaken by WRc for the Department of the Environment (DoE) in the mid-1970's (Fielding *et al*., 1981). In a survey of fourteen drinking water samples, bromochloroiodomethane was detected on 8 occasions, chlorodiiodomethane in a single sample, chloroiodomethane in 3 samples, dibromoiodomethane in 2 samples and dichloroiodomethane in 7 samples. As this survey was primarily a qualitative exercise, the concentrations of these compounds was not determined, but they appeared to be present at lower concentrations than the more commonly occurring chlorinated and brominated THMs.

The analytical methodology used for the WRc survey undertaken in the 1970s (Fielding *et al*., 1981) involved extraction of the samples using both dynamic headspace extraction (also known as Closed Loop Stripping; sample volume 2 litres) and XAD-2 resin extraction (sample volume 5 litres). The extracts were analysed using capillary gas chromatography-mass spectrometry (GCMS) in general survey mode. No pure standards were available for any of the iodinated DBPs detected, but chlorination of River Thames water to which several ppm of potassium iodide had been added produced these compounds and other iodinated DBPs including bromodiiodomethane and iodoform.

### 2.1.2 Spanish Survey 1998

In 1998, drinking water samples were taken from different parts of the drinking water process in Barcelona, Spain. Panellists had identified a medicinal odour as one of the descriptors associated with drinking water in Barcelona, therefore Cancho *et al.* (2000) aimed to evaluate six possible iodinated-THMs including, chlorodiiodomethane, dichloroiodomethane, bromodiiodomethane, dibromoiodomethane, bromochloroiodomethane and iodoform. These iodinated-THMs were measured in the drinking water to establish whether they could be associated with the odour descriptor (Cancho *et al*., 2000). The water was taken from the Sant Joan Depsí water plant in Barcelona, the water is abstracted from the Llobregat River which has a Mediterranean regime that is characterised by irregular flows. The river quality is affected by industrial pollution and salt mines located in the upper course of the river. The average total organic carbon, inorganic bromide and iodide concentrations in the raw water in 1997 were 5000, 700 and 3.2 µg/l, respectively. The water treatment plant implements conventional treatment, including prechlorination (to break-point), flocculation (settling), sand filtration, ozonation, granular activated carbon (GAC) filtration and postchlorination (with a lower dosage of chlorination to guarantee a 0.5-1 mg/l concentration of chlorine in the distribution system) (Cancho *et al*., 2000).

The average levels of iodinated-THMs detected in distribution system are shown in Table 2.1. The samples were taken from January to June 1998, however, it was unclear how many samples were taken. It was reported that THMs (bromo-, chloro-, and bromochloroderivatives) were produced in all stages of the treatment process. The brominated and chlorobrominated compounds accounted for 83% of the total THMs detected and as Table 2.1 shows, the concentration of total THMs were several hundred times greater than that of the iodinated-THMs detected. Only three out of the six iodinated-THMs were identified in the water from the treatment plant. Dichloroiodomethane, bromochloroiodomethane and dibromoiodomethane were determined in the prechlorination, sand filtration and occasionally in ozonated water. None of these iodinated-THMs were detected in the finished water in the distribution system, suggesting that they had been absorbed in GAC filters. They were not observed, at detectable levels, to be formed again with post-chlorination (Cancho *et al*., 2000). However, it is uncertain how effective GAC would be at removing iodinated-DBPs on a regular basis, as removal efficiency is likely to be greatly dependent on the age of the filters. Furthermore, removal by GAC would only be relevant for removal of iodinated-DBPs formed during prechlorination, which is little used in the UK. As well as the potential removal of these DBPs via GAC, ozonation oxidises any iodide through to iodate, thereby removing the potential for the subsequent formation of iodinated-DBPs. The data in Table 2.1, suggest that ozonation reduces the concentration of iodinated-DBPs.

**Table 2.1 Average concentration of iodinated DBPs detected in the different stages of the drinking water treatment process (Cancho *et al*., 2000)**

| Drinking water treatment stage | Average Concentration of Iodinated DBP (µg/l) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Dichloroiodomethane | Bromochloroiodomethane | Dibromoiodomethane | Chloroiiodomethane | Bromodiiodomethane | Iodoform | Total trihalomethanes[a] |
| Raw water | <LOD | <LOD | <LOD | <LOD | <LOD | <LOD | 0.5 |
| Prechlorination | 0.1 | 0.2 | 0.1 | <LOD | <LOD | <LOD | 57.1 |
| Sand filtration | 0.2 | 0.6 | 0.2 | 0.1 | <LOD | <LOD | 108.6 |
| Ozonation | <LOD | 0.2 | 0.1 | <LOD | <LOD | <LOD | 101.3 |
| GAC | <LOD | <LOD | <LOD | <LOD | <LOD | <LOD | 75 |
| Distribution system | <LOD | <LOD | <LOD | <LOD | <LOD | <LOD | 90.5 |

LOD: Limit of Detection

[a] Brominated, chlorobrominated and chlorinated THMs.

### 2.1.3 US Nationwide DBP Occurrence Study 2000-2002

Krasner *et al*. (2006) reported on the US Nationwide DBP Occurrence study detailed fully in Weinberg *et al*. (2002), a survey of 12 US full-scale treatment plants that was carried out in 2000-2002. Each plant was sampled four or five times to evaluate any seasonal variations. Sampling took place in the October-December of 2000, January-April; July-September of 2001 and January-April of 2002 (Krasner *et* al., 2006). This survey was carried out as more than 500 DBPs have been reported in the literature for main types of disinfectants used i.e. chlorine, ozone, chlorine dioxide and chloramines, including combinations of these methods. However, very few of these reported DBPs have been quantified in drinking waters and for this study it was not considered feasible to quantify all of the DBPs. Therefore they were prioritised by evaluating their predicted adverse health effects. A detailed, mechanism-based, structural activity relationship (SAR) analysis, supported by extensive literature search for genotoxicity and other data were used to rank the carcinogenic potential of these DBPs. From this prioritising exercise approximately 50 DBPs were selected as they were identified as having the highest ranking for potential toxicity and that were not already included in the US EPAs Information Collection Rule (ICR). These ~50 DBPs are reported as 'high' priority. See Table A1 in Appendix A for the Priority DBPs selected for the US Nationwide Occurrence Study (Weinberg *et al*., 2002).

The plants in this US Nationwide DBP Occurrence study were selected based on being high in total organic carbon (TOC) and/or bromide in their raw waters. This was to enable the detection of priority DBPs that contained bromide and/or iodine (such as iodinated trihalomethanes (THMs), other halomethanes, non-regulated haloacids, haloacetonitriles, haloketones, halonitromethanes, haloaldehydes, halogenated furanones, haloamides and non-halogenated carbonyls). The survey found that THMs and haloacetic acids (HAAs) made up the two main classes of halogenated DBPs produced on a weight basis. Haloacetaldehydes made up the third main class produced in many of the water. It was also discovered that even though the use of alternative disinfectants, such as ozone, chlorine dioxide and chloramines reduced the production of the four US regulated THMs, trihalogenated HAAs and total organic halogen (TOX), several priority DBPs were formed at higher levels compared to when disinfection was carried out using chlorine.

Krasner *et al*. (2006) also found that the concentration of the iodinated-THMs detected in the 2001-2002 US survey was low in comparison to the four US regulated THMs, with a ratio of iodinated-THMs to regulated THMs of 2% based on medians. The highest level of iodinated-THM formation was at Plant 12 in November 2001 (iodinated-THMs were at 81% of the four regulated THMs). At this plant chlorine and ammonia were added simultaneously to form chloramines in water with moderate amount of bromide (150 µg/l in November 2001). It was reported that free chlorine was not measurable in the sample from this plant at that sampling time. The disinfection procedure at this plant favours the formation of iodinated-DBPs i.e. the use of chloramination and no free chlorine contact time. It is not considered likely that these conditions would occur under typical UK treatment scenarios. Also, for the November 2001 sample, the total iodinated-DBPs seemed higher than for the other sampling periods (12.3, 10.8, 18.7 and 7.5 µg/l measured March 2001, September 2001, November 2001 and February 2002, respectively, Appendix A, Table A2). Krasner *et al*. (2006) stated that in previous studies it has been observed that the formation of iodinated THMs was favoured by chloramination, especially if the ammonia was added first. In the study conducted in 2001, dichloroiodomethane was, on the whole, the most commonly detected iodinated-THM and it was also detected in waters that had average levels of bromide, 60 µg/l (found at Plants 5 and

6; Table 2.2, below). It is considered that these waters would also have some iodide present (Krasner *et al*., 2006).

Along with these iodinated-THMs, the US 2001-2002 study also found, for the first time, iodoacids including iodoacetic acid, bromoiodoacetic acid, (E)-3-bromo-3-iodopropenoic acid, (Z)-3-bromo-3-iodopropenoic acid and (E)-2-iodo-3-methylbutenedioic acid. Again these iodoacids were detected in finished drinking water from Plant 12 in November 2001. This plant only used chloramines for disinfection and had detected relatively high levels of the iodinated-THMs (Krasner *et al*., 2006). Krasner *et al*. (2006) stated that the results of the US 2001-2002 survey demonstrated that increased levels of brominated and/or iodinated compounds (e.g. THMs, haloacids) were formed in water with high bromide (and iodide) concentrations.

Dichloroiodomethane was detected at the highest concentration (total mean concentration from all 12 plants, 15.9 µg/l), followed by bromochloroidomethane (11.00 µg/l) and iodoform and dibromoiodomethane (8.85 and 8.29 µg/l, respectively). Plant 12 was observed to have the greatest total iodinated-DBPs concentration (13.23 µg/l), followed by plants 2 and 8 with 5.16 and 4.94 µg/l, respectively, see Table 2.2.

**Table 2.2 The disinfection processes, mean raw bromide concentrations and total iodinated-DBP concentration at each of the 12 treatment plants over the sampling period 2000-2002 (Weinberg *et al*., 2002)**

| Plant | Disinfection process | Mean raw water bromide concentration (µg/) | Total iodinated-DBPs (µg/l) |
|---|---|---|---|
| 1 | Ozone-chlorine-chloramines | 205 | 2.58 |
| 2 | Chlorine-chloramines | 205 | 5.16 |
| 3 | Chlorine-chloramines | 70.6 | 2.96 |
| 4 | Chlorine | 70.6 | 3.12 |
| 5 | Ozone-chlorine | 65.4 | 3.91 |
| 6 | Chlorine dioxide-chlorine-chloramines | 61.8 | 4.60 |
| 7 | Chloramines-ozone | 135 | 4.03 |
| 8 | Chlorine-chloramines | 287.5 | 4.94 |
| 9 | Chlorine-chloramines | 182 | 2.83 |
| 10 | Chlorine-chloramines | 60 | 2.83 |
| 11 | Chlorine dioxide-chlorine-chloramines | 182.5 | 4.10 |
| 12 | (Chlorine dioxide)-chloramines | 187.5 | 13.23 |

Plant 12 had the single greatest mean concentration of dichloroiodomethane of 5.75 µg/l (Figure 2.1) and the greatest total mean concentration of iodinated-DBPs. Plant 12 used a combination of chlorine and ammonia to form chloramine (at one sampling point chlorine dioxide was used during pre-treatment, but not for the other three sampling points). Iodide concentrations were not recorded in this study, but mean bromide concentrations were 187.5 µg/l (Table 2.2).

Plants 2 and 8 also had larger mean concentrations of dichloroiodomethane (2.2 and 1.8 µg/l, respectively) compared with the other plants. Plant 2 used the addition of chlorine to raw, settled and filtered water. Ammonia was then added to the finished water to form chloramine. The mean bromide concentration was 205 µg/l. Plant 8 had two treatment processes operating simultaneously and parallel to one another. One treatment involved lime softening; the raw water was treated with chlorine, then lime softened and was then chloraminated, filtered and stored. The other treatment involved membrane-softening; the pH of the raw water was adjusted with sulphuric acid and this water was then filtered and treated with membranes. This water was then chlorinated and passed through an adsorber and stripper towers. The pH was then adjusted with sodium hydroxide and mixed with the lime-softened water. This combined treated water was chloraminated, stored and distributed. The mean raw water bromide concentration for plant 8 was 287.5 µg/l, which was the highest from all the plants (Table 2.2).

The mean iodinated-DBPs concentrations as well as the total iodinated-DBPs results have been compared with bromide concentrations, however, no clear relationships can be observed. The majority of the plants used some form of chloramines in their disinfection process so it was unclear from the data from this study if the concentration of iodinated-DBPs was greater when chloramination was used.

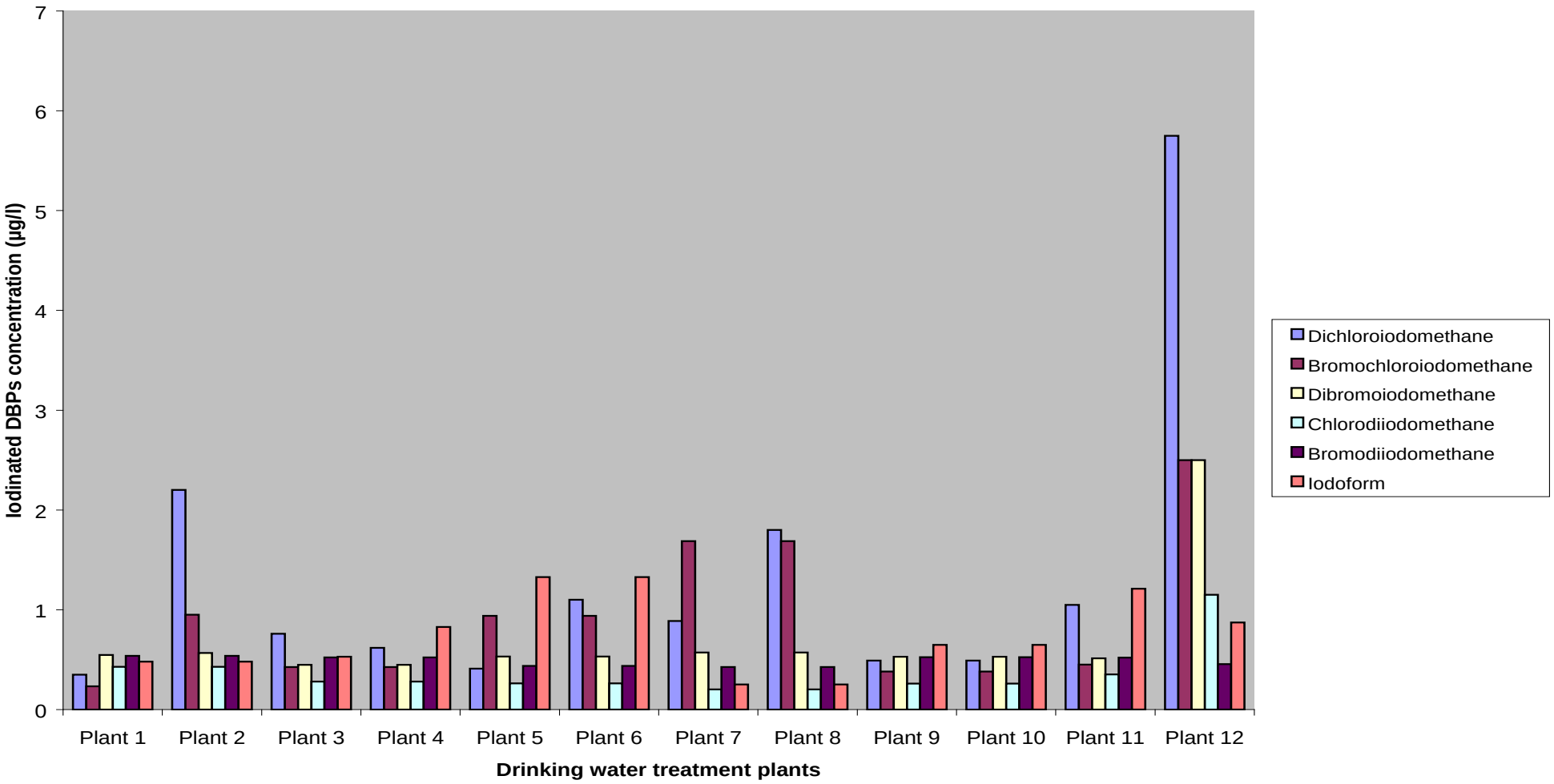


**Figure 2.1 Mean concentrations of iodinated DBPs detected in the 12 plant sampled in the 2000-2002 US Nationwide Study (Weinberg *et al*., 2002)**

### 2.1.4 US Survey 2006

In 2006, a study was conducted to measure five iodo-acids (iodoacetic acid, bromoiodoacetic acid, (Z)-3-bromo-3-iodo-propenoic acid, (E)-3-bromo-3-iodo-propenoic acid and (E)-2-iodo-3-methylbutenedioic acid) and two iodinated-THMs (dichloroiodomethane and bromochloroiodomethane) in chloraminated and chlorinated drinking water from 23 cities in the US and Canada (Richardson *et al*., 2008). Drinking water samples were collected from full-scale treatment plants in the US, including 22 cities, representing 9 states and 6 geographic regions and one plant in Canada. The first sampling round was limited to 5 cities in May 2005, the second 22 cities in autumn-winter of 2005 and the third sampled all 23 cities in 2006 (Richardson *et al*., 2008).

Due to the levels of regulated brominated THMs and HAAs, the cities selected for the study were expected to have bromide/iodide present in their source water. The majority of the treatment plants used chloramination, with two plants utilising chlorination for comparison. It is reported that normally, chloramination plants produce monochloramine by reacting chlorine and ammonia at ratios of approximately 4:1 or 5:1 chlorine to ammonia-nitrogen (by weight). In this study, however, it was found that some treatment plants added ammonia and chlorine simultaneously; others allowed an amount of free chlorine contact time before adding ammonia, and some added ammonia only at the very end. One treatment plant, 19, had natural ammonia concentrations of 1200 µg/l in its source water; this caused chloramines to be formed immediately following the addition of chlorine (Richardson *et al*., 2008).

Total organic carbon levels ranged from 700 to 16 100 µg/l with an average of 5000 µg/l. Bromide concentration in the source waters ranged from 24 to 1120 µg/l with an average of 109 µg/l, and iodide concentrations ranged from 0.4 to 104.2 µg/l with an average of 10.3 µg/l. Areas expected to have higher bromide and iodide levels were those waters from coastal locations, due to salt water intrusion. However, the water with the highest iodide concentration was not from a coastal location and five out of the six inland locations had water with an iodide concentration >10 µg/l. Source waters with the highest bromide concentrations generally also had the highest iodide concentrations, however this was not found to be consistent (Richardson *et al*., 2008).

In this 2006 study, the typical iodinated-acid concentrations were in the tens of ng/l, with the concentrations being in the low or sub µg/l range for the iodinated-THMs. Mean concentrations of 0.13, 0.13, 0.05, 0.04, 0.05, 1.08 and 1.38 µg/l (maximums of 1.7, 1.4, 0.5, 0.28, 0.58, 10.2 and 7.9 µg/l) for iodoacetic acid, bromoiodoacetic acid, (Z)-3-bromo-3-iodopropenoic acid, (E)-3-bromo-3-iodo-propenoic acid, (E)-2-iodo-3-methylbutenedioic acid, bromochloroiodomethane and dichloroiodomethane, respectively were reported (Richardson *et al*., 2008). Data from the third sampling round is shown in Figure 2.2 below; data from all three rounds of sampling are displayed in Appendix A in Table A3, Table A4, and Table A5. It was stated that the iodinated-acids and iodinated-THMs were not generally detected in the corresponding source water (Richardson *et al*., 2008).

Therefore, the iodinated-THM concentrations were greater than those of the iodinated-acid concentrations, (in Figure 2.3 and Figure 2.4, the concentrations detected of iodinated-acids and iodinated–THMs, respectively, are displayed separately). Additionally the iodinated-THM concentrations measured in this 2006 study were greater than in the US Nationwide study carried out in 2001-2002, this was considered to be due to the 2006 study focusing on treatment plants that used chloramination (Richardson *et al*., 2008). Richardson *et al*. (2008) also reported that iodinated-acids and iodinated-THMs were detected in all of the six

treatment plants that had no detectable iodide in their source waters. It was considered possible that there were alternative inorganic or organic sources of iodine to that of the inorganic iodide measured for in the source waters (Richardson *et al*., 2008). The reported method of iodide analysis was cathodic stripping square wave voltammetry (Richardson *et al*., 2008).

As with the previous US study, dichloroiodomethane and bromochloroiodomethane were detected at the greatest concentrations across the 23 plants (Figure 2.2 and Figure 2.4), followed by bromoiodoacetic acid and iodoacetic acid (Figure 2.2 and Figure 2.3).

The plants with the highest total concentrations of iodinated-DBPs were Plants 13, 1, 12, 2, 17 and 19 with concentrations of 7.99, 7.71, 6.29, 5.27, 4.38 and 2.90 µg/l, respectively (Table 2.3). All of these plants utilised chloramination for their water disinfection and all had free chlorine contact times <1 minute. Plants 1, 17 and 19 had no free contact times; at Plant 1 and 17 the chlorine and ammonia to form chloramines were added simultaneously and Plant 19 had natural levels of ammonia in its raw water and as soon as chlorine was added in the treatment process, chloramines were formed.

The lowest total iodinated-DBPs concentration was found at Plant 5 with a total concentration of 0.02 µg/l (Table 2.3). The raw water iodide concentration at this plant was reported to be 10.3 µg/l, with iodide concentrations at the other plants ranging from 0.13-104.2 µg/l. It did not have lowest iodide concentration out of the 23 plants sampled. The plant used chloramination, but, unlike the plants with the highest concentrations of iodinated-DBPs measured, it had a moderate free contact time of >1 minute. Plant 10 that used chlorination disinfection also had low total iodinated-DBPs concentration of 0.52 µg/l and an iodide concentration of 7.3 µg/l (Table 2.3).

Regarding the plants with the highest concentrations of total iodinated-DBPs detected it was difficult to associate high iodide concentrations in the raw source water with the high iodinated-DBPs concentrations. However, Plants 19, 1, 17 and 13 had the highest reported iodide concentrations (104.2, 65, 22.4 and 22.3 µg/l, respectively). All these plants were also found to have some of the highest concentrations of total iodinated-DBPs in their finished waters (see Table 2.3). Richardson *et al*. (2008) reported a trend between iodinated-acid concentrations and iodide concentration. This trend supported the hypothesis that increasing iodide levels in the raw water increased the formation of iodinated-DBPs. It was considered by Richardson *et al*. (2008) that the trend was not as clear with the iodinated-THMs due to a complete set not being measured as it had been with the iodinated-acids.

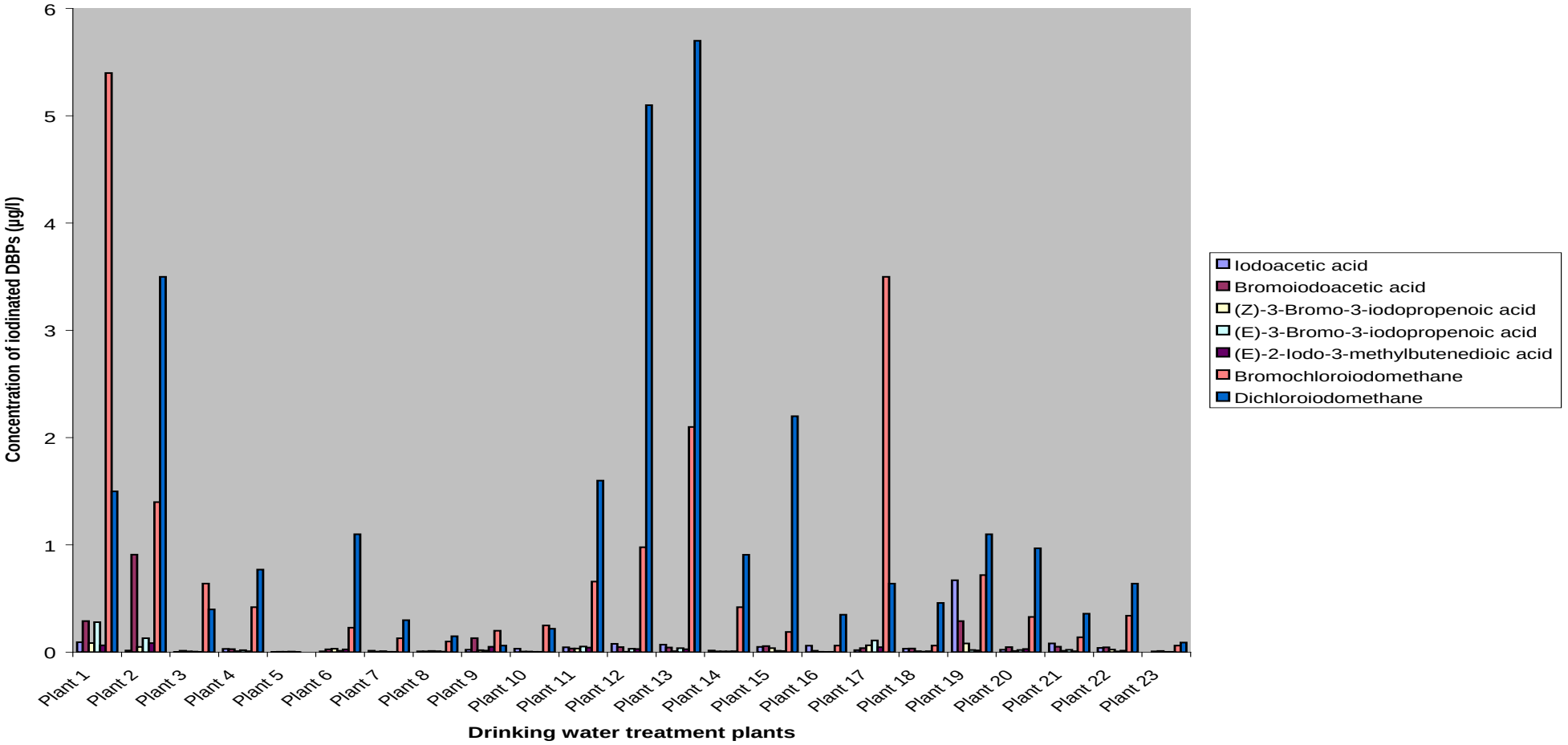


**Figure 2.2 Concentration of iodinated DBPs in the US occurrence study reported in the third round of sampling (Richardson *et al*., 2008)**

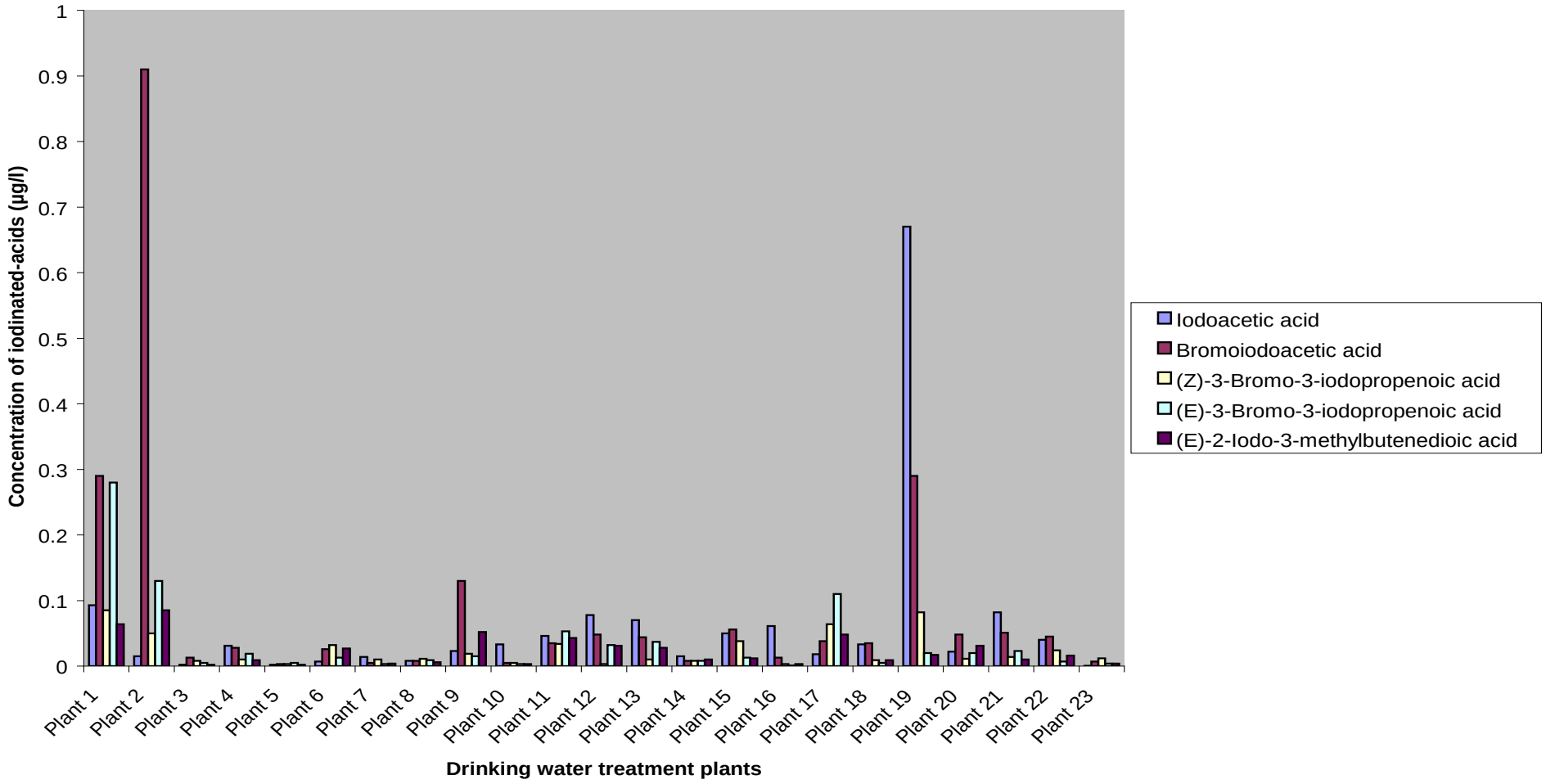


**Figure 2.3 Concentration of iodinated-acids in the US occurrence study reported in the third round of sampling (Richardson et al., 2008)**

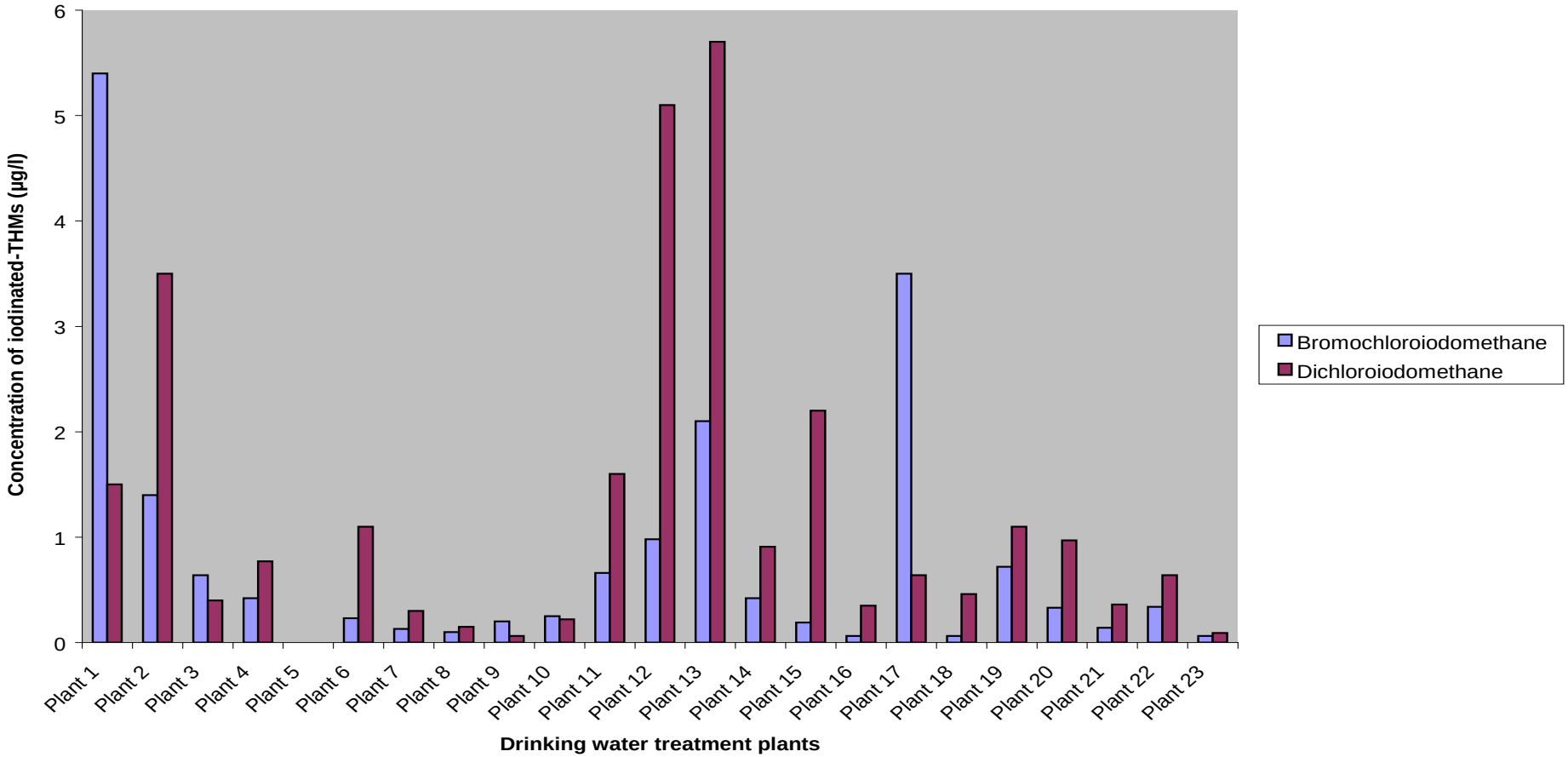


**Figure 2.4 Concentration of iodinated-THMs in the US occurrence study reported in the third round of sampling (Richardson et al., 2008)**

**Table 2.3 Drinking water disinfection treatments, raw water bromide and iodide concentration and total iodinated-DBPs concentrations reported in the third round of sampling in the US survey (Richardson *et al*., 2008)**

| Plant | Drinking water treatment | Free chlorine contact time (minutes)[b] | Bromide concentration (µg/l) | Iodide concentration (µg/l) | Total iodinated-DBPs concentration (µg/l)[c] |
|---|---|---|---|---|---|
| Plant 1 | Chloramination | 0 | 699 | 65 | 7.71 |
| Plant 2 | Chloramination | <1 | 133 | 1 | 5.27 |
| Plant 3 | Chloramination | >1-<45 | 230 | 10.3 | 1.03 |
| Plant 4 | Chloramination | >1-<45 | 96 | <0.13 | 1.3 |
| Plant 5 | Chloramination | >1-<45 | 230 | 10.3 | 0.02 |
| Plant 6 | Chloramination | <1 | 96 | 0.4 | 1.41 |
| Plant 7 | Chloramination | >45 | 105 | <0.13 | 0.47 |
| Plant 8 | Chloramination | >45 | 67 | <0.13 | 0.29 |
| Plant 9 | Chloramination | >1-<45 | 277 | 1.9 | 0.44 |
| Plant 10 | Chlorination | N/A | 214 | 7.3 | 0.52 |
| Plant 11 | Chloramination | >1-<45 | 104 | 1.5 | 2.51 |
| Plant 12 | Chloramination | <1 | 204 | 10.3 | 6.29 |
| Plant 13 | Chloramination | <1 | 186 | 22.3 | 7.99 |
| Plant 14 | Chloramination | >1-<45 | 107 | 1.1 | 1.35 |
| Plant 15 | Chloramination | <1 | 107 | <0.13 | 2.57 |
| Plant 16 | Chloramination | >1-<45 | 24 | <0.13 | 0.49 |
| Plant 17 | Chloramination | 0 | NR | 22.4 | 4.38 |
| Plant 18 | Chloramination | >45 | 35 | 10.4 | 0.55 |
| Plant 19 | Chlorination [a] | 0 | 300 | 104.2 | 2.9 |
| Plant 20 | Chloramination | >45 | 193 | <0.13 | 1.41 |
| Plant 21 | Chloramination | >1-<45 | 65 | 0.4 | 0.68 |
| Plant 22 | Chloramination | >1-<45 | 103 | 10.8 | 1.11 |
| Plant 23 | Chloramination | >45 | 37 | 2.7 | 0.12 |

[a] However, there was natural ammonia present to form chloramines.

[b] The contact times reported in the study were no free chlorine contact time (reported as 0 minutes for the purposes of this report), because either chlorine and ammonia were added simultaneously to produce chloramines or in the case of Plant 19 there was natural ammonia in the raw water. The other times were reported as plants with short free chlorine contact time (<1 minute), plants with the longest free contact ties (>45 minutes) and the plants that were not specified were presumed to have a free contact time of >1 minute but <45 minutes.

[c] The sums of iodinated-acids and iodinated-THMs were reported in the study, this total is the sum of the total iodinated-acids and –THMs. The individual results are displayed in Appendix A, Table A5.

N/A: Not applicable due to the treatment being chlorination rather than chloramination.

### 2.1.5 Scottish Survey 2008

A more recent study has just been completed in Scotland whereby seven drinking water treatment works were surveyed for the occurrence of several DBPs, including a number of iodinated-DBPs. The works selected for the survey allowed comparisons between water sources, treatment processes and disinfection practices. Sampling was undertaken in 2008 in the months of January, May and August (winter, spring and summer, respectively). The sources of water included upland reservoirs, reservoirs and rivers. The treatment processes covered a wide range of options including coagulation, lime softening, rapid gravity and pressure filtration, ozonation, chlorination and chloramination. Four of the works that were included in the survey use chloramination, which is carried out at a chlorine:nitrogen weight ratio of 3:1 to 4:1 and normally involves a period of chlorination (approximately 30 minutes) before ammonium salt addition (Parsons *et al*., 2009).

Parsons *et al*. (2009) reported that the concentration of iodinated-THMs detected in their survey was low compared to $THM_4$ and the ratio of iodinated-THMs and $THM_4$ was on 1.2% on a median basis. They also stated that this ratio was comparable with what was reported by Krasner *et al*. (2006), 2% on a median basis, however, this included six iodinated-THMs compared with the Scottish survey that only looked at two. As with the survey conducted by Krasner *et al*. (2006), Parsons *et al*. (2009) observed that dichloroiodomethane was typically detected at higher levels than bromochloroiodomethane. Parsons *et al*. (2009) reported that the highest concentration of these two iodinated-THMs was observed at works 2 in the spring with a sum of 3.7 µg/l. However, examining the data displayed in the report (Table 2.4, below) it is considered that this maximum sum of the two iodinated-THMs was actually seen at works 4 in the summer in the final water sample. Parsons *et al*. (2009) also stated that the concentration of iodinated-THMs increased with increasing iodide levels, which were reported to increase from a median of 2 µg/l in the winter to 6 µg/l in the summer. This would correlate with the increased concentration of iodinated-THMs being seen in the summer. The relationship between concentrations of iodinated-THMs and iodide levels was reported to have a strong linear relationship with an outlier at works 6 (Figure 2.5). This was considered to be due to the plant utilising ozone treatment, and it is understood that ozone oxidises iodide to iodate and therefore reduces the potential for iodinated-THM formation (Parsons *et al*., 2009). Therefore it would be important when considering areas at risk of iodinated-DBPs formation due to high iodide levels in the raw source water to consider whether the treatment works use ozone as this could significantly reduce their formation as shown in the Scottish study.

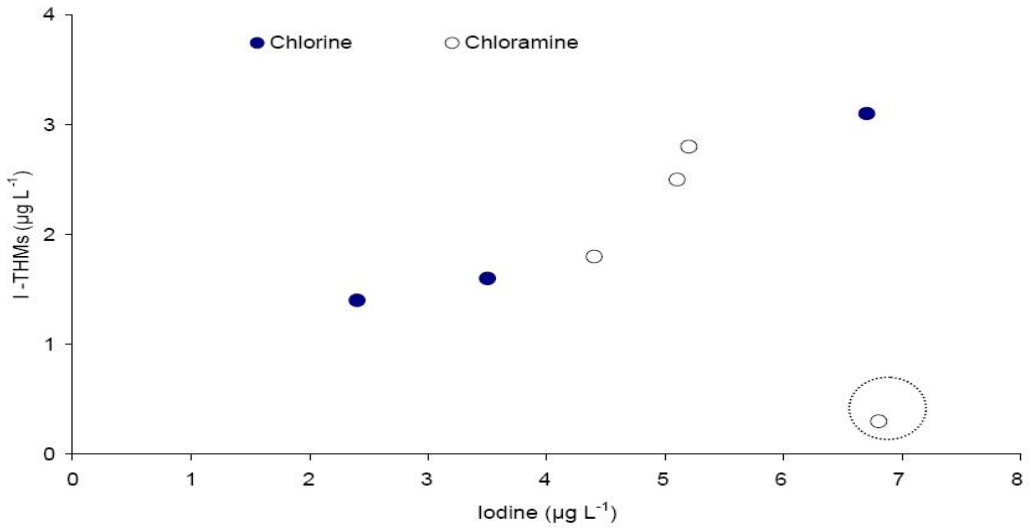


**Figure 2.5 Iodide concentration against iodinated-THMs formed at the different works (Parsons *et al*., 2009)**

**Table 2.4 Results from the 2008 Scottish survey – Iodinated-THMs sampled (Parsons *et al*., 2009)**

| Works | Sample | Winter | | | Spring | | | Summer | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | DCIM | BCIM | I-THM2 | DCIM | BCIM | I-THM2 | DCIM | BCIM | I-THM2 |
| 1 | Final | NM | NM | NM | 2 | <MRL | 2 | 1.6 | <MRL | 1.6 |
| | Dist 1 | NS | NS | NS | 1.9 | <MRL | 1.9 | <MRL | <MRL | <MRL |
| 2* | Final | NM | NM | NM | 0.3 | <MRL | 0.3 | 1.4 | <MRL | 1.4 |
| | Dist 1 | NM | NM | NM | <MRL | 0.4 | 0.6 | 2.6 | <MRL | 2.6 |
| | Dist 2 | NM | NM | NM | <MRL | 0.6 | 0.7 | 2.8 | <MRL | 2.8 |
| 3* | Final | NM | NM | NM | <MRL | 0.5 | 0.6 | 2.6 | <MRL | 2.6 |
| | Dist 1 | NM | NM | NM | <MRL | <MRL | 0.4 | 2.4 | <MRL | 2.4 |
| | Dist 2 | NM | NM | NM | <MRL | <MRL | 0.2 | 2.3 | <MRL | 2.5 |
| 4 | Final | NM | NM | NM | 0.4 | <MRL | 0.5 | 3.7 | <MRL | 3.7 |
| | Dist 1 | NM | NM | NM | 0.5 | <MRL | 0.5 | 3.1 | <MRL | 3.2 |
| | Dist 2 | NM | NM | NM | 0.6 | <MRL | 0.8 | 0.7 | <MRL | 0.7 |
| 5* | Final | NM | NM | NM | 1.2 | <MRL | 1.2 | 1.4 | <MRL | 1.4 |
| | Dist 1 | NM | NM | NM | <MRL | 0.5 | 0.6 | <MRL | <MRL | <MRL |
| | Dist 2 | NM | NM | NM | 0.3 | 0.4 | 0.7 | 1.8 | <MRL | 1.8 |
| 6* | Final | NM | NM | NM | 0.3 | <MRL | 0.5 | 0.3 | <MRL | 0.3 |
| | Dist 1 | NM | NM | NM | <MRL | <MRL | <MRL | <MRL | <MRL | <MRL |
| | Dist 2 | NM | NM | NM | 0.4 | 0.4 | 0.8 | <MRL | <MRL | <MRL |
| 7 | Final | NM | NM | NM | 1.6 | <MRL | 1.6 | 1.8 | <MRL | 2 |
| | Dist 1 | NM | NM | NM | 1.9 | <MRL | 1.9 | 0.9 | <MRL | 1.1 |
| | Dist 2 | NM | NM | NM | 1.1 | <MRL | 1.1 | 1.4 | <MRL | 1.5 |

DCIM: dichloroiodomethane; BCIM: bromochloroiodomethane; I-THM2: sum of the two iodinated-THMs measured.
Final: Final water samples.
Dist 1: Distribution sample 1.
Dist 2: Distribution sample 2.
NM: Not measured.
NS: No sample taken.
<MRL: Below the minimum reporting level.
* The plant uses chloramination.

## 2.2 Available Monitoring Data from the UK Drinking Water

From the data provided by UK water companies it is evident that iodinated DBPs are not monitored on a routine or otherwise basis. Very limited data were available on the levels of these DBPs in UK drinking water.

The UK water companies contacted were Anglian Water, Bournemouth & West Hampshire Water, Bristol Water, Cambridge Water, Cholderton & District Water, Council of the Isle of Scilly, Dee Valley Water, Dwr Cymru Welsh Water, Folkestone & Dover Water Services, Guernsey Water, Isle of Man Water Authority, Jersey Water, Mid Kent Water, Northern Ireland Water, Northumbrian Water, Portsmouth Water, Scottish Water, Severn Trent, South East Water, Southern Water, South Staffordshire Water, South West Water, Sutton & East Surrey Water, Thames Water, Three Valleys Water, United Utilities, Wessex Water and Yorkshire Water.

Each company were asked if they had any information on the following:

1. Monitoring data for concentration of iodinated-DBPs measured.

2. Monitoring data for levels of iodide and bromide in raw source water.

3. If any monitoring information was available, what methods of treatment were used at the corresponding sites.

4. Any taste and odour effects associated with iodinated-DBPs, as it has been noted that iodinated-THMs cause taste and odour effects.

Of those 28 companies contacted, 24 responded with two companies reporting the detection of iodinated-DBPs. Company A reported sometimes detecting iodinated-DBPs at low levels usually associated with low TOC underground waters. They suggested that hypochlorous acid (produced when water is chlorinated) is less reactive than the bromine or iodine analogues. Therefore, if there is bromide or iodide present then there would be the preferential formation of these analogues following chlorination i.e. bromine or iodine displaces chlorine from the reactive species. This is more likely when the TOC is low. This leads to preferential formation of bromine or iodine analogues of the halogenated DBPs (e.g. haloforms, acetonitriles or haloacetic acids).

Company B reported that chloroiodomethane and chlorobromoiodomethane was detected in highly chlorinated samples. However, they stated that there is not a regular monitoring programme for iodinated-DBPs, but that they monitored iodinated compounds on occasion in the flush water from new GAC filters by GCMS. This was because of the possible presence of silver iodide and consequently iodinated-DBPs, if they have not been flushed long enough, but this is more ‘presence or absence’ than quantitative.

The other 22 companies had no data and these DBPs were not something that appeared to be widely monitored by the UK water companies.

## 2.3 Taste and Odour

It is reported that in the late 1980s, iodinated-THM, in particular iodoform, were found to be responsible for the occurrence of bad taste and odour in drinking waters (Bichsel and Gunten,

2000). Iodinated-DBPs are reportedly associated with characteristic pharmaceutical or medicinal odours and taste in water (Cancho *et al*., 2000). The organoleptic threshold concentration of iodoform is reported to range from 0.03 to 1 µg/l, which is stated to be the lowest value of all the iodinated-THMs (Bichsel and Gunten, 2000), as well as the odour threshold concentration of 0.02 µg/l and the taste concentration for iodoform is reported as 5 µg/l. (Cancho *et al*., 2000). These threshold concentrations are significantly lower than that of chloroform or bromoform, 100 and 300 µg/l, respectively (Cancho *et al*., 2000). Consequently, iodinated-THMs at concentrations between 0.02 and 10 µg/l or higher are capable of causing medicinal taste and odour problems in drinking water (Cancho *et al*., 2000). Cancho *et al*. (2000) stated that in France, there have been consumer complaints relating to iodoform and in Australia following treatment with chloramination.

In 1998 a study in Barcelona, Spain identified three iodinated-THMs, dichloroiodomethane, bromochloroiodomethane and dibromoiodomethane in the prechlorination, sand filtration and ozonation stages of the treatment processes, but found that they were removed by granular activated carbon (GAC) filtration and were below the limit of detection in the distribution system (Cancho *et al*., 2000). However, the authors concluded that they could still be responsible for the medicinal odours reported by panellists testing the drinking water in Barcelona. This was concluded to be due to the very low estimated odour threshold concentrations for bromodiiodomethane (0.8 µg/l) and chlorodiiodomethane (1.1 µg/l), compared with higher concentrations of 6.4, 8.0 and 8.4 µg/l reported for dibromoiodomethane, dichloroiodomethane and bromochloroiodomethane, respectively. Cancho *et al*., (2000) stated that the results observed in the Barcelona study that some iodinated-THMs concentrations were present at around 1.0 µg/l could be associated with odours in the finished water.

As stated in Section 2.2 above, in this study 28 UK water companies were contacted and from those 24 responded, and none of them especially highlighted any problems of taste and odour that could be associated with iodinated-DBPs. However, it was noted that they are not compounds that are monitored so could not be completely discounted as the cause of complaints.

In the 2008 Scottish study, stated that there had been few complaints from the public served by the water treatment works surveyed in their study, therefore, the issues surrounding taste and odour were not considered further by the authors. However, they did assess the odour of dichloroiodomethane, bromochloroiodomethane, dibromoiodomethane, chlorodiiodomethane, bromodiiodomethane and iodoform where one panellist detected odour at concentrations of 5.8, 5.1, 2.9, 0.2, 0.1 and 0.03 µg/l, respectively (Parsons *et al*., 2009).

# 3. FACTORS AFFECTING THE LEVEL OF IODINATED DISINFECTION BY-PRODUCTS

As highlighted in the introduction section a number of factors are considered to influence the formation of iodinated DBPs, these include iodide and bromide level in raw source water and disinfection process.

## 3.1 Level of Iodide and Bromide in the Raw Source Water

It is reported that the total iodine concentrations in water resources are typically in the range of 0.01 to 20 µg/l, but can exceed 50 µg/l in certain groundwaters near the sea coast or under special geological circumstances (Bichsel and Gunten, 2000; Cancho *et al*., 2000). In water containing iodide the formation of iodinated-THMs is reported to occur. This is the consequence of the incorporation of one or more iodine atoms into a THM (Bichsel and Gunten, 2000).

It is considered that in general increasing iodide concentrations in the source waters in turn increased the iodinated-DBPs formation This trend was observed in a US study carried out in 2006 (Richardson *et al*., 2008) and supported by the results of the Scottish study in respect of iodinated THMs (Parsons *et al*., 2009).

Richardson *et al*. (2008) stated found that generally source waters with the highest bromide levels contained the highest concentrations of iodide. However, this relationship was not consistent. Also, it was considered in an earlier study (US occurrence study 2000-2002) that high bromide (and iodide), caused more brominated and/or iodinated compounds (Krasner *et al*., 2006). In this earlier study iodide was not measured, only bromide, while in the latest survey available data for iodide and bromide were collected, with a greater importance being placed on the iodide data as the correlation between the two was not clear. The recent Scottish study demonstrated that whereas iodide levels increase in the summer, bromide levels seem to decrease, suggesting seasonality has a potential influence on the levels.

### 3.1.1 Environment Agency Monitoring Data

The Environment Agency for England and Wales have monitored the levels of iodide and bromide in raw waters from eight regions; Anglian, Midlands, North-East, North-West, South, South-West and Wales (Thames data were not supplied).

Monitoring data for each of these regions has shown wide variation in the concentration of iodide, not only between regions, but within the same region. However, in each region, the majority of samples taken (ranging from 74 to 91%) have iodide concentrations below the limit of detection. Unfortunately, the limit of detection for these samples showed wide variation (2.5-5000 µg/l), which makes interpretation of these data extremely difficult. Data are presented in Table 3.1, Table 3.2 and Table 3.3 and in Appendix B Figure B1 to Figure B3 on the occurrence of iodide in the raw water monitoring programme conducted by the Environment Agency. These three tables and graphs each consider different methods for the treatment of the limit of detection in an effort to obtain meaningful data on the potential levels of iodide throughout the UK.

In Table 3.1 and illustrated graphically in Appendix B, Figure B1, values reported to be below the limit of detection have been assumed to be equal to the limit of detection. These data are likely to be an over-estimate of the concentration of iodide in raw water in the UK, and any estimation of iodinated-DBP formation based on this data will provide a 'worst-case' scenario.

In Table 3.2 and illustrated graphically in Appendix B, Figure B2, values that were reported to be below the limit of detection have been excluded. These data therefore provide an indication of the measurable concentrations for each of the regions.

In Table 3.3 and illustrated graphically in Appendix B, Figure B3, values that were reported to be below the limit of detection were assumed to be equal to 0 µg/l.

These data would appear to indicate that the highest concentration of iodide was detected in the North-East region (5000 µg/l), however, the data indicate that the limit of detection was particularly high on the occasion these samples were analysed, and all of these samples were below the limit of detection. Therefore, the concentration of 5000 µg/l reported in Table 3.1 and Figure B1 is an over-estimate. The highest concentration of iodide detected above the limit of detection in the North-East region was 232 µg/l.

The highest concentration of iodide detected above the limit of detection in all regions was in Wales (4350 µg/l).

The Anglian region had the largest percentage of samples above the limit of detection; approximately 25% of all samples taken in this region contained detectable levels of iodide. Excluding the samples detected below the limit of detection, the Anglian region also displayed the widest variation in iodide concentrations.

**Table 3.1 Results of iodide raw water monitoring survey conducted by the Environment Agency of England and Wales (values reported to be below the limit of detection assumed to be equal to the limit of detection)**

| | Region | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Anglian** | **Midlands** | **North-East** | **North-West** | **South** | **South-West** | **Wales** |
| Minimum concentration (µg/l) | 2.5 | 2.5 | 2.5 | 2.5 | 3 | 3 | 2.5 |
| Maximum concentration (µg/l) | 3260 | 100 | 5000 | 510 | 177 | 106 | 4350 |
| Mean (µg/l) | 34.2 | 6.4 | 433.1 | 55.5 | 4.7 | 4.3 | 23.7 |
| Standard deviation | 215.9 | 11.4 | 1026.5 | 50.0 | 11 | 7.7 | 151.5 |
| N | 913 | 659 | 893 | 1904 | 344 | 814 | 1482 |
| Number of samples <LOD | 681 | 575 | 761 | 1654 | 307 | 742 | 1227 |
| % of samples <LOD | 74.6 | 87.3 | 85.2 | 86.9 | 89.2 | 91.2 | 84.8 |

**Table 3.2 Results of iodide raw water monitoring survey conducted by the Environment Agency of England and Wales (excluding values reported to be below the limit of detection)**

| | Region | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Anglian** | **Midlands** | **North-East** | **North-West** | **South** | **South-West** | **Wales** |
| Minimum concentration (µg/l) | 2.8 | 3 | 3 | 2.5 | 3.1 | 3.1 | 2.5 |
| Maximum concentration (µg/l) | 3260 | 96.2 | 232 | 510 | 177 | 106 | 4350 |
| Mean (µg/l) | 116.9 | 14.6 | 27.5 | 18.2 | 19.2 | 17.4 | 53.2 |
| Standard deviation | 417.1 | 18.6 | 41.7 | 49.8 | 30.2 | 22.0 | 378.9 |
| N | 232 | 84 | 132 | 250 | 37 | 72 | 255 |

**Table 3.3 Results of iodide raw water monitoring survey conducted by the Environment Agency of England and Wales (assuming values reported below the limit of detection are equal to 0 µg/l)**

| | Region | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Anglian** | **Midlands** | **North-East** | **North-West** | **South** | **South-West** | **Wales** |
| Minimum concentration (µg/l) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maximum concentration (µg/l) | 3260 | 96.2 | 232 | 510 | 177 | 106 | 4350 |
| Mean (µg/l) | 29.7 | 1.9 | 4.1 | 2.4 | 2.1 | 1.5 | 8.1 |
| Standard deviation | 216.0 | 8.2 | 18.7 | 19.1 | 11.4 | 8.1 | 148.6 |
| N | 913 | 659 | 893 | 1904 | 344 | 814 | 1482 |
| Number of samples <LOD | 681 | 575 | 761 | 1654 | 307 | 742 | 1227 |
| % of samples <LOD | 74.6 | 87.3 | 85.2 | 86.9 | 89.2 | 91.2 | 84.8 |

As well as data supplied by the Environment Agency, iodide levels were measured in the recent Scottish survey, and these are shown in Table 3.4, below. There was slight confusion as to whether iodide or iodine was being measured, as on the graph included in this report (Figure 2.5) taken from Parsons *et* al. (2009) states iodine concentration on the X axis, but throughout the report and in the methodology it was stated that iodide was measured. The data show a clear increase in iodide concentrations in the summer months. Also, plant 4 was observed to have the highest level of iodinated-THMs measured, (this maximum level, 3.7 µg/l was also detected in summer) which corresponds with the highest recorded iodide concentration of 12.1 µg/l. This could lead to iodinated-DBPs being an increased problem in summer months.

The levels of iodide observed in this study are similar to those seen in the US survey. It is difficult to interpret the Environment Agency iodide data but, by omitting the data below the levels of detection or assuming they are 0, it appears that the general level of iodide in the UK is no higher than that seen in the USA with perhaps one region, Anglian, having slightly higher levels.

**Table 3.4 Iodide concentration in raw water at the seven works sampled (Parsons *et al*., 2009)**

| Works | Iodide concentration (µg/l) | | |
|---|---|---|---|
| | Winter | Spring | Summer |
| 1 | 1.95 | 1.62 | 3.61 |
| 2* | 1.62 | 1.53 | 6.28 |
| 3* | 2.95 | 3.29 | 7.61 |
| 4 | 6.84 | 8.13 | 12.1 |
| 5* | 1.80 | 1.85 | 6.08 |
| 6* | 2.87 | 2.61 | 6.14 |
| 7 | 3.88 | 4.21 | 8.99 |

* Works uses chloramination.

One possible explanation for the large variation observed in the concentration of iodide supplied by the Environment Agency could be seasonal variation as seen with the Scottish data. However, it was not possible to sort the Environment Agency data into seasons due to the volume and variation of sampling points.

Monitoring of bromide by the Environment Agency in the eight regions displayed extremely wide variations in bromide concentrations both within and between regions. These data are presented in Table 3.5 to Table 3.7 and illustrated graphically in Appendix B, Figures B4, to B6.

In Table 3.5 and illustrated graphically in Appendix B, Figure B4, values reported to be below the limit of detection have been assumed to be equal to the limit of detection. These data are likely to be an over-estimate of the concentration of bromide in raw water in the UK, and any estimation of brominated-DBP formation based on this data will provide a ‘worst-case’ scenario.

In Table 3.6 and illustrated graphically in Appendix B, Figure B5, values that were reported to be below the limit of detection have been excluded. These data therefore provide an indication of the measurable concentrations for each of the regions.

In Table 3.7 and illustrated graphically in Appendix B, Figure B6, values that were reported to be below the limit of detection were assumed to be equal to 0 µg/l.

Bromide was more frequently detected above the limit of detection than iodide and had a more consistent limit of detection, which typically ranged from 50-2000 µg/l, although a single sample reported a limit of detection of 12500 µg/l.

These data indicate that the concentration of bromide in raw waters is extremely variable. This variability makes it extremely difficult to identify any clear differences between regions, however, it would appear that raw water in the South-west and Wales contain the lowest levels of bromide. These two regions also display the smallest amount of variation.

**Table 3.5 Results of bromide raw water monitoring survey conducted by the Environment Agency of England and Wales (values reported to be below the limit of detection assumed to be equal to the limit of detection)**

| | Region | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Anglian** | **Midlands** | **North-East** | **North-West** | **South** | **South-West** | **Wales** |
| Minimum concentration (µg/l) | 50 | 50 | 50 | 50 | 0 | 32 | 5 |
| Maximum concentration (µg/l) | 418000 | 285900 | 55700 | 1010080 | 174000 | 2880 | 13100 |
| Mean (µg/l) | 872.4 | 2006.1 | 432.7 | 952.7 | 2128.2 | 95.8 | 171.3 |
| Standard deviation | 10779.5 | 18889.9 | 2250.0 | 17730.6 | 13550.1 | 115.7 | 512.1 |
| n | 3668 | 3221 | 2543 | 7375 | 1705 | 5370 | 1783 |
| Number of samples <LOD | 263 | 552 | 969 | 2623 | 186 | 1246 | 416 |
| % of samples <LOD | 7.2 | 17.1 | 38.1 | 35.6 | 10.9 | 23.2 | 23.3 |

**Table 3.6 Results of bromide raw water monitoring survey conducted by the Environment Agency of England and Wales (excluding values reported to be below the limit of detection)**

| | Region | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Anglian** | **Midlands** | **North-East** | **North-West** | **South** | **South-West** | **Wales** |
| Minimum concentration (µg/l) | 50 | 50 | 50 | 50 | 0 | 32 | 9 |
| Maximum concentration (µg/l) | 418000 | 285900 | 55700 | 1010080 | 174000 | 2880 | 13100 |
| Mean (µg/l) | 927.9 | 2410.5 | 477.4 | 1449.3 | 2382.8 | 109.5 | 207.3 |
| Standard deviation | 11185.62 | 2079.2 | 2831.3 | 22073.6 | 14335.6 | 128.9 | 579.2 |
| n | 3405 | 2269 | 1574 | 4752 | 1519 | 4124 | 1367 |

**Table 3.7 Results of bromide raw water monitoring survey conducted by the Environment Agency of England and Wales (assuming values reported below the limit of detection are equal to 0 µg/l)**

| | Region | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Anglian** | **Midlands** | **North-East** | **North-West** | **South** | **South-West** | **Wales** |
| Minimum concentration (µg/l) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maximum concentration (µg/l) | 418000 | 285900 | 55700 | 1010080 | 174 | 2880 | 13100 |
| Mean (µg/l) | 861.4 | 1997.4 | 295.5 | 933.9 | 2128.2 | 84.1 | 158.9 |
| Standard deviation | 10779.7 | 18890.8 | 2239.2 | 17731.5 | 13350.1 | 122.1 | 514.6 |
| n | 3668 | 3221 | 2543 | 7375 | 1705 | 5370 | 1783 |
| Number of samples <LOD | 263 | 552 | 969 | 2623 | 186 | 1246 | 416 |
| % of samples <LOD | 7.2 | 17.1 | 38.1 | 35.6 | 10.9 | 23.2 | 23.3 |

Excluding the samples in which iodide and bromide were reported to be below the limits of detection, a correlation comparison between the mean concentrations of iodide and bromide was performed. However, these data do not indicate any clear correlation between iodide and bromide concentrations (data not shown).

As with the iodide data, bromide data were collected for the Scottish survey, Table 3.8. The data seems to suggest that there is an opposite effect regarding seasonal variation compared with the iodide concentrations that increased in the summer.

In general, the levels of bromide in this Scottish study are lower than those observed in the Environment Agency survey, however the data were interpreted.

**Table 3.8 Bromide concentration in raw water at the seven works sampled (Parsons *et al*., 2009)**

| Works | Bromide concentration (µg/l) | | |
|---|---|---|---|
| | Winter | Spring | Summer |
| 1 | 248 | 259 | 103 |
| 2 | 63.9 | 95.5 | 41.4 |
| 3 | 140 | 117 | 70.9 |
| 4 | 224 | 222 | 165 |
| 5 | 71.3 | 43.8 | 32.8 |
| 6 | 54.2 | 30.6 | 21.5 |
| 7 | 69.7 | 64.8 | 56.1 |

Data provided by the Environment Agency were from numerous sites in each specified region. Each site had a 'site description' for example groundwater borehole, river point, groundwater spring etc. The following sites descriptions were removed from the data analysis process as it was considered, from their description, unlikely that they would have been used as a drinking water source: unspecified; trade discharge; waste site; groundwater-landfill site; groundwater-unspecified; saline water-estuarine sites-non-bathing/shellfish; sewage discharges-final/treated effluent-water company; mine water; miscellaneous environment-unspecified; pollution investigation points; freshwater unspecified; freshwater-canal-non-classified; miscellaneous discharge-surface water; saline water-coastal sites-non-bathing; sewage and trade combined-unspecified; saline water-designated bathing beaches; and groundwater pit.

The numerous sites sampled within each region did not seem to have been sampled over a specified time period. Also, the frequency of sampling at each site seemed to vary greatly, for example some sampling sites had data for four time points whereas other had just the one data point. No correlation between the year of sampling and the sensitivity of the Limit of Detection (LoD) was observed i.e. the LoD did not seem to decrease with time. It is considered that the variation observed within the LoDs would be more likely to be due to the variation within the different laboratories the analysis took place at rather than improved techniques.

The year in which sampling begun varied greatly from region to region as well as for iodide and bromide, some had data from 1998 to 2008, others from 2006 to 2008. It was considered

that data from one specific year could have been used, however, with the variability and uncertainty of the data, an inaccurate evaluation of the data may have been created.

## 3.2 Water Company C Monitoring Data

Monitoring of iodide in raw water by Water Company C indicates that it is rarely detected above analytical limits of detection. In monitoring data of their region, of 120 samples taken, iodide was detected above the limit of detection in only 6 (7.2%) of samples. As with the Environment Agency monitoring data, limits of detection varied widely (2.5-100 µg/l), making interpretation of data extremely difficult. Samples that were detected above the limits of detection ranged from 2.5-510 µg/l. These six samples and their locations are provided in Appendix B, Table B2.

The complete results of iodide monitoring conducted by Water Company C, including samples at which iodide was reported to be below the limit of detection, are shown in Appendix B, Figure B7. These results have been tabulated in Appendix B Table B1. In Appendix B Figure B7, samples that were identified to be below the limit of detection have been treated to be equal to the limit of detection. Therefore, these data are likely to over-estimate the concentration of iodide in raw water on the UK and any estimation of iodinated-DBP formation based on these data will provide a 'worse-case' scenario. It should be noted that at nine sites only a single sample was taken, therefore standard deviations for these sites have not been calculated. Only one of these nine sites had a detectable level of iodide (V1), concentrations at all of the other sites were reported to be below the limit of detection (100 µg/l in each case).

Due to the limited number of samples detected above the limit of detection, and each of these samples only being detected at each site on a single occasion, it is not possible to provide a more comprehensive analysis of the data. The raw data are shown in Table B2 in Appendix B. Unfortunately, the only conclusion that can be drawn from the data of Water Company C is that general iodide levels are low (except at site Z1) and similar to those seen in the Scottish and US surveys.

## 3.3 Drinking Water Disinfection Process

The formation of iodinated acids and iodinated THMs were found to increase with chloramination (Richardson *et al*., 2007). The alternatives to chlorine disinfection of drinking water include ozone, chloramines and chlorine dioxide. These have been found to reduce greatly the formation of the four US regulated trihalomethanes (THMs), most of the haloacetic acids (HAAs) and total organic halogen (TOX), and in the USA many water utilities have switched or are in the progress of switching from the use of chlorine to these alternative disinfectants. However, it has been reported that even though some of these DBPs are reduced, other priority DBPs have been found in higher levels (Krasner *et al*., 2006; Cancho *et al*., 2000). Chloramination is often chosen for disinfection in distribution systems due to its long-term stability and in comparison to chlorination, its small production of DBPs such as THMs (Bichsel and Gunten, 1999).

Cancho *et al*. (2000) reported that in Australia there had been taste and odour complaints associated with the presence of iodoform in the drinking water following chloramination treatment. This problem was eliminated when chlorine was added before ammonia, instead of the reverse order. Cancho *et al*. (2000), stated that in other studies it had shown that

5 minutes of chlorination prior to the addition of ammonia eliminated the medicinal odour of iodoform.

It is reported that in the presence of ozone, chlorine or chloramine, iodide rapidly oxidises to form hypoiodous acid. Further reaction of this acid with natural organic matter can lead to the formation of iodinated-THMs (Bichsel and Gunten, 2000). In the ozonation process the half-life of hypoiodous acid is reported to be very short and varies between the extremes of 0.19 seconds (2 mg ozone/l, pH 9) and 3.7 seconds (0.25 mg ozone/l, pH 6). Therefore, for iodinated compounds to be formed during ozonation, the reaction would have to occur very rapidly. In natural waters with a TOC concentration of 2.5 mg/l, iodoform was reported to be formed within hours. In this water, ozonation would oxidise hypoiodous acid much more rapidly than the formation of iodoform would occur. Furthermore, it is reported that ozone is in high excess, and so hypoiodous acid would have to react extremely specifically with the functional groups of natural organic matter. Therefore, it is considered by the authors that it is unlikely that iodinated compounds would be formed following disinfection with ozone (Bichsel and Gunten, 1999).

During chlorination it is reported that the half-life of hypoiodous acid is longer than in the ozonation process. At a chlorine concentration of 2 mg/l and pH 9, a half-life of 8 minutes was reported for the acid. At a chlorine concentration of 0.2 mg/l and pH 6, this half-life was reported to be 10 hours (Bichsel and Gunten, 1999). The formation of iodinated compounds have been observed to occur in a similar time range, therefore it is considered possible that these compounds could be formed during chlorination, especially at low pHs and low chlorine concentrations. Although, the sites on the natural organic matter that are reactive with hypoiodous acid may also be oxidised by HOCl in a competing reaction, HOCl is present in a large excess relative to hypoiodous acid (2 to 4 orders of magnitude), a rate constant for hypoiodous acid of $10^2$ to $10^4$ fold the corresponding HOCl rate constant would be required to have a 1:1 distribution of chlorinated and iodinated organic product. Therefore it is considered by the authors that this factor significantly reduces the likelihood of the formation of iodinated compounds during chlorination (Bichsel and Gunten, 1999).

The half-life of hypoiodous acid in chloramination processes is reported to be long. Other factors make conditions during chloramination favourable for the formation of iodinated compounds (Bichsel and Gunten, 1999). The formation of iodinated compounds during chloramination occurs as follows; iodide is oxidised to hypoiodous acid by chloramine, which then can further react with natural organic matter in two different ways. The acid can react with natural organic matter to form iodinated compounds. Also, it is possible that the hypoiodous acid can be reduced back to form iodide. Due to chloramine being in high excess relative to iodide, the iodide can be oxidised to hypoiodous acid again and undergo the two reactions. It is considered that due to the cyclic nature of this reaction process with the-iodinated compounds being a final sink, increased concentrations of iodinated-DBPs may be a consequence of this choice of disinfection process (Bichsel and Gunten, 1999). This has been observed to be the case in studies reported in the literature.

In the study conducted in 2001-2002 by Krasner *et al*. (2006), iodinated-THMs concentrations were highest in waters disinfected with chloramines only. The use of only chloramines for disinfection is reported not always to meet virus or *Giardia* inactivation requirements in the US, therefore this disinfection process is not utilised at many plants that treat surface water (Krasner *et al*., 2006). It has been reported that the order of the addition of chlorine and ammonia during the disinfection process strongly influences the formation of iodinated-DBPs (Bichsel and Gunten, 1999). Bichsel and Gunten (1999) stated that when chlorine was added first, there was no iodoform formed. The lag-period between the addition of the chlorine and

the addition of the ammonia was 80 seconds. Within this short time, hypoiodous acid cannot be completely oxidised to iodate. It is considered that the formation of iodinated-THMs may be stalled by a reaction of HOCl with THM precursor sites on the natural organic matter (Bichsel and Gunten, 1999). The formation of iodinated compounds has been observed when ammonia is added before HOCl. Then the HOCl immediately reacts with ammonia to form chloramine, which will then lead to the cyclic reaction mentioned previously with the iodinated compounds as the final sink (Bichsel and Gunten, 1999). It is considered that when chloramines are used at plants as the secondary disinfectant, it should be possible to reduce the formation of iodinated-DBPs via sufficient free-chlorine contact time before the addition of ammonia to form chloramines or via the use of preozonation. This was observed in the US 2001-2002 survey where iodinated-THM formation was low in plants using free chlorine or ozone for primary disinfection (Krasner *et al*., 2006).

There is a case reported whereby a change from chlorination to chloramination caused the formation of 5 µg iodoform/l from an iodide concentration of 50 µg/l. In another case, where iodide concentrations were reported to be 200 µg/l and chloramination was used, up to 30 µg iodoform/l was formed with only low unspecified concentrations of traditional THMs detected. However, when chlorine was used to treat the same water, only traditional THMs were detected, with no iodoform being detected (Bichsel and Gunten, 2000). Although, iodoform has been detected in water following treatment with chlorination, this water had high levels of iodide, 150-200 µg/l, and iodination-THMs have been formed in an ozonation process, but this occurred during the failure of the ozonation step and iodide levels were relatively high, 90 µg/l (Bichsel and Gunten, 2000). Iodinated-THMs have been reported to occur in waters treated with chlorine, but having considerably lower iodide concentrations compared to that of the concentration of bromide (Bichsel and Gunten, 2000).

Laboratory studies have estimated that an increased free chlorine contact time resulted in reduced iodinated-DBPs formation. This is due to the rapid oxidation of iodide by chlorine to form iodate, which acts as a sink for iodide. A shorter free chlorine contact time is likely to increase the formation of iodinated-DBPs due to the oxidation of iodide to iodate by monochloramine is much slower than the reaction with natural organic matter (Richardson *et al*., 2008). Data gathered from an US study conducted in 2006 (Richardson *et al*., 2008), in which 23 treatment plants were sampled, supported the prediction of reduced iodinated-DBPs production with increased free chlorine contact time. At plant 10 (Table 2.3) where chlorination was utilised, iodinated-DBPs levels were among the lowest detected with concentrations of 0.049 and 0.47 µg/l of sum of iodinated acids and the sum of iodinated-THMs, respectively, and corresponding iodide levels and total organic carbon concentrations were 7.3 and 3500 µg/l, respectively. In those plants that used chloramination and utilised longer free chlorine contact times (>45 minutes), these included Plants 7, 8, 18, 20 and 23 were observed to have lower concentration of iodinated-DBPs. This was illustrated in Plant 18 which had a free chlorine contact time of approximately 1080 minutes and was reported to have very low iodinated-acids and iodinated-THMs levels of 0.09 and 0.46 µg/l, respectively with corresponding moderate iodide levels in the source water of 10.4 µg/l. The plants identified to have short free chlorine contact times (<1 minute), Plants 1, 2, 6, 12, 13, 15, 17 and 19, were found to have the highest levels of iodinated-DBPs. This was particularly evident in the three Plants, 1, 17 and 19 that had no free chlorine contact time, because chlorine and ammonia are added simultaneously to form chloramines or natural ammonia in the source waters which causes the immediate formation of chloramines upon addition of chlorine. These results show that the chlorine free contact time greatly effects the formation of iodinated-DBPs even where there are moderate levels of iodide in the source waters (Richardson *et al*., 2008).

The data in Table 3.9 below shows the extent that chloramination is used in the UK by the 24 UK water companies. Approximately 6% of the drinking water plants in the UK use chloramination.

**Table 3.9 UK water companies that use chloramination**

| Water Company | Number of drinking water plants | Number of drinking water plants that use chloramination |
|---|---|---|
| A | 142 | 10 |
| B | 18 | 0 |
| C | 7 | 7 |
| D | 22 | 0 |
| E | 1 | 0 |
| F | 6 | 1 |
| G | 79 | 6 |
| H | 26 | 9 |
| I | 18 | 0 |
| J | 3 | 0 |
| K | 39 | 1 |
| L | 19 | 0 |
| M | 8 | 8 |
| N | 97 | 0 |
| O | 95 | 0 |
| P | 27 | 0 |
| Q | 169 | 8 |
| R | 33 | 0 |
| S | 3 | 0 |
| T | 104 | 16 |
| U | 83 | 1 |
| V | 98 | 0 |
| W | 105 | 0 |
| X | 85 | 6 |

Companies A-X in the above table are not correlated to companies A-B mentioned in Section 2.2.

# 4. ESTIMATION OF IODINATED DBP CONCENTRATIONS

There have been several publications on the kinetics of formation of iodinated-DBPs (e.g. Bichsel and Von Gunten 2000) but these generally contain little information that could be used to create a model relating iodinated-DBP concentrations to water quality and treatment applied. However, in the case of chlorine as disinfectant, Hua *et al*. (2006) derived an equation that can be used to estimate the concentration of iodine that will be present as iodinated-DBPs (Total Organic Iodine, TOI).

Addition of chlorine to iodide-containing solutions results in the rapid and essentially complete oxidation of iodide to hypoiodous acid (HOI). The HOI then reacts either with natural organic matter (NOM) to yield iodinated-DBPs or with hypochlorous acid to yield iodate ion ($IO_3^-$). Hua *et al*. (2006) provide an equation for calculating $[IO_3^-]/[TOI]$ from which, for a given iodide concentration, TOI can be calculated.

Hua *et al*. (2006) listed the following important reactions:

$HOCl + I^- \rightarrow HOI + Cl^-$ $k_1 = 4.3 \times 10^8\ M^{-1}s^{-1}$ (1)

$HOCl + Br^- \rightarrow HOBr + Cl^-$ $k_2 = 1.55 \times 10^3\ M^{-1}s^{-1}$ (2)

$2HOCl + HOI \rightarrow IO_3^- + 2Cl^- + 3H^+$ $k_3 = 8.2\ M^{-1}s^{-1}$ (3)

$2OCl^- + HOI \rightarrow IO_3^- + 2Cl^- + H^+$ $k_4 = 52\ M^{-1}s^{-1}$ (4)

$HOCl + NOM \rightarrow Products$ $k_5 = 0.7 – 5\ M^{-1}s^{-1}$ (5)

$HOBr + NOM \rightarrow Products$ $k_6 = 15 – 167\ M^{-1}s^{-1}$ (6)

$HOI + NOM \rightarrow Products$ $k_7 = 0.1 – 0.4\ M^{-1}s^{-1}$ (7)

The ratio of $IO_3^-$ to TOI can be obtained by combining equations 3, 4 and 7:

$$\frac{[IO_3^-]}{[TOI]} = \frac{(\alpha_0 k_3 + \alpha_1 k_4)[HOCl]}{k_7[NOM]} \quad (8)$$

where square brackets represent molar concentrations and $\alpha_0$ and $\alpha_1$ are the proportions of HOCl and $OCl^-$ respectively.

The equilibrium constants for the formation of HOCl and $OCl^-$ are (Deborde and von Gunten 2008):

$Cl_{2(aq)} + H_2O \rightarrow HOCl + Cl^- + H^+$ $K_1 = 5.1 \times 10^{-4}$ (9)

$HOCl \rightarrow OCl^- + H^+$ $K_2 = 2.9 \times 10^{-8}$ (10)

By rearranging equations 9 and 10 and substituting in the mass balance equation

$$Total\ Chlorine = [Cl_{2(aq)}] + [HOCl] + [OCl^-] \quad (11)$$

the proportions of each of the chlorine species can be calculated as a function of pH. This is illustrated in Figure 4.1 (for an initial chloride concentration of 35 mg/l).

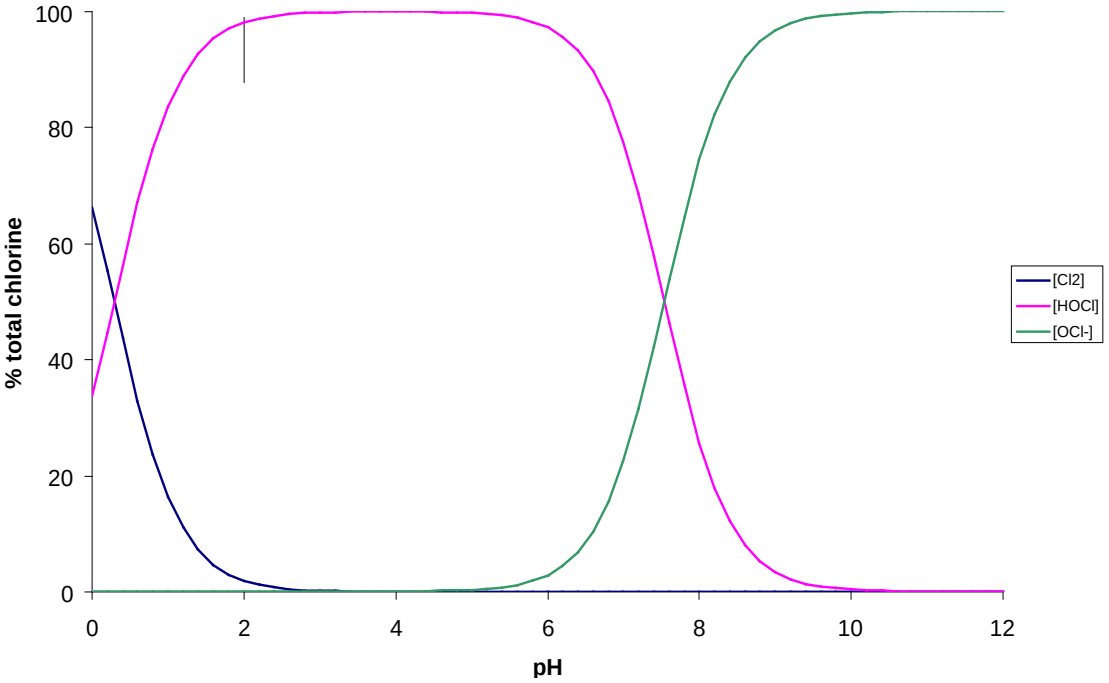


**Figure 4.1 Chlorine speciation diagram**

These proportions can be substituted in equation 8 and used to calculate the proportion of total iodide which will be incorporated in TOI (the remainder being present as iodate). To examine the effects of important variables a set of default conditions was chosen:

- pH 7
- Total chlorine 2 mg/l $Cl_2$
- TOC 5 mg/l C
- $k_7 = 0.25\ M^{-1}s^{-1}$

The effect of changing each of these variables in turn was examined whilst holding the other three at their default values. The results are given in Figure 4.2 to Figure 4.5:

- The formation of TOI is lowest at approximately pH 7.5 – a typical value during chlorination.
- TOI formation decreases with increasing chlorine dose – this is because higher chlorine concentrations favour the formation of iodate over TOI.
- TOI concentration increases with increasing TOC concentration (as expected).
- TOI concentration increases as $k_7$ is increased over the reported range (as expected).

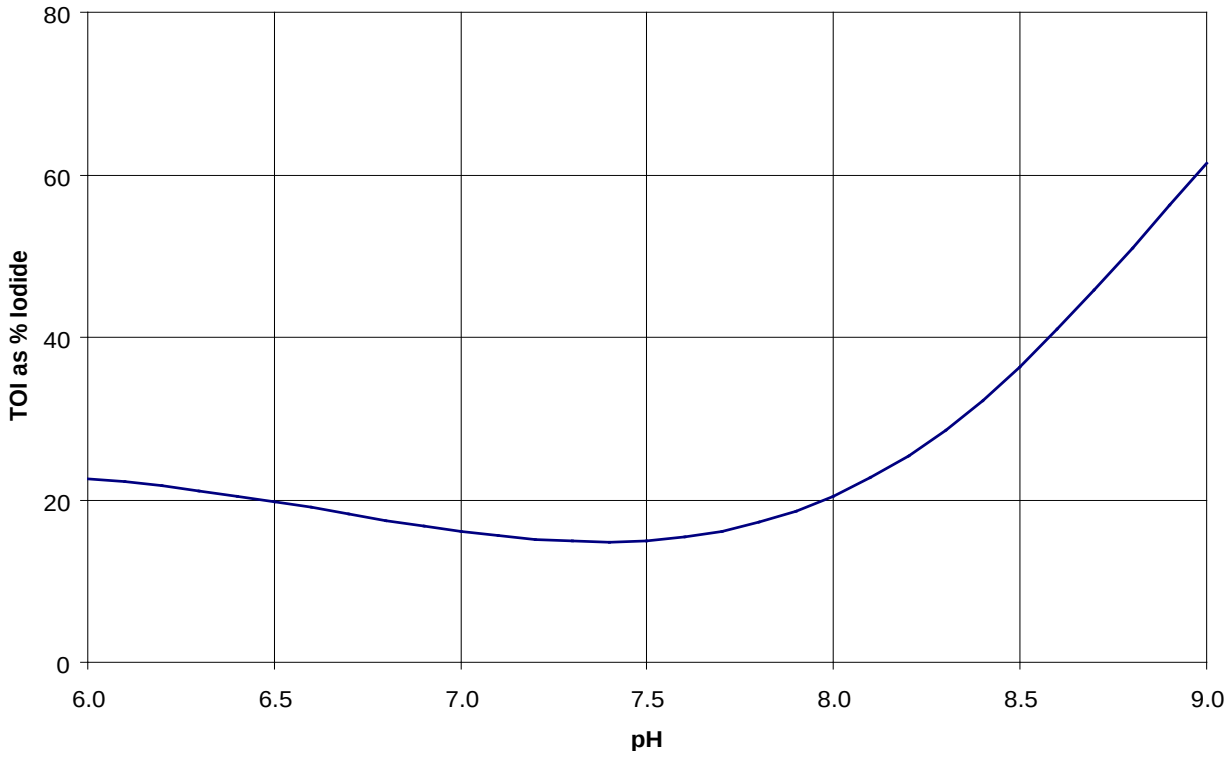


**Figure 4.2 Effect of pH on organic iodine concentration**

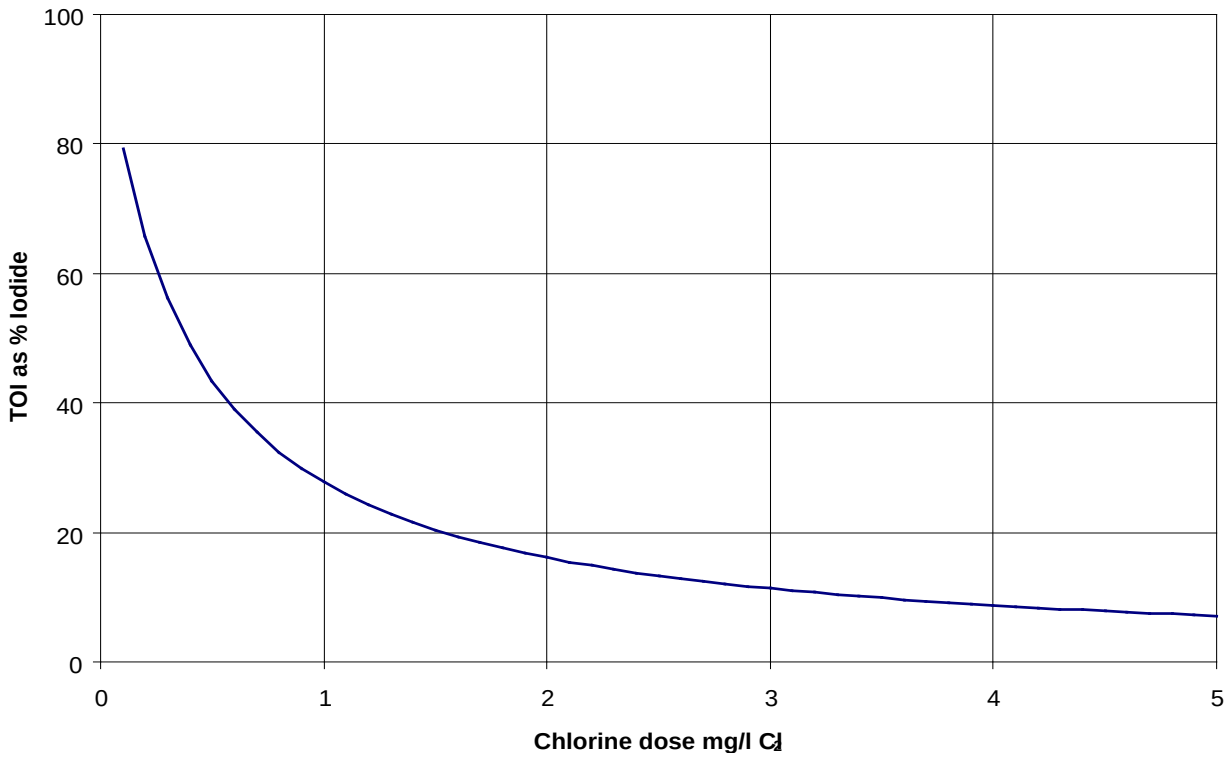


**Figure 4.3 Effect of chlorine dose on organic iodine concentration**

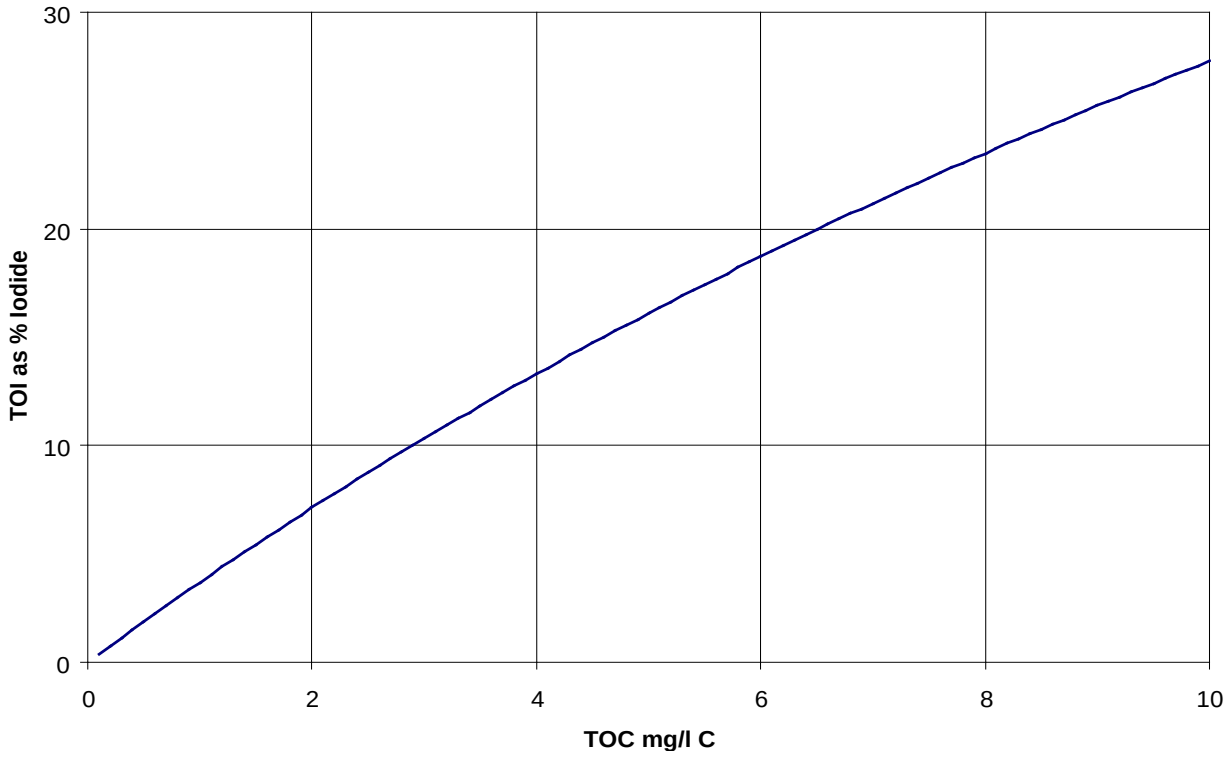


**Figure 4.4 Effect of TOC on organic iodine concentration**

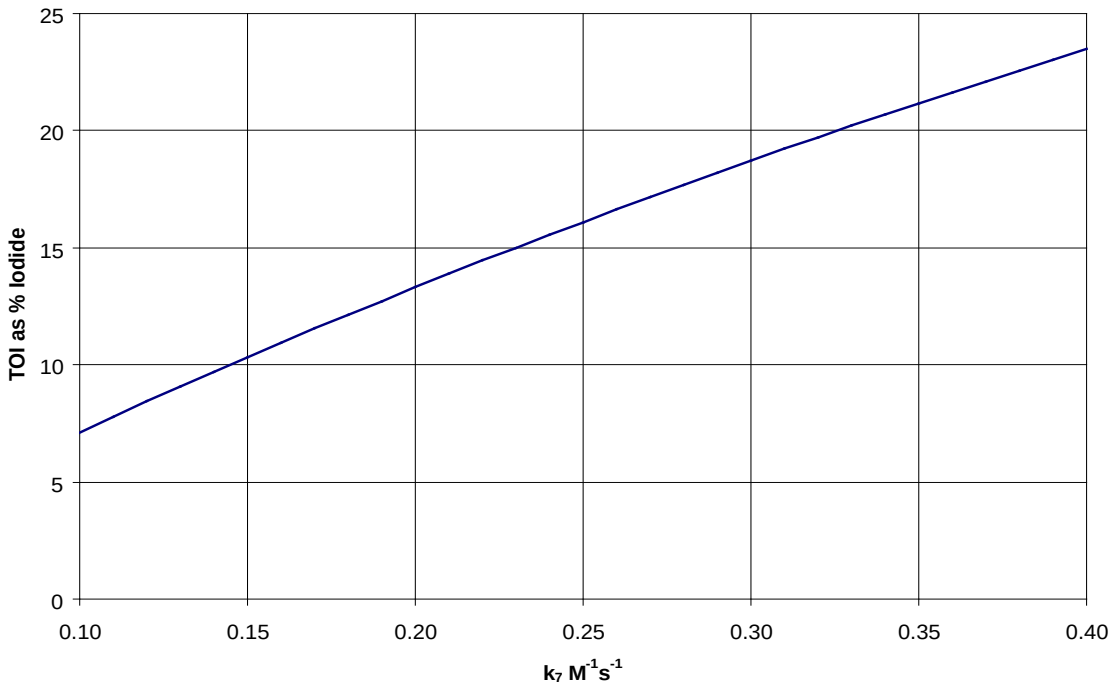


**Figure 4.5 Effect of $k_7$ on organic iodine concentration**

The results of using this model are in good agreement with the results of Bichsel and von Gunten (2000) for lake water but not river water. The reasons for this are unclear but the published study analysed for iodinated-DBPs, not TOI as modelled here.

Unfortunately the variability of the raw water iodide data (together with variable LODs) summarised in Section 3 means that it would not be appropriate to try to model TOI formation for 'real' iodide data. However, as a guide, for a raw water iodide concentration of 50 µg/l, the TOI concentration would be unlikely to exceed 10 µg/l under normal water quality and treatment conditions. This is probably an iodide concentration that is a high estimate from the studies outlined earlier in the report and for the maximum value of 12 µg/l of iodide seen in the Scottish study, the TOI would be 2-3 µg/l. Under the default assumptions and a raw water iodide concentration of 50 µg/l the resulting iodate concentration would be approximately 42 µg/l.

At present there is insufficient information to carry out similar modelling for other disinfectants such as chloramine and ozone. However, published information (e.g. Bichsel and von Gunten 1999, Bichsel and von Gunten 2000) indicates that chloramine will produce more iodinated-DBPs than chlorine because iodate is not formed in a competing reaction. However, the extent of iodinated-DBP formation during chloramination will depend on factors such as order of addition and delay time between addition of chlorine and ammonia. In the US 2006 study described above most sites used chloramination, the majority of iodide levels were at or below 10 µg/l and the majority of iodinated-DBP levels were below 2 µg/l see Table 2.3. Ozone does not produce organic iodinated-DBPs because practically all of the iodide present is converted to iodate.

# 5. TOXICOLOGICAL RISK ASSESSMENT OF IODINATED DISINFECTION BY-PRODUCTS

## 5.1 Glossary

CHO: Chinese hamster ovary

EU: European Union

IP: Intraperitoneal

IV: Intravenous

LD50: Lethal Dose required to kill 50% of a population

LC50: Lethal Concentration required to kill 50% of a population

NOAEL: No Observed Adverse Effect Level

NTP: National Toxicology Program

SCGE: Single Cell Gel Electrophoresis

## 5.2 Klimisch Codes

Klimisch codes are designed to provide a level for the quality of a study. They are based on three principles: adequacy, reliability and relevance of the available data (Klimisch *et al*., 1997). Definitions of Klimisch codes are provided below:

Reliable without restrictions (1): Studies or data generated according to internationally accepted testing guidelines, or test parameters documented are based on a specific testing guideline.

Reliable with restrictions (2): Studies or data that do not totally comply with the specific testing guideline, but are sufficient to accept the data as well documented and scientifically acceptable.

Not reliable (3): Studies or data in which there were interferences between the measuring system and the test substance or in which organisms/test systems were used which are not relevant, or generated according to a method which is not acceptable, the documentation of which is not sufficient for assessment and which is not convincing for an expert judgment.

Not assignable (4): Studies or data that do not give sufficient experimental details and are only listed in short abstracts or secondary literature.

The iodinated DBPs considered below are those for which there are some data although this are extremely limited. However, all the headings for toxicological data required have been included to indicate the gaps in knowledge needed to be filled for a complete risk assessment.

In the absence of a dataset of basic toxicological information for iodinated DBPs, most of the toxicity data in this section is based on the work of Michael Plewa and his group using a cytotoxicity assay in CHO cells together with an *in vitro* Comet assay. The cytotoxicity test is not indicative of mutagenicity but the results are included in the Genotoxicity section as they were conducted together with the Comet assay and may give some preliminary insight into possible toxicity that could be further investigated. The cytotoxicity assay was based on a range of concentrations from which a dose response was measured and a dose giving 50% cytotoxicity is derived (an $LC_{50}$). For the Comet assay, again a range of concentrations were measured which was determined by acute cytotoxicity although it is not clear whether the concentrations chosen were cytotoxic, not cytotoxic or spanning a range of toxicity.

Although the COMET assay has not been formally validated, the UK Committee on Mutagenicity of Chemicals in Food, Consumer Products and the Environment (COM) stated in 2005 that "the comet assay is well established as a supplementary assay to the standard battery of genotoxicity tests and can be used to assist in evaluating chemicals which have given equivocal results in other *in-vivo* mutagenicity tests or to investigate the potential mechanisms of tumourigenic responses.

The principle concerns that may arise in respect of the use of the comet assay are the relevance of the measured endpoint to the carcinogenic process, and the robustness and sensitivity of the method." (COM, 2005a).

However, these comments were for use of the Comet assay used *in vivo*, and for its use *in vitro,* there is more uncertainty and the COM has stated that "the relevance of the endpoint measured in the comet assay has yet to be established, as it is usually the result of a temporary strand breakage, which is repaired within a few hours under normal circumstances and may or may not become fixed as a mutation" (COM, 2005b)

Therefore, although the studies of Plewa *et al*. (2008) and Richardson *et al*. (2008) have led to much interest in the potential toxicity of iodinated DBPs, at present, there are insufficient toxicological data upon which to base a sound risk assessment.

## 5.3 Iodoacetic acid (CAS No: 64-69-7)

### 5.3.1 Toxicokinetics

No data have been located on the toxicokinetics of iodoacetic acid.

### 5.3.2 Acute toxicity

An oral $LD_{50}$ of 83 mg/kg bodyweight has been identified in mice (strain unknown), indicating that iodoacetic acid is of high acute toxicity (Lewis, 1996).[Klimisch code: 3]

No data are available on the acute toxicity of iodoacetic acid following dermal or inhalation routes of exposure. Iodoacetic acid is classified by the EU Directive on Classification and Labelling of Dangerous Substances as Toxic if Swallowed (EC, ATP, Unknown).

### 5.3.3 Irritation and sensitisation

Depilated guinea pigs (group size and strain unknown) were administered with iodoacetic acid onto their dorsum. Visible blisters appeared on the skin in 30 – 40 minutes. No further details are available (Flesch *et al*,1990). [Klimisch code: 3]

A number of inadequately reported studies examining iodoacetic acid's effects in the eye have been located. Iodoacetic acid causes destruction of the cells of the retina (in rabbits, strain unknown) and causes it to become oedematous. Cataracts have been detected in the eyes of rats (strain unknown) following intraperitoneal (IP) injection of iodoacetic acid. No details on testing regimens are available (HSDB, 2003). [Klimisch code: 3]

Although the studies available for these endpoints are not adequately reported, the effects seen indicate that iodoacetic acid is capable of causing severe damage to the skin and eyes of experimental animals. Iodoacetic acid is classified by the EU Directive on Classification and Labelling of Dangerous Substances as Corrosive (EC, ATP, Unknown).

### 5.3.4 Sensitisation

No data have been located on the sensitising properties of iodoacetic acid. Due to iodoacetic acid's corrosive nature, it is not considered that skin sensitisation will occur.

### 5.3.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of iodoacetic acid.

### 5.3.6 Genotoxicity

***In vitro***

Iodoacetic acid was mutagenic in a pre-incubation Ames test using *Salmonella* (strain TA100) (Plewa *et al*., 2008, Richardson *et al*., 2008). [Klimisch code: 1]

Weakly positive and inconclusive results were obtained in *Salmonella* Ames assays using iodoacetic acid (NTP, 1985). [Klimisch code: 1]

Iodoacetic acid was cytotoxic in Chinese hamster ovary (CHO) cells. Iodoacetic acid was also found to be positive in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Plewa *et al*., 2008, Richardson *et al*., 2008). [Klimisch code: 2]

Negative results were obtained in a reciprocal translocation/sex-linked recessive lethal assay with iodoacetic acid in *Drosophila* (Valencia *et al*, 1985). [Klimisch code: 1]

Overall, the limited data available suggest that iodoacetic acid has some genotoxic potential *in vitro.*

***In vivo***

No *in vivo* mutagenicity data are available.

### 5.3.7 Carcinogenicity

No data have been located on the carcinogenic potential of iodoacetic acid.

### 5.3.8 Reproductive Toxicity

No data have been located on the reproductive potential iodoacetic acid.

### 5.3.9 Summary

The publically available data for iodoacetic acid are limited and in some cases, poorly reported. Iodoacetic acid is acutely toxic via the oral route, corrosive and induces severe toxicity to the eye. There is limited evidence of mutagenicity *in vitro* but this is insufficient to draw any conclusions. Lack of data inhibits the identification of long term or reproductive effects and the establishment of NOAELs.

## 5.4 (E)-3-bromo-3-iodopropanoic acid (CAS No: 59110-12-2)

### 5.4.1 Toxicokinetics

No data have been located on the toxicokinetics of (e)-3-bromo-3-iodopropanoic acid.

### 5.4.2 Acute Toxicity

No data have been located on the acute toxicity of (e)-3-bromo-3-iodopropanoic acid.

### 5.4.3 Irritation

No data have been located on the potential for (e)-3-bromo-3-iodopropanoic acid to cause irritation.

### 5.4.4 Sensitisation

No data have been located on the potential for (e)-3-bromo-3-iodopropanoic acid to cause sensitisation.

### 5.4.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of (e)-3-bromo-3-iodopropanoic acid.

### 5.4.6 Genotoxicity

(E)-3-bromo-3-iodopropanoic acid was cytotoxic in Chinese hamster ovary (CHO) cells. (E)-3-bromo-3-iodopropanoic acid was also found to be positive in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.4.7 Carcinogenicity

No data have been located on the carcinogenicity of (e)-3-bromo-3-iodopropanoic acid.

### 5.4.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of (e)-3-bromo-3-iodopropanoic acid.

### 5.4.9 Summary

Limited data are available on the toxicity of (e)-3-bromo-3-iodopropanoic acid. The one available study indicates that (e)-3-bromo-3-iodopropanoic acid is cytotoxic and there is limited evidence of mutagenicity *in vitro* but this is insufficient to draw any conclusions.

## 5.5 (Z)-3-bromo-3-iodopropanoic acid (CAS No: 59110-12-2)

### 5.5.1 Toxicokinetics

No data have been located on the toxicokinetics of (z)-3-bromo-3-iodopropanoic acid.

### 5.5.2 Acute Toxicity

No data have been located on the acute toxicity of (z)-3-bromo-3-iodopropanoic acid.

### 5.5.3 Irritation

No data have been located on the potential for (z)-3-bromo-3-iodopropanoic acid to cause irritation.

### 5.5.4 Sensitisation

No data have been located on the potential for (z)-3-bromo-3-iodopropanoic acid to cause sensitisation.

### 5.5.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of (z)-3-bromo-3-iodopropanoic acid.

### 5.5.6 Genotoxicity

(Z)-3-bromo-3-iodopropanoic acid was cytotoxic in Chinese hamster ovary (CHO) cells. However, (z)-3-bromo-3-iodopropanoic acid was negative in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.5.7 Carcinogenicity

No data have been located on the carcinogenicity of (z)-3-bromo-3-iodopropanoic acid.

### 5.5.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of (z)-3-bromo-3-iodopropanoic acid.

### 5.5.9 Summary

Limited data are available on the toxicity of (z)-3-bromo-3-iodopropanoic acid. The one available study indicates that (z)-3-bromo-3-iodopropanoic acid is cytotoxic, but is not genotoxic *in vitro*.

## 5.6 Bromoiodoacetic acid (CAS No: 71815-43-5)

### 5.6.1 Toxicokinetics

No data have been located on the toxicokinetics of bromoiodoacetic acid.

### 5.6.2 Acute Toxicity

No data have been located on the acute toxicity of bromoiodoacetic acid.

### 5.6.3 Irritation

No data have been located on the potential for bromoiodoacetic acid to cause irritation.

### 5.6.4 Sensitisation

No data have been located on the potential for bromoiodoacetic acid to cause sensitisation.

### 5.6.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of bromoiodoacetic acid.

### 5.6.6 Genotoxicity

Bromoiodoacetic acid was cytotoxic in Chinese hamster ovary (CHO) cells. Bromoiodoacetic acid was also found to be positive in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.6.7 Carcinogenicity

No data have been located on the carcinogenicity of bromoiodoacetic acid.

### 5.6.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of bromiodoacetic acid.

### 5.6.9 Summary

Limited data are available on the toxicity of bromiodoacetic acid. The one available study indicates that bromiodoacetic acid is cytotoxic, and there is limited evidence of mutagenicity *in vitro* but this is insufficient to draw any conclusions.

## 5.7 Bromodiiodomethane (CAS No: 557-95-9)

### 5.7.1 Toxicokinetics

No data have been located on the toxicokinetics of bromodiiodomethane.

### 5.7.2 Acute Toxicity

No data have been located on the acute toxicity of bromodiiodomethane.

### 5.7.3 Irritation

No data have been located on the potential for bromodiiodomethane to cause irritation.

### 5.7.4 Sensitisation

No data have been located on the potential for bromodiiodomethane to cause sensitisation.

### 5.7.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of bromodiiodomethane.

### 5.7.6 Genotoxicity

Bromodiiodomethane was cytotoxic in Chinese hamster ovary (CHO) cells. However, bromodiiodomethane was negative in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.7.7 Carcinogenicity

No data have been located on the carcinogenicity of bromodiiodomethane.

### 5.7.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of bromodiiodomethane.

### 5.7.9 Summary

Limited data are available on the toxicity of bromodiiodomethane. The one available study indicates that bromodiiodomethane is cytotoxic, but does not cause genotoxicity, *in vitro*.

## 5.8 Iodoform (CAS No: 75-47-8)

### 5.8.1 Toxicokinetics

No data have been located on the toxicokinetics of iodoform.

### 5.8.2 Acute Toxicity

Several acute toxicity studies are available for iodoform.

**Oral**

Oral $LD_{50}$s of 355, 450 and 487 mg iodoform/kg bodyweight have been identified in the rat, rabbit and guinea pig, respectively. Altered sleeping duration, general depression of activity and changes in righting reflex and dyspnoea were observed in all of these species (Turkmenistana, 1983). [Klimisch code: 3]

A mouse oral $LD_{50}$ of 470 mg/kg bodyweight has been identified (Sanitariya, 1987). [Klimisch code: 3]

**Inhalation**

An inhalation $LC_{50}$ of 165 mg iodoform/kg has been identified in Sprague Dawley rats. Respiratory stimulation was observed following administration of the test compound (Tansy *et al*., 1981). [Klimisch code: 2]

**Dermal**

A dermal $LD_{50}$ of 1184 mg iodoform/kg bodyweight was identified in rats. Altered sleeping duration, general depression of activity and changes in righting reflex and dyspnoea were observed (Turkmenistana, 1983). [Klimisch code: 3]

Iodoform is of moderate acute oral toxicity, low acute toxicity via inhalation, and of moderate acute toxicity to the skin.

### 5.8.3 Irritation

No data have been located on the potential for iodoform to cause irritation.

### 5.8.4 Sensitisation

No data have been located on the potential for iodoform to cause sensitisation.

### 5.8.5 Repeat Dose Toxicity

A 6 week range-finding oral study has been completed in Osborne Mendel rats and B6C3F1 mice. Rats (5/dose group) were dosed for 5 days per week via gavage with 0, 56, 100, 178, 316 or 562 mg iodoform/kg bw/day, whereas mice (5/dose group) were dosed with 0, 18, 32, 56, 100 or 178 mg iodoform/kg bw/day (NTP, 1978). Animals were observed for a further two weeks following cessation of dosing.

Deaths occurred in the two highest male rat dose groups and in all the female dose groups. Reduced bodyweight was also observed in male rats in the two highest dose groups and in female rats in all dose groups.

Male mice died in the two highest dose groups and female mice died in highest dose group. A reduction in bodyweight was also observed in female mice in the highest dose group.

A NOAEL of 178 mg/kg bw/day can be identified for male rats. Due to effects at the lowest dose, a NOAEL cannot be derived for female rats. However, using this lowest dose an arbitrary LOAEL of 56 mg/kg bw/day for female rats can be identified from this study. NOAELs of 56 and 100 mg/kg bw/day can be identified for male and female mice, respectively.

Deaths and an associated decrease in bodyweight occurred in rats and mice administered with iodoform via gavage in a repeated dose study. The severity of the effect seen (i.e. mortality) may indicate that the doses used in the available study are too high to be able to assess underlying, less toxic, effects. [Klimisch code: 1]

### 5.8.6 Genotoxicity

***In vitro***

Iodoform was positive in two *Salmonella* Ames assays. Iodoform was also weakly positive in a Sister Chromatid Exchange assay, but negative in a chromosome aberration assay (Haworth S *et al*, 1983). [Klimisch code: 2]

Iodoform was cytotoxic in Chinese hamster ovary (CHO) cells. However, iodoform was negative in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

***In vivo***

No *in vivo* mutagenicity studies have been located for iodoform.

Results indicate that iodoform has some genotoxic potential *in vitro*, but the *in vivo* mutagenicity of iodoform cannot be assessed, owing to lack of data.

### 5.8.7 Carcinogenicity

Osborne Mendel rats (50/sex/dose group) were administered 0, 71 or 142 (males) and 0, 27 or 55 (females) mg iodoform/kg bw/day for 5 days per week for 78 weeks via gavage. Animals were observed for a further 34 weeks following cessation of dosing. Animals were observed for bodyweight changes, changes in food consumption, evidence of clinical signs and palpable masses. Micro- and gross histopathology were performed on deceased animals.

Clinical signs remained similar in control and treated animals. A significant dose related increase in time of mortality occurred in male rats; 26/50 males in the low dose group had died by week 76 and 25/50 males in the high dose group had died by week 46 of the study. Food consumption and bodyweight were not affected by administration of iodoform. An increase in thyroid follicular cell carcinomas (and adenoma, combined, in males) were detected in male and female rats (0/16, 8/35 and 4/18 for control, low and high dose males and 0/20, 4/40 and 2/42 for control, low and high dose females, respectively). However, the incidences of these tumours were not statistically significant. Due to effects at the lowest dose, a NOAEL cannot be derived for male rats, however, using this lowest dose a LOAEL of 71 mg/kg bw/day for males and a NOAEL of 55 mg/kg bw/day for females have been identified from this study (NTP, 1978).. [Klimisch code 1]

B6C3F1 mice (50/sex/dose group) were administered 0, 47 or 93 mg iodoform/kg bw/day for 5 days per week for 78 weeks via gavage. Animals were observed for a further 12 or 14 weeks following cessation of dosing. Animals were observed for bodyweight changes, changes in food consumption, evidence of clinical signs, palpable masses. Micro and gross histopathology were performed on deceased animals.

Clinical signs and survival remained similar in control and treated animals. Food consumption and bodyweight were not affected by administration of iodoform. An increase in malignant lymphomas were detected in male mice in the high dose group (2/19, 3/50 and 10/50 for control, low and high dose males, respectively). However, the incidences of these tumours were not statistically significant and are of a tumour type known to occur commonly in mice.

Statistically significant increases in substance related tumours were not observed in female mice. A NOAEL of 93 mg/kg bw/day for male and female mice has been identified from this study (NTP, 1978). [Klimisch code 1]

No evidence of a statistically significant increase in tumours in rats and mice due to the administration of iodoform was found in well reported long-term studies.

### 5.8.8 Reproductive Toxicity

No data on the reproductive toxicity of iodoform have been located.

### 5.8.9 Summary

Iodoform is of moderate acute oral toxicity, of low acute toxicity via inhalation, and of moderate acute toxicity to the skin. Iodoform is an *in vitro* mutagen, but the *in vivo* mutagenicity of iodoform cannot be assessed, due to lack of data. Iodoform was not carcinogenic in rats or mice in well reported 2-year bioassays. A NOAEL of 178 mg/kg bw/day for male rats and an arbitrary LOAEL of 56 mg/kg bw/day for female rats can be identified from a short term study. NOAELs of 56 and 100 mg/kg bw/day can be identified for male and female mice, respectively, also from a short term study. In rats, an arbitrary LOAEL of 71 mg/kg bw/day for males and a NOAEL of 55 mg/kg bw/day for females have been identified from a long term study and a NOAEL of 93 mg/kg bw/day has been identified for male and female mice (NTP, 1978).

**Table 5.1 NOAEL and LOAELs derived for iodoform**

| Study Duration | Species | Sex | NOAEL (mg/kg bw/day) dosage based on 5 days per week exposure | NOAEL (mg/kg bw/day) dosage based on daily exposure (approximate and rounded) | LOAEL (mg/kg bw/day) dosage based on 5 days per week exposure | LOAEL (mg/kg bw/day) dosage based on daily exposure (approximate and rounded) | Klimisch Code | Reference |
|---|---|---|---|---|---|---|---|---|
| 60 days | rat | M | 178 | 127 | - | - | 1 | NTP, 1978 |
| | | F | - | - | 56 | 40 | | |
| 60 days | mouse | M | 56 | 40 | - | - | 1 | NTP, 1978 |
| | | F | 100 | 71 | - | - | | |
| 78 weeks | rat | M | - | - | 71 | 51 | 1 | NTP, 1978 |
| | | F | 55 | 39 | - | - | | |
| 78 weeks | mouse | M | 93 | 66 | - | - | 1 | NTP, 1978 |
| | | F | 93 | 66 | - | - | | |

For a chemical with a threshold level for toxicity, it would be possible to use the NOAELs from the above studies to derive a Tolerable Daily Intake (TDI) for humans using appropriate uncertainty factors. However, iodoform, although it is not carcinogenic in animal tests, is potentially mutagenic as it is positive in the Ames test and there are no data for *in vivo* mutagenicity to confirm or deny this potential. Therefore, until further toxicity data are available, it must be assumed to have no threshold of effect and exposure should be as low as reasonably practicable. Therefore, in the absence of sufficient toxicological data, it is not possible to identify a concentration of iodoform (either as a TDI or a potential concentration in water) that is of no concern for human health.

## 5.9 (E)-2-iodo-3-methylbutenedioic acid (CAS No: 769146-63-6)

### 5.9.1 Toxicokinetics

No data have been located on the toxicokinetics of (e)-2-iodo-3-methylbutenedioic acid.

### 5.9.2 Acute Toxicity

No data have been located on the acute toxicity of (e)-2-iodo-3-methylbutenedioic acid.

### 5.9.3 Irritation

No data have been located on the potential for (e)-2-iodo-3-methylbutenedioic acid to cause irritation.

### 5.9.4 Sensitisation

No data have been located on the potential for (e)-2-iodo-3-methylbutenedioic acid to cause sensitisation.

### 5.9.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of (e)-2-iodo-3-methylbutenedioic acid.

### 5.9.6 Genotoxicity

(E)-2-iodo-3-methylbutenedioic acid was cytotoxic in Chinese hamster ovary (CHO) cells. (E)-2-iodo-3-methylbutenedioic acid was also found to be positive in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.9.7 Carcinogenicity

No data have been located on the carcinogenicity of (e)-2-iodo-3-methylbutenedioic acid.

### 5.9.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of (e)-2-iodo-3-methylbutenedioic acid.

### 5.9.9 Summary

Limited data are available on the toxicity of (e)-2-iodo-3-methylbutenedioic acid. The one available study indicates that (e)-2-iodo-3-methylbutenedioic acid is cytotoxic, and there is limited evidence of mutagenicity *in vitro* but this is insufficient to draw any conclusions.

## 5.10 Dichloroiodomethane (CAS No: 594-04-7)

### 5.10.1 Toxicokinetics

No data have been located on the toxicokinetics of dichloroiodomethane.

### 5.10.2 Acute Toxicity

No data have been located on the acute toxicity of dichloroiodomethane.

### 5.10.3 Irritation

No data have been located on the potential for dichloroiodomethane to cause irritation.

### 5.10.4 Sensitisation

No data have been located on the potential for dichloroiodomethane to cause sensitisation.

### 5.10.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of dichloroiodomethane.

### 5.10.6 Genotoxicity

Dichloroiodomethane was cytotoxic in Chinese hamster ovary (CHO) cells. However, dichloroiodomethane was negative in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.10.7 Carcinogenicity

No data have been located on the carcinogenicity of dichloroiodomethane.

### 5.10.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of dichloroiodomethane.

### 5.10.9 Summary

Limited data are available on the toxicity of dichloroiodomethane. The one available study indicates that dichloroiodomethane is cytotoxic, but is not genotoxic.

## 5.11 Chlorodiiodomethane (CAS No: 638-73-3)

### 5.11.1 Toxicokinetics

No data have been located on the toxicokinetics of chlorodiiodomethane.

### 5.11.2 Acute Toxicity

No data have been located on the acute toxicity of chlorodiiodomethane.

### 5.11.3 Irritation

No data have been located on the potential for chlorodiiodomethane to cause irritation.

### 5.11.4 Sensitisation

No data have been located on the potential for chlorodiiodomethane to cause sensitisation.

### 5.11.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of chlorodiiodomethane.

### 5.11.6 Genotoxicity

Chlorodiiodomethane was cytotoxic in Chinese hamster ovary (CHO) cells. Chlorodiiodomethane was also found to be positive in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.11.7 Carcinogenicity

No data have been located on the carcinogenicity of chlorodiiodomethane.

### 5.11.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of chlorodiiodomethane.

### 5.11.9 Summary

Limited data are available on the toxicity of chlorodiiodomethane. The one available study indicates that chlorodiiodomethane is cytotoxic and there is limited evidence of mutagenicity *in vitro* but this is insufficient to draw any conclusions.

## 5.12 Dibromoiodomethane (CAS No: 593-94-2)

### 5.12.1 Toxicokinetics

No data have been located on the toxicokinetics of dibromoiodomethane.

### 5.12.2 Acute Toxicity

No data have been located on the acute toxicity of dibromoiodomethane.

### 5.12.3 Irritation

No data have been located on the potential for dibromoiodomethane to cause irritation.

### 5.12.4 Sensitisation

No data have been located on the potential for dibromoiodomethane to cause sensitisation.

### 5.12.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of dibromoiodomethane.

### 5.12.6 Genotoxicity

Dibromoiodomethane was cytotoxic in Chinese hamster ovary (CHO) cells. However, dibromoiodomethane was negative in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.12.7 Carcinogenicity

No data have been located on the carcinogenicity of dibromoiodomethane.

### 5.12.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of dibromoiodomethane.

### 5.12.9 Summary

Limited data are available on the toxicity of dibromoiodomethane. The one available study indicates that dibromoiodomethane is cytotoxic, but is not genotoxic *in vitro*.

## 5.13 Bromochloroiodomethane (CAS No: 34970-00-8)

### 5.13.1 Toxicokinetics

No data have been located on the toxicokinetics of bromochloroiodomethane.

### 5.13.2 Acute Toxicity

No data have been located on the acute toxicity of bromochloroiodomethane.

### 5.13.3 Irritation

No data have been located on the potential for bromochloroiodomethane to cause irritation.

### 5.13.4 Sensitisation

No data have been located on the potential for bromochloroiodomethane to cause sensitisation.

### 5.13.5 Repeat Dose Toxicity

No data have been located on the repeat dose toxicity of bromochloroiodomethane.

### 5.13.6 Genotoxicity

Bromochloroiodomethane was cytotoxic in Chinese hamster ovary (CHO) cells. However, bromochloroiodomethane was negative in a Single Cell Gel Electrophoresis (SCGE) COMET assay in Chinese hamster ovary (CHO) cells (Richardson *et al*., 2008). [Klimisch code: 2]

### 5.13.7 Carcinogenicity

No data have been located on the carcinogenicity of bromochloroiodomethane.

### 5.13.8 Reproductive Toxicity

No data have been located on the reproductive toxicity of bromochloroiodomethane.

### 5.13.9 Summary

Limited data are available on the toxicity of bromochloroiodomethane. The one available study indicates that bromochloroiodomethane is cytotoxic, but is not genotoxic *in vitro*.

## 5.14 Iodate (CAS No: 1545-4-31-6)

The majority of the available data, for iodate are for sodium or potassium iodate salts (CAS No. 7681-55-2 and 7758-05-6, respectively).

### 5.14.1 Human toxicity

A 22 year old man was reported to have ingested a highly concentrated solution of potassium iodate (quantity unknown). Nausea, vomiting, diarrhoea and marked loss of visual acuity occurred. Ophthalmoscopic examination revealed extensive retinal damage with degeneration of photoreceptor layers. It is expected that the dose exceeded 100 mg/kg bw (Webster, 1957). [Klimisch code: 4]

Systemic administration of an antibacterial preparation containing iodate prescribed for septicaemia (Septojod), resulted in blindness, following damage to the pigment epithelium (Lewis, 1996). [Klimisch code: 4]

The recommended level of iodine is between 20 and 80 mg/kg of salt (equal to 28 - 110 mg iodate/kg salt). Assuming a maximum daily intake of salt of 15 g, a human exposure of 440 - 1700 µg of iodate/day occurs (9-34 µg/kg bw/day, assuming body weights of 50-70 kg) (Burgi *et al*., 2001). [Klimisch code: 4]

### 5.14.2 Toxicokinetics

Radiolabelled iodate ($^{131}$I) was administered via i.v. injection to rabbits (no further experimental details available) (Grant, 1974). Radiolabel was absorbed rapidly into aqueous and vitreous humours of the eye (time unknown). Any radiolabel remaining in blood persisted for many hours and was gradually reduced by the liver to iodide. [Klimisch code: 4]

Rats and rabbits (strain unknown) were administered 0.75-1 µg iodine via the oral route or intraperitoneally. Radioiodine was extensively distributed and found in the liver, kidney, brain, heart, muscle, small intestine, stomach, testes, submaxillary gland, skin, hair and thyroid (values unknown). Tissue distribution was the same for both iodine and iodate (Taurog *et al*., 1966). [Klimisch code: 3]

When added to animal feed, iodate increases the level of iodine in eggs and milk (animal species unknown) (Burgi *et al*., 2001). No further details are available. [Klimisch code: 4]

Iodate was administered via i.v. injection to rats (dose and strain unknown). Iodate in blood was reduced to iodide within 40 minutes (Burgi *et al*., 2001). No further details are available. [Klimisch code: 4]

The reduction of iodate has been shown to be a non-enzymatic process and depends on the availability of sulfhydryl groups. It is inhibited by N-ethyl-maleimide (Burgi *et al*., 2001). No further details are available. [Klimisch code: 4]

Dogs (strain unknown) were fed gelatine capsules containing a single dose of 200 mg potassium iodate/kg bw. Urine from these dogs contained iodide and iodate (Burgi *et al*., 2001) (no further details are available). This suggests that iodate is converted to iodine (extent unknown) and the urine is a primary route of excretion (extent unknown). [Klimisch code: 4]

Iodate is rapidly absorbed and extensively distributed. It is metabolised via a non-enzymatic process, with a proportion of the available iodate converted to iodine. Iodate is excreted via the kidneys.

### 5.14.3 Acute Toxicity

A review states that in humans, iodate salts are rated as very toxic. The lethal dose is of the same magnitude as the $LD_{50}$ for experimental animals (outlined below; Anon, 1995). [Klimisch code: 4]

Webster *et al.* (1995) investigated acute oral toxicity of iodate in white Swiss mice. Intoxification occurred in animals administered iodate, followed by mortality. Mortality was attributed to renal damage, with retention of non-protein nitrogen. Haemoglobinuria occurred in the animals and haemoglobin casts and haemosiderin deposits were found in the kidneys. Non-specific fatty visceral changes also occurred in animals, within 24 hours of exposure to iodate. The pH of the animals' gastric contents was increased, accompanied by degenerative changes in the parietal cells, however, the effects was transient and pH recovered 24 hours after administration of the test compound. Oral $LD_{50}$s of 500-1100 mg iodate/kg bw have been identified from this study, indicating that iodate is of low acute oral toxicity. [Klimisch code: 3]

An oral $LD_{50}$ of 505 mg sodium iodate (6%)/kg bw was identified in female white Swiss mice, indicating that it is of low acute oral toxicity (Anon, 1995). [Klimisch code: 4]

Rabbits (strain, sex and dose group size unknown) were dosed with 50 mg/kg bw via i.v. injection. Mortality did not occur, but characteristic pigmentation changes were observed in the retina, 7 days post dose (Murray, 1953). No further details are available. [Klimisch code: 4]

### 5.14.4 Irritation

No data have been located on the potential for iodate to cause irritation.

### 5.14.5 Sensitisation

No data have been located on the potential for iodate to cause sensitisation.

### 5.14.6 Repeat Dose Toxicity

Three male and 4 female rabbits (strain unknown) were orally administered 1 mg iodate/kg bw, twice weekly for up to 14 months. Two rabbits were killed after 4 months and 5 after 8 months. Reasons for sacrifice were not stated. Animals were examined ophthalmoscopically and histologically. The thyroid, liver and kidneys of the animals were also examined histopathologically. No adverse clinical signs were observed during the study. No adverse ophthalmalogical findings were observed and all histological examinations were considered to be normal (Murray, 1953). Due to the use of a single dose group, a NOAEL cannot be identified from this study. [Klimisch code: 3]

In a poorly reported study, mice were administered iodate in drinking water (strain, dose group and sizes and study duration unknown). Haemolysis and renal damage were reported to occur from 300 mg/kg bw/day, in a dose dependent manner. A NOAEL of 120 mg iodate/kg bw/day has been reported for this study (Webster *et al*., 1957). [Klimisch code: 4]

In a second poorly reported study, guinea pigs were administered iodate in drinking water (strain, dose group and sizes and study duration unknown). No effects were observed at doses of 300 mg/kg bw/day (Webster *et al*., 1957). An arbitrary NOAEL of 300 mg/kg bw/day can be identified from this study (due to lack of effects at the highest dose tested). [Klimisch code: 4]

Four dogs were administered 6 to 100 mg iodate/kg bw/day via capsule for several months (strain, dose group and sizes and exact study duration unknown). Retinal damage did not occur. Gastric toxicity (unspecified) and haemolysis were observed (doses at which effects occurred are unknown) (Webster *et al*., 1966). [Klimisch code: 4]

### 5.14.7 Mechanistic studies

The retinal pigment epithelium is a specific target of iodate toxicity and is associated with the oxidising properties of iodate. Several studies have been performed to further elucidate this response.

Rats were administered a single dose of 10 mg sodium iodate/kg via i.v. injection. The retinal pigment epithelium of the animals was visibly damaged, inducing cell injury and a proliferative response (Burgi *et al*., 2001). No further details are available. [Klimisch code: 4]

Following administration of iodate and subsequent recording via electroretinograms, i.v. injection of 20 mg iodate/kg produced retinal damage, whereas 12.5 mg iodate/kg had no effect (Burgi *et al*., 2001). No further details are available. [Klimisch code: 4]

### 5.14.8 Genotoxicity

Sodium iodate gave negative results in *in vitro* Ames, micronucleus and recessive lethal (*D. melanogaster*) genotoxicity tests (Eckhardt *et al*., 1982). Conversely, bromate which is considered a genotoxic agent, induced a significant increase in the frequency of micronucleated cells. No further details on the experiments are available. [Klimisch code: 4]

Potassium iodate has been tested for genotoxicity in a COMET assay and a micronucleus assay in CHO cells (Poul, 2004). Concentrations of up to 10mM potassium iodate did not

result in DNA damage in the COMET assay. Absence of primary DNA damage was confirmed in the micronucleus assay. [Klimisch code: 2]

In a further COMET assay, iodate induced DNA strand breakages in the rat kidney epithelium (dose and route of administration not stated). This effect was apparent at the first measured time point (15 minutes following treatment). DNA strand breakage then decreased at 4 hours and remained constant until 24 hours. DNA strand breakage by bromate displayed a second activity peak at 24 hours. (Burgi *et al*., 2001). No further details are available. [Klimisch code: 4]

Sodium iodate has radiosensitising activity and has been shown to increase the number of gamma radiation-induced single-strand DNA breaks in bacteria (Myers and Chetty, 1973). No further information available. [Klimisch code: 3]

### 5.14.9 Carcinogenicity

No data have been located on the carcinogenicity of iodate.

### 5.14.10 Reproductive Toxicity

Three male and 4 female rabbits (strain unknown) were orally administered 1 mg iodate/kg bw, twice weekly. Two rabbits were killed after 4 months and 5 after 8 months. Reasons for sacrifice were not stated. Animals were examined ophthalmoscopically and histologically. The thyroid, liver and kidneys of the animals were also examined histopathologically. No adverse clinical signs were observed during the study. No adverse ophthalmalogical findings were observed and all histological examinations were considered to be normal.

Offspring of the exposed rabbits (who were exposed *in utero* and during lactation; details were not reported) were also administered orally administered 1 mg iodate/kg bw, twice weekly from 2 months of age. Three rabbits were killed after 5.5 months dosing and 2 after 7 months dosing. The study lasted for 14 months. It is reported that no toxic effects were observed (Murray, 1953). Due to the use of a single dose group, a NOAEL cannot be identified from this study. [Klimisch code: 3]

### 5.14.11 Summary

Iodate is rapidly absorbed and extensively distributed. It is metabolised via a non-enzymatic process, with a proportion of the available iodate converted to iodine. It is then excreted via the kidneys.

Iodate is of low acute oral toxicity in experimental animals. Data for longer term studies are limited; however, gastric, renal, and ophthalmological effects are manifested in the longer-term studies available. Iodate is negative in an array of *in vitro* genotoxicity studies, although positive and negative results were obtained in the COMET assay. There is no evidence of reproductive or developmental toxicity although the quality of the studies is poor.

**Table 5.2 NOAEL and LOAELs derived for iodate**

| Study Duration | Species | Sex | NOAEL (mg/kg bw/day) | LOAEL (mg/kg bw/day) | Klimisch Code | Reference |
|---|---|---|---|---|---|---|
| unknown | mouse | unknown | 120 | - | 4 | Webster, 1957 |
| unknown | guinea pig | unknown | 300 | - | 4 | Webster, 1957 |

## 5.15 Toxicology Summary

Publically available mammalian toxicity data for twelve iodinated substances has been reviewed. For the majority of the compounds only cytotoxicity and COMET assay data are available. Further limited data are available for iodoacetic acid, iodoform and iodate. Iodoacetic acid is of high acute toxicity by the oral route, corrosive and induces toxicity to the eye, and is positive in the Ames test. Iodoform is of lower toxicity and is not carcinogenic, although positive in an Ames test. Iodate is of low acute toxicity but leads to renal, gastric, and retinal damage when administered longer term. Six of the iodinated DBPs show some evidence of cytotoxicity or mutagenicity *in vitro* (by the COMET assay), but there are no data on *in vivo* effects. In general, the iodo-THMs were not genotoxic while the iodoacids were positive in the Comet assay.

The lack of conventional toxicity data makes it impossible to assess the risk to human health of the presence of iodinated DBPs in drinking water. The only comparative data available are from the work of Plewa and his group on the CHO cell cytotoxicity assay (Plewa *et al*., 2008; Richardson *et al*., 2008; Richardson, S. Pers. Comm., 2009). The results from these studies show that, generally, in terms of cytotoxicity and mutagenicity in the Comet assay *in vitro*, iodoacetic acid > bromoacetic acid > chloroacetic acid. To date, it has been concluded that, in the assays used by this group, iodoacetic acid is the most mutagenic of all the DBPs studied so far (Richardson, S. Pers. Comm., 2009). However, it should be stressed that these are non-regulatory *in vitro* and cannot be used to assess the general toxicity of these compounds.

# 6. METHODS OF ANALYSIS

As noted elsewhere in this report, iodinated trihalomethanes were originally detected in the mid-1970s using common analytical techniques such as solvent extraction or solid phase resin extraction followed by GCMS. Other iodinated DBPs such as iodinated acids were only detected following the development of reliable analytical techniques for other haloacetic acids (bromo- and chloro-), as a result of concern regarding the latter's potential presence in drinking waters.

This section reviews the current methodology that is available to determine the eleven iodinated DBPs detected the US Nationwide DBP Occurrence Study, as described in Weinberg *et al.* (2002). These are as follows: dichloroiodomethane, bromochloroiodomethane, dibromiodomethane, chlorodiiodomethane, bromodiiodomethane, iodoform, iodoacetic acid, bromiodoacetic acid, (*Z*)-3-bromo-3-iodopropenoic acid, (*E*)-3-bromo-3-iodopropenoic acid and (*E*)-2-iodo-3-methylbutenedioic acid.

## 6.1 Availability of standards

The majority of these compounds of interest are not commercially available as pure standards.

The synthesis of the iodo-acid methyl esters (they are detected by GCMS following methylation of the extracted acids) is described in the Supporting Information provided with the paper by Richardson *et al*. (2008), available on-line from the Environmental Science and Technology website.

The iodinated-THMs detected and quantified as described in the Nationwide DBP Occurrence Study were custom synthesised by Agbar (Aigues de Barcelona), and more recently the synthesis of dichloroiodomethane and bromochloroiodomethane, as well as their isotopically-labelled (deuterated) analogues that were used as internal standards for the determination of iodinated THMs, has been reported (Silva *et al*., 2006). Other syntheses of these THMs have been reported (Cancho *et al*., 2000), and the synthesis of dibromoiodomethane had been reported earlier (Kennedy *et al*., 1979).

It is unlikely that UK water industry laboratories have the facilities to carry out the syntheses of either of these iodinated groups (acids and THMs), so it may be necessary to approach a custom synthesis company to produce adequate quantities for use as standards if, for example, it is deemed necessary to undertake a comprehensive survey of UK drinking waters for these compounds.

## 6.2 Analytical methods

### 6.2.1 Iodinated THMs

Several methods are described by Weinberg *et al*., (2002), but as this report includes method development work utilising various GC columns and different mass spectrometers for GCMS detection, and also GC-ecd following liquid-liquid extraction, it is difficult to be certain which is the best overall method. However due to the fact that the GC-ecd method involved the

simultaneous analysis of one sample injection onto two different GC columns (each of which needs its own electron capture detector) in order to resolve co-eluting peaks, it seems unlikely to be attractive to UK water industry laboratories, so only the GCMS methods are discussed below. Another approach, utilising solid-phase microextraction (SPME) fibres and gas chromatography-high resolution mass spectrometry (GC-HRMS) has been reported (Silva *et al*., 2006). Although it is not known how many UK water industry laboratories have mass spectrometers with sufficiently high resolution coupled to gas chromatographs (several laboratories have time of flight (TOF) LCMS systems), as GC-HRMS provides very much lower limits of detection for the iodinated-THMs than those reported in the US EPA study, details are provided below. In a recently reported study (Parsons *et al*., 2009) GC-ecd was used for the detection and quantification of dichloroiodomethane and bromochloroiodomethane, although no information was provided on limits of detection.

**Solid phase extraction (SPE)-GCMS method**

The final method developed used Bond Elut PPL SPE cartridges (3 ml) to extract the water samples (100 ml), and a 1:1 mixture of hexane and dichloromethane (2 ml) as the elution solvent. 0.5 ml of the eluent was transferred to an autosampler vial and analysed by GCMS. A DB-1 (30 m) GC column was used, coupled to a Saturn 2000 ion trap mass spectrometer operated in MID mode with positive electron ionisation.

The ions monitored (quantitation ion followed by confirmation ion), the retention times of the compounds monitored and their minimum reporting levels were as follows:

| | **m/z** | **Retn. Time (min)** | **MRL (µg/l)** |
|---|---|---|---|
| dichloroiodomethane | 83, 127 | 25.08 | 0.25 |
| bromochloroiodomethane | 127, 175 | 33.90 | 0.25 |
| dibromoiodomethane | 127, 173 | 39.99 | 1.0 |
| chlorodiiodomethane | 175, 127 | 41.44 | 0.50 |
| bromodiiodomethane | 219, 127 | 46.23 | 2.5 |
| iodoform | 127, 267 | 50.69 | 2.5 |

The minimum reporting level was based on summing the quantitation and confirmation ions to maximise the observed (summed) signal.

**Closed-loop stripping analysis**

Although this approach was investigated, and the iodinated-THMs were recovered (albeit poorly), for various reasons (including the zero recoveries for other compounds included in the total DBP suite) it was abandoned before sufficient information was available to gauge its usefulness.

**Purge and trap GCMS**

The instrumentation used comprised a Saturn 2000 mass spectrometer coupled to a Varian 3800 GC and a Varian Archon P&T autosampler. Ascorbic acid (1.4 mg) was added to the samples to quench residual chlorine, and sulphuric acid used to reduce the pH to 3.0-3.5. 25 ml of the sample (from the 40 ml sampling vials) was analysed. A DB-a GC column was used (in preference to a DB-624 column), and again summation of the relevant ion responses was used to maximise sensitivity.

The reported method detection limits were as follows:

| | **MDL (µg/l)** |
|---|---|
| dichloroiodomethane | 0.82 |
| bromochloroiodomethane | 0.75 |
| dibromoiodomethane | 1.3 |
| chlorodiiodomethane | 0.67 |
| bromodiiodomethane | 0.81 |

No data was reported for iodoform as it was not included in the standard spiking solution mixture. However as it is the least volatile of the iodinated THMs it is likely that it is poorly recovered using P&T, and therefore the MDL would be expected to be no better than any of those for the other iodinated THMs, and probably higher.

Although the MDLs for P&T GCMS are not as low as the MRLs reported for the SPE GCMS approach, it is likely that P&T GCMS is more attractive for many laboratories as it is a less labour-intensive procedure.

**SPME GC-HRMS**

Using 75 µm carboxen-polydimethylsiloxane fibres with a suitable autosampler, a DB-624 (25 m $\times$ 0.20 mm i.d., 1.12 µm film thickness) GC column coupled to a MAT 95XP high resolution magnetic sector mass spectrometer operated in the positive ion EI mode with multiple ion detection (MID) at 10,000 mass resolution, limits of detection of 2 ng/l were obtained for dichloroiodomethane and bromochloroiodomethane (Silva et al 2006). These LODs are over two orders of magnitude lower than those reported for the methods used in the US EPA survey. Although the remaining iodinated THMs of interest were not determined, it seems likely that a similar improvement in their LODs would also be obtained. If it is considered essential to produce data on potential low concentrations of iodinated-THMs (rather than merely report “less than” concentrations when using P&T GCMS or SPE GCMS) the use of SPME GC-HRMS would be essential.

### 6.2.2 Iodinated acids

The supporting information provided with the publication by Richardson *et al*. (2008) (available from the Environmental Science and Technology website) describes the determination of the iodinated acids of interest. The acids were extracted using methyl t-butyl ether following acidification of the samples to pH 0.5 and salting out with sodium sulphate. Following concentration of the extract, the acids were derivatised using diazomethane to form their methyl esters (dimethyl ester in the case of (*E*)-2-iodo-3-methylbutenedioic acid). Gas chromatography-negative ion chemical ionisation mass spectrometry (GC-NCIMS) was used for the analysis of the derivatised extracts, with methane used as the CI gas. This technique is available in most water company laboratories. The mass spectrometer was operated in selected ion monitoring mode, the only ion monitored being m/z 127, and the method detection limits were below 1 ng/l when an Agilent 5973 MSD mass spectrometer was used. However as only a single ion was monitored, the capacity of detection relied heavily on the reproducibility of the GC retention times of the acids monitored. As no internal standards were used, quantification was based on comparison with calibration standards run with each batch of samples.

Other techniques have been used to determine haloacetic acids in water e.g. LCMS using ion-pair liquid chromatography-electrospray ionization mass spectrometry (Takino *et al*., 2000), capillary electrophoresis (Urbansky, 2000) and ion chromatography (IC)-mass spectrometry (Slingsby *et al*., 2008). However it is not known whether the iodinated acids of interest can be determined using these methods as only the chloro- and bromo-haloacids were analysed.

# 7. SUMMARY

## Toxicity

The toxicity of iodinated DBPs and how this compares to that shown by other DBPs is unclear at present. The studies carried out so far indicate that some of these iodinated compounds are cytotoxic and have a genotoxic potential using the COMET assay *in vitro*. However, this research has been conducted using non-standard assays which have not been completely validated and so comparison with the toxicity shown by other DBPs is problematic. In these assays iodo-acetic acids are more toxic than bromo- or chloro-acetic acids. These iodoacetic acids also appear to have some genotoxic potential while the iodinated THMs are generally non-genotoxic although no conclusions can be drawn at present. There are more data available on iodoacetic acid, iodoform and iodate. Iodoacetic acid is the most toxic DBP tested so far in these cytotoxic and genotoxic assays and it is also of high acute toxicity and is toxic to the eye. There is no evidence on its carcinogenicity. Iodoform is less toxic and is the only iodinated DBP that has been tested in a two-year rodent bioassay which indicated that it was not carcinogenic, although it is mutagenic in the Ames test. There are, however, insufficient data on which to base a sound risk assessment on any iodinated DBP. Iodate is of low acute oral toxicity in experimental animals and the results of longer term studies are limited; but suggested that toxicity to the eye may be important. Iodate is negative in an array of *in vitro* genotoxicity studies.

Concern has arisen that iodinated-DBPs are of greater toxicological concern than their brominated and chlorinated analogues (Richardson *et al*., 2007). This view is predominantly based on non-regulatory research *in vitro* cytotoxicity and genotoxicity assays as a dataset of basic toxicological information on the iodinated-DBPs is not available at present. Therefore, further research into their basic toxicity would be prudent, although the evidence from monitoring and estimations at present suggest they are only present at low concentrations in drinking water. At present there is much interest in this area in the USA and research has been commissioned to study the potential toxicity of these compounds further.

## Analytical methods

Although there is increasing interest in iodinated DBPs and more monitoring is likely to be undertaken, at present the analytical methodology is research-based. To produce a spectrum of iodinated DBPs may require a number of methods as iodoforms and other non-polar compounds are easily measured while the iodoacetic acids are more difficult. Appropriate standards for the full spectrum of iodinated DBPs would have to be produced commercially. Any iodinated DBPs that have been detected so far by UK water companies so far is qualitative, appearing in GCMS scans.

The toxicity studies conducted so far for many iodinated DBPs are inadequate to define the concentrations that may be of concern and so sensitive methods may have to be developed.

**Potential Concentrations in UK drinking water**

There are a number of determinants present in raw and treated water that will affect the rate of production and the presence of iodinated DBPs in drinking water. The levels of iodide (and to a lesser extent, bromide), organic matter and chlorine are all important.

There are data on iodide levels in the UK. Monitoring by United Utilities and the Environment Agency suggest levels of between 2.5 to 510 µg/l although these studies have variable Limits of Detection (from 2.5 to 5000 µg/l) which makes conclusions about the mean levels of iodide in UK waters difficult. Worst case mean levels in most EA regions were below 10 µg/l, in other regions data may have been skewed by high LODs. The recent Scottish study gave values in seven treatment works of between 1.62-6.8 µg/l in winter increasing to 3.61-12.1 µg/l in summer. The US EPA study gave levels of iodide of between <0.13 µg/l and 104 µg/l but with most levels being at or below 10 µg/l.

Bromide was detected in the Environment Agency monitoring at levels of 96-2128 µg/l although there were again variable LODs. The Scottish study gave levels of 54-248 µg/l in winter falling to 21.5-165 µg/l in summer with similar levels being detected in the US study of 60-287 µg/l.

Chloramination will produce more iodinated DBPs than chlorine alone as iodate is not formed in a competing reaction leaving iodide to form other iodinated products. The increased iodinated DBP (and in particular iodoacids) formation with chloramines has, in general, been confirmed by the US data. Ozonation will oxidise all the iodide present to iodate and so iodinated organic DBPs will not be produced. This is seen in one of the Scottish treatment works where there was ozonation and no iodinated THMs were detected even in presence of chloramination.

The estimation derived in Section 4 suggest that under normal water quality and treatment conditions using chlorination, a maximum iodinated organic DBP concentration will be approximately 20% of the iodide concentration. Therefore, for a raw water iodide concentration of 50 µg/l seen in the Environment Agency data, the iodinated organic DBP concentration would be unlikely to exceed 10 µg/l. This iodide concentration is probably a high estimate (due to the measurement difficulties outlined elsewhere in this report) and for the maximum value of 12 µg/l of iodide seen in the Scottish study, the iodinated DBP levels would not exceed 2-3 µg/l. This is consistent with the concentration of iodinated DBPs detected with this level of iodide detected in the US study, although higher concentrations were detected with chloramination. This estimation cannot be made with chloramination owing to a lack of data. However, chloramination is not widely used in the UK as a method of disinfection. The concentration of iodinated DBPs, both estimated and in the monitoring studies, appears to be low as compared to chlorinated/brominated THMs. However, at present, the comparative toxicity of these compounds is unclear.

In conclusion, it appears that there is no evidence that iodide levels are higher in the UK than those detected in the USA. There is evidence that the formation of iodinated DBPs is increased by chloramination and reduced by ozonation and that iodinated-THMs may be removed by GAC. Chloramination is not common in the UK while ozonation and GAC are widely used. Taking all this information, it appears likely that the levels of iodinated DBPs in England and Wales will be no higher and will probably be lower than in the USA. It should be noted that the introduction of a standard for haloacetic acids in England and Wales may lead to an increased use of chloramination and if this occurred, further consideration of concentration of iodinated DBPs in drinking water would be advisable.

# 8. FUTURE RESEARCH

### Toxicology

The potential genotoxicity of iodinated DBPs has generated much interest in these compounds, particularly in the USA, where they are being studied in a number of *in vitro* human cell systems. In particular, it appears that the iodoacids may have some cytotoxic and genotoxic potential. If these studies confirm the potential toxicity and their presence in drinking water is confirmed, it will be important to expand the dataset on iodinated DBPs using more conventional toxicological methods. As these studies have already been commissioned it would advisable to remain in contact with Dr Susan Richardson of the US EPA for the latest findings of these studies.

### Monitoring and Analysis

Studies in the USA have identified a potential for iodinated DBP formation with the process of chloramination of water. The current review of the EU Drinking Water Directive recommends the setting of a standard for nine haloacetic acids for the first time. Difficulties in meeting standards for haloacetic acids and THMs in the USA have led to the use of more chloramination which lowers these THMs and haloacetic acids. If this was to occur in the UK, then there is a potential for an increase in the formation of iodinated DBPs.

If chloramination were to become more widespread in England and Wales, then there might be a need for the development of robust methods for the detection of iodinated DBPs. The specific species of iodinated DBPs may also be important as there is some suggestion that particular compounds such as the iodoacids may be particularly toxic. Monitoring in different water conditions and drinking water treatment processes could also then be considered, particularly those which may affect the production of iodinated DBPs such as chloramination, ozonation and GAC.

At present, the monitoring of iodide is inadequate owing to the use of different methods using a wide range of limits of detection. It would be useful to have a good study of iodide concentrations in environmental waters, in particular, where there is abstraction for drinking water. This would enable the identification of any area of high iodide where the likelihood of iodinated DBPs production may be increased during drinking water treatment (particularly where chloramination may be used).

### Prioritisation of iodinated DBPs for future work

The prioritisation of iodinated DBPs for future study depends considerably on the results of further toxicity testing. It does appear that iodoacids, iodoform and iodate may be of greater toxic potential than iodinated THMs although this remains to be confirmed. It appears that the presence of iodide (although a role for bromide, if any, is as yet unclear) in the source water and chloramination in the drinking water treatment process may increase the likelihood of iodinated DBP formation. Unfortunately current surveys of iodide levels in environmental waters have not yielded data that will enable the identification of areas of the UK with higher iodide levels which may be of greater risk for iodinated DBP production, in particular, when

chloramination may be in use. Gathering of this basic information may be the priority before the identification of iodinated DBPs of particular importance for further research.

# REFERENCES

Anitariya, G.I. (1987). HYSAAV, 52(11), 44.

Anon (1995) Final report on the safety assessment of sodium iodate. Journal of the American College of Toxicology 14: 231-239.

Bichsel, Y. and von Gunten, U. (1999). Oxidation of Iodide and Hypoiodous Acid in Disinfection of Natural Waters. Environmental Science and Technology 33: 4040-4045.

Bichsel, Y. and von Gunten, U. (2000). Formation of Iodo-Trihalomethanes during Disinfection and Oxidation of Iodide-Containing Waters. Environmental Science and Technology 34: 2784-2791.

Burgu, H., Schaffer, T. and Seiler, J. (2001). The toxicology of iodate: a review of the literature. Thyroid, 11: 449-456.

Cancho, B., Ventura, F., Galceran, M., Diaz, A. and Ricart, S. (2000). Determination, Synthesis and Survey of Iodinated Trihalomethanes in Water Treatment Process. Water Research 34(13): 3380-3390.

Committee on Mutagencity (COM) (2005a). Statement on joint COC and COM meeting 9 June 2005. Use of target organ mutagenicity data in carcinogen risk assessment.COM/05/S6 and COC/05/S3. Committee on Mutagenicity of Chemicals in Food, Consumer Products and the Environment.

Committee on Mutagenicity (COM) (2005b) Statement: review of biomonitoring studies of genotoxicity in pesticide applicators. COM/05/S5 – October 2005 Committee on Mutagenicity of Chemicals in Food, Consumer Products and the Environment.

Council Directive 67/548/EEC of 27 June 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances (as amended). Adaptation to Technical Progress (ATP). Year unknown.

Deborde, M. and von Gunten, U. (2008). Reactions of chlorine with inorganic and organic compounds during water treatment – kinetics and mechanisms: A critical review. Water Research 42(1/2): 13-51.

Eckhardt, K., Gocke, E., King, M.T. and Wild, D. (1982). Mutagenic activity of chlorate, bromate and iodate. Mutation Research, 97: 185.

Fielding, M., Gibson, T.M., James, H.A., McLoughlin, K. and Steel, C.P. (1981). Organic Micropollutants in Drinking Water. WRc TR159.

Flesch, P., Golstone, S.B., Weidman, F.D. (1990). Blister formation and separation of the epidermis from the corium in laboratory animals. Journal of Investigative Dermatology 18: 187-192.

Haworth, S., Lawlor, T., Mortelmans, K., Speck, W. and Zeiger, E. (1983). Salmonella mutagenicity test results for 250 chemicals. Environmental Mutagenesis 5 (suppl1): 3-142.

HSDB (2003). Hazardous Substances Databank (HSDB). Iodoacetic acid. Available from: http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB

Hua, G., Reckhow, D.A. and Kim, J. (2006). Effect of bromide and iodide ions on the formation and speciation of disinfection byproducts during chlorination. Environmental Science and Technology 40(9): 3050-3056.

Kennedy, J.R., Vickrey, T.M., Somayajulu, G.R. and Zwolinski, B.J. (1979). Synthesis of $CHCl_2I$, $CCl_3I$, $CHBr_2I$ and $CBr_3I$. Journal of Chemical and Engineering Data 24(3): 251-252.

Klimisch, H.J., Andreae, E. and Tillmann, U. (1997). A systematic approach for evaluating the quality of experimental and ecotoxicological data. Register of Toxicology. and Pharmacology 25:1-5

Krasner, S.W., Weinberg, H.S., Richardson, S.D., Pastor, S.J., Chinn, R., Sclimenti, M.J., Onstad, G.D. and Thruston, A.D. (2006). Occurrence of a New Generation of Disinfection Byproducts. Environmental Science and Technology 40:1775-7185.

Lewis, R.J. (1996). Sax's Dangerous Properties of Industrial Materials. 9th Edition, Vol 1-3.

Murray, M. (1953). The effects of administration of sodium iodate to man and animals. Bulletin of the World Health Organization, 9, 211-216.

Myers, D.K. and Chetty, K.G. (1973). Effects of radiosensitizing agents on DNA strand breaks and their rapid repair during irradiation. Radiation Research 53: 307-314.

NTP (1978). Bioassay of Iodoform for Possible Carcinogenicity, TR-110. National Toxicology Program.

NTP (1985). Testing Status of Iodoacetic acid, M200018. National Toxicology Program.

Parsons, S.A., Goslan, E.H., Rocks, S.A., Holmes, P., Levy, L.S. and Krasner, S. (2009). Study into the formation of disinfection by-products of chloramination, potential health implications and techniques for minimisation. Cranfield University.

Plewa, M.J., Wagner, E.D., Richardson, S.D., Thruston, A.D. Jr., Woo, Y.T. and McKague, A.B. (2004). Chemical and biological characterization of newly discovered iodoacid drinking water disinfection byproducts. Environmental Science Technology 38(18): 4713-22.

Poul, J.M., Huet, S., Godard, T. and Sanders, P. (2004). Lack of genotoxicity of potassium iodate in the alkaline comet assay and in the cytokinesis-block micronucleus test. Comparison to potassium bromate. Food chemical toxicology 42(2): 209-215.

Richardson, S.D., Fasano, F., Ellington, J.J., Crumley, F.G., Buetner, K.M., Evans, J.J., Blount, B.C., Silva, L.K. Waite, T.J., Luther, G.W., Mckague, A.B., Mitner, R.J., Wagner, E.D. and Plewa, M.J. (2008). Occurrence and mammalian cell toxicity of iodinated disinfection byproducts in drinking water. Environmental Science Technology 42(22): 8330-8.

Richardson, S.D., Plewa, M.J., Wagner, E.D., Schoeny, R. and DeMarini, D.M. (2007). Occurrence, genotoxicity, and carcinogenicity of regulated and emerging disinfection by-products in drinking water: A review and roadmap for research. Mutation Research 636:178-242.

Silva, L.K., Bonin, M.A., McKague, B. and Blount, B.C. (2006). Quantification of Dichloroiodomethane and Bromochloroiodomethane in Human Blood by Solid-Phase Microextraction Coupled with Gas Chromatography-High-Resolution Mass Spectrometry. Journal of Analytical Toxicology 30(9): 67-678.

Slingsby, R., Saini, C., Pohl, C. and Jack, R. (2008). The Measurement of Haloacetic Acids in Drinking Water Using IC-MS/MS – Method Performance. Dionex Application Note, Pittcon 2008 Presentation. Available from: http://www.dionex.com/en-us/webdocs/68678_LPN-2117-01-HAA-IC-MS-MS-note.pdf.

Takino, M., Daishima, S. and Yamaguchi, K. (2000). Determination of haloacetic acids in water by liquid chromatography-electrospray ionization-mass spectrometry using volatile ion-pairing reagents. Analyst 125(6): 1097-1102.

Tansy, M.F., Werley, M., Landin, W., Oberly, R., Kendall, F.M., Miller, A., Sherman, W. (1981). Subacute inhalation toxicity testing with iodoform vapor. Journal of Toxicology and Environmental Health 8: 59.

Taurog, A., Howells, E.M. and Nachimson, H.I. (1966). Conversion of iodate to iodide *in vivo* and *in vitro*. Journal of Biological Chemistry 241: 4686-4693.

Turkmenistana, Z. (1983). Public Health of Turkmenistan, 27(5), 9.

Urbansky, E.T. (2000). Techniques and methods for the determination of haloacetic acids in potable water. Journal of Environmental Monitoring 2(4): 285-291.

Valencia, R., Mason, J.M., Woodruff, R.C. and Zimmering, S. (1985). Chemical mutagenesis testing in Drosophila: III. Results of 48 coded compounds tested for the National Toxicology Program. Environmental Mutagenesis 7: 325-348.

Webster, S., Stohlman, E. and Highman, B. (1966). The toxicology of potassium and sodium iodate:III. Acute and subacute oral toxicity of potassium iodate in dogs. Toxicology and Applied Pharmacology 8: 185-192.

Webster, S., Rise, M., Highman, B. and Oettingen, W. (1957). The toxicology of potassium and sodium iodates: acute toxicity in mice. Journal of Pharmacology and Experimental Therapeutics 120: 171-178.

Weinberg, H.S., Krasner, S.W., Richardson, S.D. and Thruston, A.D. (2002). The Occurrence of Disinfection By-Products (DBPs) of Health Concern in Drinking Water: Results of a Nationwide DBP Occurrence Study. EPA/600-02/068. Available from: http://www.epa.gov/athens/publications/reports/EPA_600_R02_068.pdf

# APPENDIX A

**Table A1 Priority DBPs selected for the US Nationwide Occurrence Study (Weinberg *et al*., 2002)**

| **MX and MX-Analogues:** |
|---|
| 3-Chloro-4-(dichloromethyl)-5-hydroxy-2(5H)-furanone (MX) |
| 3-Chloro-4-(dichloromethyl)-2-(5H)-furanone (red-MX) |
| (E)-2-Chloro-3-(dichloromethyl)-butenedioic acid (ox-MX) |
| (E)-2-Chloro-3-(dichloromethyl)-4-oxobutenoic acid (EMX) |
| 2,3-Dichloro-4-oxobutenoic acid (Mucochlric acid) [87-56-9] |
| 3-Chloro-4-(bromochloromethyl)-5-hydroxy-2(5H)furanone (BMX-1) [132059-51-9] |
| 3-Chloro-4-(dibromomethyl)-5-hydroxy-2(5H)-furanone (BMX-2) [132059-51-9] |
| 3-Bromo-4-(dibromomethyl)-5-hydroxy-2(5H)-furanone (BMX-3) [132059-53-1] |
| (E)-2-Chloro-3-(bromochloromethyl)-4-oxobutenoic acid (BEMX-1) |
| (E)-2-Chloro-3-(dibromomethyl)-4-oxobutenoic acid (BEMX-2) |
| (E)-2-Bromo-3-(dibromomethyl)-4-oxobutenoic acid (BEMX-3) |
| **Haloacids:** |
| 3,3-Dichloropropenoic acid |
| **Halomethanes:** |
| Chloromethane [74-87-3] |
| Bromomethane (methyl bromide0 [74-83-9] |
| Dibromomethane [74-95-3] |
| Bromochloromethane [74-97-5] |
| Bromochloroiodomethane [34970-00-8] |
| Dichloroiodomethane [594-04-7] |
| Dibromoiodomethane [593-94-2] |
| Chlorodiiodomethane [638-73-3] |

| |
|---|
| Bromodiiodomethane [557-95-9] |
| Iodoform [75-47-8] |
| Chlorotribromomethane [594-15-0] |
| Carbon tetrachloride [56-23-5] |
| **Halonitromethanes** |
| Bromonitromethane [563-70-2] |
| Chloronitromethane [1794-84-9] |
| Dibromonitromethane [598-91-4] |
| Dichloronitromethane [7119-89-3] |
| Bromochloronitromethane [135531-25-8] |
| Bromodichloronitromethane [918-01-4] |
| Dibromochloronitromethane [1184-89-0] |
| Tribromonitromethane (bromopicrin) [464-10-8] |
| **Haloacetonitriles** |
| Bromoacetonitrile [590-17-0] |
| Chloroacetonitrile [107-14-2] |
| Tribromoacetonitrile [75519-19-6] |
| Bromodichloroacetonitrile [60523-73-1] |
| Dibromochloroacetonitrile [144772-39-4] |
| **Haloketones** |
| Chloropropanone [78-95-5] |
| 1,3-Dichloropropanone [534-07-6] |
| 1,1-Dibromopropanone |
| 1,1,3-Trichloropropanone [921-03-9] |
| 1-Bromo-1,1-dichloropropanone |
| 1,1,1,3-Tetrachloropropanone [16995-35-0] |

| |
|---|
| 1,1,3,3-Tetrachloropropanone [632-21-3] |
| 1,1,3,3-Tetrabromopropanone [22612-89-1] |
| 1,1,1,3,3-Pentachloropropanone [1768-31-6] |
| Hexachloropropanone [116-16-5] |
| **Haloaldehydes** |
| Chloroacetaldehyde [107-20-0] |
| Dichloroacetaldehyde [70-02-7] |
| Bromochloroacetaldehyde [98136-99-3] |
| Tribromoacetaldehyde [115-17-3] |
| **Haloacetates** |
| Bromochloromethyl acetate [247943-54-0] |
| **Haloamides** |
| Monochloroacetamide [79-07-2] |
| Monobromoacetamide [683-57-8] |
| Dichloroacetamide [683-72-7] |
| Dibromoacetamide [598-70-9] |
| Trichloroacetamide [594-65-0] |
| **Non-Halogenated Aldehydes and Ketones** |
| 2-Hexenal [505-57-7]; [6728-26-3] |
| 5-Keto-1-hexanal |
| Cyanoformaldehyde [4471-47-0] |
| Methylethyl ketone (2-butanone) [78-93-3] |
| 6-Hydroxy-2-hexanone |
| Dimethylglyoxal (2,3-butanedione) [431-03-8] |
| **Volatile organic compounds (VOCs) and Miscellaneous DBPs** |
| 1,1,1,2-Tetrabromo-2-chloroethane |

| |
|---|
| 1,1,2,2-Tetrabromo-2-chloroethane |
| Methyl-*tert*-butyl ether [1634-04-4] |
| Benzy chloride [100-44-7] |

## Table A2 Results of iodinated DBPs from US Nationwide DBP Occurrence Study (Weinberg *et al*., 2002)

| Plant | Date | MRL (µg/l) | Dichloroiodo-methane (µg/l) | MRL (µg/l) | Bromochloro-iodomethane (µg/l) | MRL (µg/l) | Dibromoiodo-methane (µg/l) | MRL (µg/l) | Chlorodiiodo-methane (µg/l) | MRL (µg/l) | Bromodiiodo-methane (µg/l) | MRL (µg/l) | Iodoform (µg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plant 1 | 30/10/00 | 0.5 | NR | 0.5 | NR | 0.5 | NR | 0.59 | ND | 0.53 | ND | 0.22 | ND |
| | 23/01/01 | 0.25 | 0.2 | 0.2 | ND | 0.64 | ND | 0.52 | ND | 0.6 | ND | 0.7 | ND |
| | 17/07/01 | 0.50 | ND | 0.25 | ND | 0.5 | ND | 0.1-0.5 | ND | 0.5 | ND | 0.5 | ND |
| | 19/03/02 | 0.25 | NR | 0.25 | ND | 0.5 | ND | 0.1 | ND | 0.52 | ND | 0.5 | ND |
| Plant 2 | 30/10/00 | 0.50 | NR | 0.5 | 1 | 0.5 | NR | 0.59 | ND | 0.53 | ND | 0.22 | ND |
| | 23/01/01 | 0.25 | 0.6 | 0.2 | 0.8 | 0.64 | 0.6 | 0.52 | ND | 0.6 | ND | 0.7 | ND |
| | 17/07/01 | 0.50 | 4 | 0.25 | 1 | 0.5 | <0.5 | 0.1-0.5 | <0.5 | 0.5 | ND | 0.5 | ND |
| | 19/03/02 | 0.25 | 2 | 0.25 | 1 | 0.5 | 0.6 | 0.1 | <0.5 | 0.52 | ND | 0.5 | ND |
| Plant 3 | 13/11/00 | 0.10 | 2 | 0.5 | NR | 0.1 | ND | 0.59 | ND | 0.53 | ND | 0.22 | 0.5 |
| | 05/02/01 | 0.25 | 0.3 | 0.2 | ND | 0.6 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 01/08/01 | 0.50 | ND | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.5 | ND |
| | 16/01/01 | 0.50 | ND | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 28/01/02 | 0.50 | ND | 0.5 | ND | 0.5 | ND | 0.1 | ND | 0.52 | ND | 1 | ND |
| Plant 4 | 13/11/00 | 0.10 | 1 | 0.5 | NR | 0.1 | ND | 0.59 | ND | 0.53 | ND | 0.22 | 2 |
| | 05/02/01 | 0.25 | 0.29 | 0.2 | ND | 0.6 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 01/08/01 | 0.50 | ND | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.5 | ND |
| | 16/01/01 | 0.50 | 0.8 | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 28/01/02 | 0.50 | ND | 0.5 | ND | 0.5 | ND | 0.1 | ND | 0.52 | ND | 1 | ND |
| Plant 5 | 27/11/00 | 0.25 | ND | 3 | <3 | 0.64 | ND | 0.1 | ND | 0.12 | ND | 3 | ND |
| | 26/02/01 | 0.25 | 0.3 | 0.2 | ND | 0.48 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 13/08/01 | 0.50 | ND | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 22/10/01 | 0.50 | <0.5 | 0.5 | ND | 0.52 | ND | 0.1-0.5 | ND | 0.5 | ND | 1 | ND |
| | 15/04/02 | 0.50 | ND | 0.5 | ND | 0.5 | ND | 0.1 | ND | 0.5 | ND | 2 | ND |
| Plant 6 | 27/11/00 | 0.25 | 0.3 | 3 | <3 | 0.64 | ND | 0.1 | ND | 0.12 | ND | 3 | ND |
| | 26/02/01 | 0.25 | 0.3 | 0.2 | ND | 0.48 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 13/08/01 | 0.50 | 0.9 | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 22/10/01 | 0.50 | 3 | 0.5 | <0.5 | 0.52 | ND | 0.1-0.5 | ND | 0.5 | ND | 1 | ND |
| | 15/04/02 | 0.50 | 1 | 0.5 | <1 | 0.5 | ND | 0.1 | ND | 0.5 | ND | 2 | ND |
| Plant 7 | 11/12/00 | 0.10 | 0.3 | 3 | ND | 0.64 | ND | 0.1 | ND | 0.12 | ND | 0.14 | ND |

| Plant | Date | MRL (µg/l) | Dichloroiodo-methane (µg/l) | MRL (µg/l) | Bromochloro-iodomethane (µg/l) | MRL (µg/l) | Dibromoiodo-methane (µg/l) | MRL (µg/l) | Chlorodiiodo-methane (µg/l) | MRL (µg/l) | Bromodiiodo-methane (µg/l) | MRL (µg/l) | Iodoform (µg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12/03/01 | 0.25 | ND | 3 | ND | 0.6 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 24/09/01 | 0.50 | ND | 0.25 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 14/01/02 | 2.50 | ND | 0.5 | ND | 0.53 | ND | 0.1 | ND | 0.52 | ND | 0.22 | ND |
| Plant 8 | 11/12/00 | 0.10 | 1 | 3 | <1 | 0.64 | <1 | 0.1 | ND | 0.12 | ND | 0.14 | ND |
| | 12/03/01 | 0.25 | 0.7 | 3 | <1 | 0.6 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 24/09/01 | 0.50 | 3 | 0.25 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 16/01/02 | 2.50 | <2.5 | 0.5 | ND | 0.53 | ND | 0.1 | ND | 0.52 | ND | 0.22 | ND |
| Plant 9 | 10/01/01 | 0.25 | ND | 0.2 | ND | 0.6 | ND | 0.5 | ND | 0.6 | ND | 0.14 | ND |
| | 09/04/01 | 0.20 | ND | 0.2 | ND | 0.5 | ND | 0.5 | ND | 0.5 | ND | 0.5 | ND |
| | 27/08/01 | 0.50 | ND | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 26/11/01 | 0.50 | 1 | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 2 | ND |
| | 25/02/02 | 0.50 | <0.5 | 0.5 | <0.5 | 0.5 | ND | 0.1 | ND | 0.52 | ND | 0.5 | ND |
| Plant 10 | 10/01/01 | 0.25 | ND | 0.2 | ND | 0.6 | ND | 0.5 | ND | 0.6 | ND | 0.14 | ND |
| | 09/04/01 | 0.20 | ND | 0.2 | ND | 0.5 | ND | 0.5 | ND | 0.5 | ND | 0.5 | ND |
| | 05/09/01 | 0.50 | ND | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 0.1 | ND |
| | 26/11/01 | 0.50 | 1 | 0.5 | ND | 0.52 | ND | 0.1 | ND | 0.5 | ND | 2 | ND |
| | 25/02/02 | 0.50 | <0.5 | 0.5 | ND | 0.5 | ND | 0.1 | ND | 0.52 | ND | 0.5 | ND |
| Plant 11 | 26/03/01 | 0.20 | ND | 0.2 | ND | 0.6 | ND | 0.51 | ND | 0.56 | ND | 0.54 | ND |
| | 10/09/01 | 0.50 | 2 | 0.5 | 0.7 | 0.25 | 0.4 | 0.1 | 0.3 | 0.5 | ND | 0.1 | ND |
| | 05/11/01 | 0.50 | 1 | 0.25 | 0.4 | 0.52 | ND | 0.5 | ND | 0.5 | ND | 2 | ND |
| | 11/02/02 | 1.00 | <1 | 0.5 | <0.5 | 0.53 | ND | 0.1 | ND | 0.52 | ND | 2.2 | ND |
| Plant 12 | 26/03/01 | 0.20 | 4 | 0.2 | 3 | 0.6 | 3 | 0.51 | 2 | 0.56 | 0.3 | 0.54 | ND |
| | 10/09/01 | 0.50 | 7 | 0.5 | 2 | 0.52 | 1 | 0.25 | 0.5 | 0.25 | 0.3 | 0.25 | ND |
| | 15/11/01 | 0.50 | 11 | 0.25 | 3 | 0.52 | 2 | 0.5 | 2 | 0.5 | 0.7 | 0.5 | ND |
| | 12/02/02 | 1.00 | <1 | 0.5 | 2 | 0.53 | 4 | 0.1 | ND | 0.52 | <0.5 | 2.2 | ND |

**Table A3 First sampling event May 2005 (Richardson *et al*., 2008)**

| Plant | Iodoacetic acid (µg/l) | Bromoiodoacetic acid (µg/l) | (Z)-3-Bromo-3-iodopropenoic acid (µg/l) | (E)-3-Bromo-3-iodopropenoic acid (µg/l) | (E)-2-Iodo-3-methylbutenedioic acid (µg/l) |
|---|---|---|---|---|---|
| Plant 1 | 1.7 | 0.52 | 0.077 | 0.061 | 0.36 |
| Plant 2 | 1.7 | 0.083 | <0.00025 | <0.00028 | <0.00031 |
| Plant 3 | 0.42 | 0.063 | <0.00025 | <0.00028 | <0.00031 |
| Plant 4 | 0.24 | <0.00031 | <0.00025 | <0.00028 | <0.00031 |
| Plant 5 | 0.36 | 0.066 | <0.00025 | <0.00028 | <0.00031 |

**Table A4 Second sampling even fall-winter 2005 (Richardson *et al*., 2008)**

| Plant | Iodoacetic acid (µg/l) | Bromoiodoacetic acid (µg/l) | (Z)-3-Bromo-3-iodopropenoic acid (µg/l) | (E)-3-Bromo-3-iodopropenoic acid (µg/l) | (E)-2-Iodo-3-methylbutenedioic acid (µg/l) | Bromochloro-iodomethane (µg/l) | Dichloro-iodomethane (µg/l) | Bromide (µg/l) |
|---|---|---|---|---|---|---|---|---|
| Plant 1 | 0.018 | 0.069 | 0.043 | 0.03 | 0.05 | 6.6 | 2.1 | 545 |
| Plant 2 | 0.02 | 0.27 | ND | ND | 0.05 | 1.6 | 3.5 | 47 |
| Plant 3 | 0.008 | 0.033 | ND | ND | 0.031 | 1 | 0.61 | NA |
| Plant 4 | NR | NR | NR | NR | NR | 0.08 | 0.2 | 87 |
| Plant 5 | 0.008 | 0.021 | ND | ND | 0.062 | 0.03 | 0.19 | NA |
| Plant 6 | NR | NR | NR | NR | NR | 0.24 | 1.2 | 74 |
| Plant 7 | 0.006 | 0.013 | ND | ND | 0.014 | 0.29 | 0.47 | 111 |
| Plant 8 | 0.006 | 0.013 | ND | ND | 0.015 | 0.11 | 0.29 | 58 |
| Plant 9 | 0.018 | 0.077 | ND | ND | 0.038 | 0.17 | 0.037 | 233 |
| Plant 11 | 0.015 | 0.16 | 0.021 | 0.008 | 0.032 | 2.1 | 2.2 | 476 |
| Plant 12 | 0.006 | 0.03 | ND | ND | 0.077 | 1.5 | 7.9 | 316 |
| Plant 13 | 0.012 | 0.42 | 0.085 | ND | 0.055 | 1.9 | 3.4 | 400 |
| Plant 14 | 0.006 | 0.021 | ND | ND | 0.016 | 0.32 | 0.4 | 240 |
| Plant 15 | 0.026 | 0.15 | ND | ND | 0.046 | 0.31 | 2.5 | 273 |
| Plant 16 | 0.006 | 0.017 | ND | ND | 0.013 | 0.12 | 0.28 | 16 |
| Plant 17 | 0.021 | 0.49 | 0.5 | 0.086 | 0.31 | 10.2 | 2.1 | 1087 |
| Plant 18 | 0.008 | 0.031 | ND | ND | 0.038 | 0.21 | 1.6 | 26 |
| Plant 19 | 0.062 | 1.4 | ND | ND | 0.58 | 0.16 | 0.61 | 545 |
| Plant 20 | 0.006 | 0.019 | ND | ND | 0.018 | 0.47 | 0.57 | 171 |
| Plant 21 | 0.008 | 0.032 | ND | ND | 0.011 | 0.14 | 0.4 | 47 |
| Plant 22 | 0.008 | 0.035 | ND | ND | 0.031 | 0.47 | 1.1 | 75 |

**Table A5 Third sampling event 2006 (Richardson *et al*., 2008)**

| Plant | Iodoacetic acid (µg/l) | Bromoiodoacetic acid (µg/l) | (Z)-3-Bromo-3-iodopropenoic acid (µg/l) | (E)-3-Bromo-3-iodopropenoic acid (µg/l) | (E)-2-Iodo-3-methylbutenedioic acid (µg/l) | Bromochloro-iodomethane (µg/l) | Dichloro-iodomethane (µg/l) | Sum iodo-acids (µg/l) | Sum iodo-THMs (µg/l) | Bromide (µg/l) | Iodide (µg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Plant 1 | 0.093 | 0.29 | 0.085 | 0.28 | 0.064 | 5.4 | 1.5 | 0.81 | 6.9 | 699 | 65 |
| Plant 2 | 0.015 | 0.91 | 0.05 | 0.13 | 0.085 | 1.4 | 3.5 | 0.37 | 4.9 | 133 | 1 |
| Plant 3 | 0.002 | 0.013 | 0.008 | 0.005 | 0.002 | 0.64 | 0.4 | 0.03 | 1 | 230 | 10.3 |
| Plant 4 | 0.031 | 0.028 | 0.01 | 0.019 | 0.009 | 0.42 | 0.77 | 0.1 | 1.2 | 96 | <0.13 |
| Plant 5 | 0.002 | 0.003 | 0.003 | 0.005 | 0.002 | NA | NA | 0.02 | NA | 230 | 10.3 |
| Plant 6 | 0.007 | 0.026 | 0.032 | 0.013 | 0.027 | 0.23 | 1.1 | 0.11 | 1.3 | 96 | 0.4 |
| Plant 7 | 0.014 | 0.005 | 0.01 | 0.003 | 0.004 | 0.13 | 0.3 | 0.04 | 0.43 | 105 | <0.13 |
| Plant 8 | 0.008 | 0.008 | 0.011 | 0.009 | 0.006 | 0.1 | 0.15 | 0.04 | 0.25 | 67 | <0.13 |
| Plant 9 | 0.023 | 0.13 | 0.019 | 0.015 | 0.052 | 0.2 | <0.062 | 0.24 | 0.2 | 277 | 1.9 |
| Plant 10 | 0.033 | 0.005 | 0.005 | 0.003 | 0.003 | 0.25 | 0.22 | 0.05 | 0.47 | 214 | 7.3 |
| Plant 11 | 0.046 | 0.035 | 0.034 | 0.053 | 0.043 | 0.66 | 1.6 | 0.21 | 2.3 | 104 | 1.5 |
| Plant 12 | 0.078 | 0.048 | 0.003 | 0.032 | 0.031 | 0.98 | 5.1 | 0.19 | 6.1 | 204 | 10.3 |
| Plant 13 | 0.07 | 0.044 | 0.01 | 0.037 | 0.028 | 2.1 | 5.7 | 0.19 | 7.8 | 186 | 22.3 |
| Plant 14 | 0.015 | 0.008 | 0.008 | 0.008 | 0.01 | 0.42 | 0.91 | 0.05 | 1.3 | 107 | 1.1 |
| Plant 15 | 0.05 | 0.056 | 0.038 | 0.013 | 0.012 | 0.19 | 2.2 | 0.17 | 2.4 | 107 | <0.13 |
| Plant 16 | 0.061 | 0.013 | 0.003 | 0.001 | 0.003 | 0.062 | 0.35 | 0.08 | 0.41 | 24 | <0.13 |
| Plant 17 | 0.018 | 0.038 | 0.064 | 0.11 | 0.048 | 3.5 | 0.64 | 0.28 | 4.1 | NR | 22.4 |
| Plant 18 | 0.033 | 0.035 | 0.009 | 0.005 | 0.009 | <0.062 | 0.46 | 0.09 | 0.46 | 35 | 10.4 |
| Plant 19 | 0.67 | 0.29 | 0.082 | <0.020 | 0.017 | 0.72 | 1.1 | 1.1 | 1.8 | 300 | 104.2 |
| Plant 20 | 0.022 | 0.048 | 0.011 | <0.020 | 0.031 | 0.33 | 0.97 | 0.11 | 1.3 | 193 | <0.13 |
| Plant 21 | 0.082 | 0.051 | 0.014 | 0.023 | 0.01 | 0.14 | 0.36 | 0.18 | 0.5 | 65 | 0.4 |
| Plant 22 | 0.04 | 0.045 | 0.024 | 0.007 | 0.016 | 0.34 | 0.64 | 0.13 | 0.98 | 103 | 10.8 |
| Plant 23 | <0.0002 | 0.007 | 0.012 | 0.004 | 0.004 | <0.062 | 0.09 | 0.03 | 0.09 | 37 | 2.7 |

# APPENDIX B

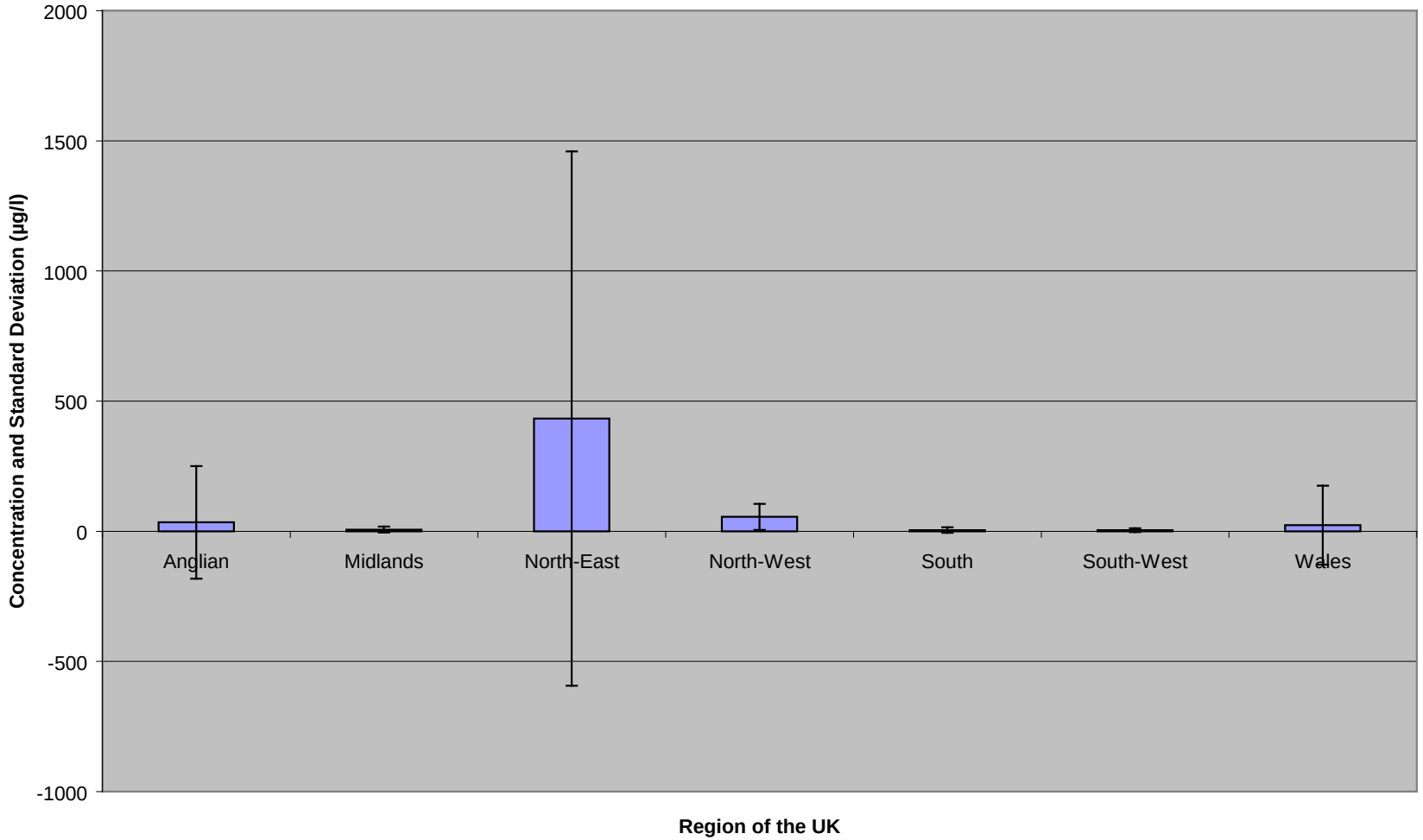


**Figure B1 Concentration of iodide in raw water in England and Wales (values reported to be below the limit of detection assumed to be equal to the limit of detection)**

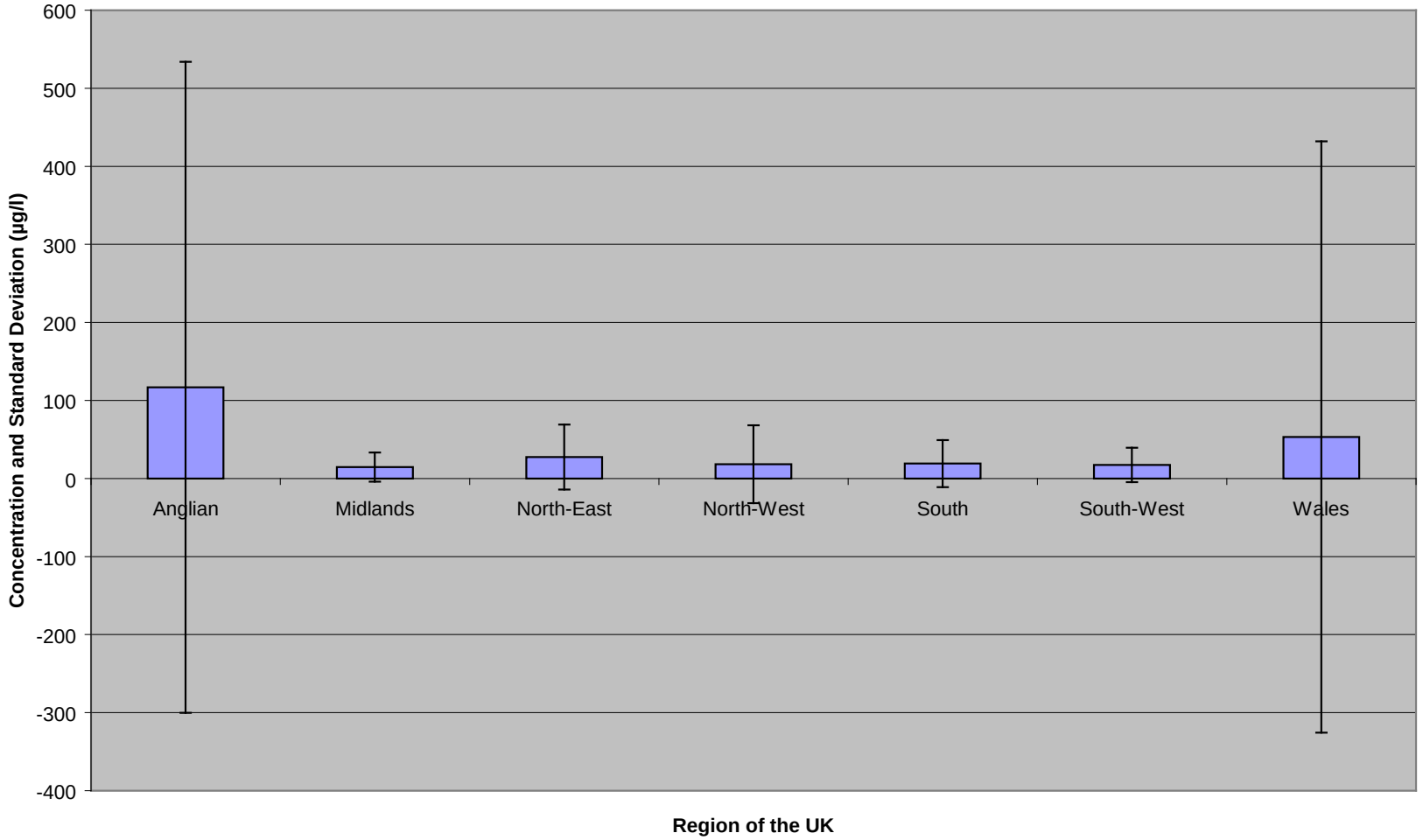


**Figure B2 Concentration of iodide in raw water in England and Wales (excluding values reported to be below the limit of detection)**

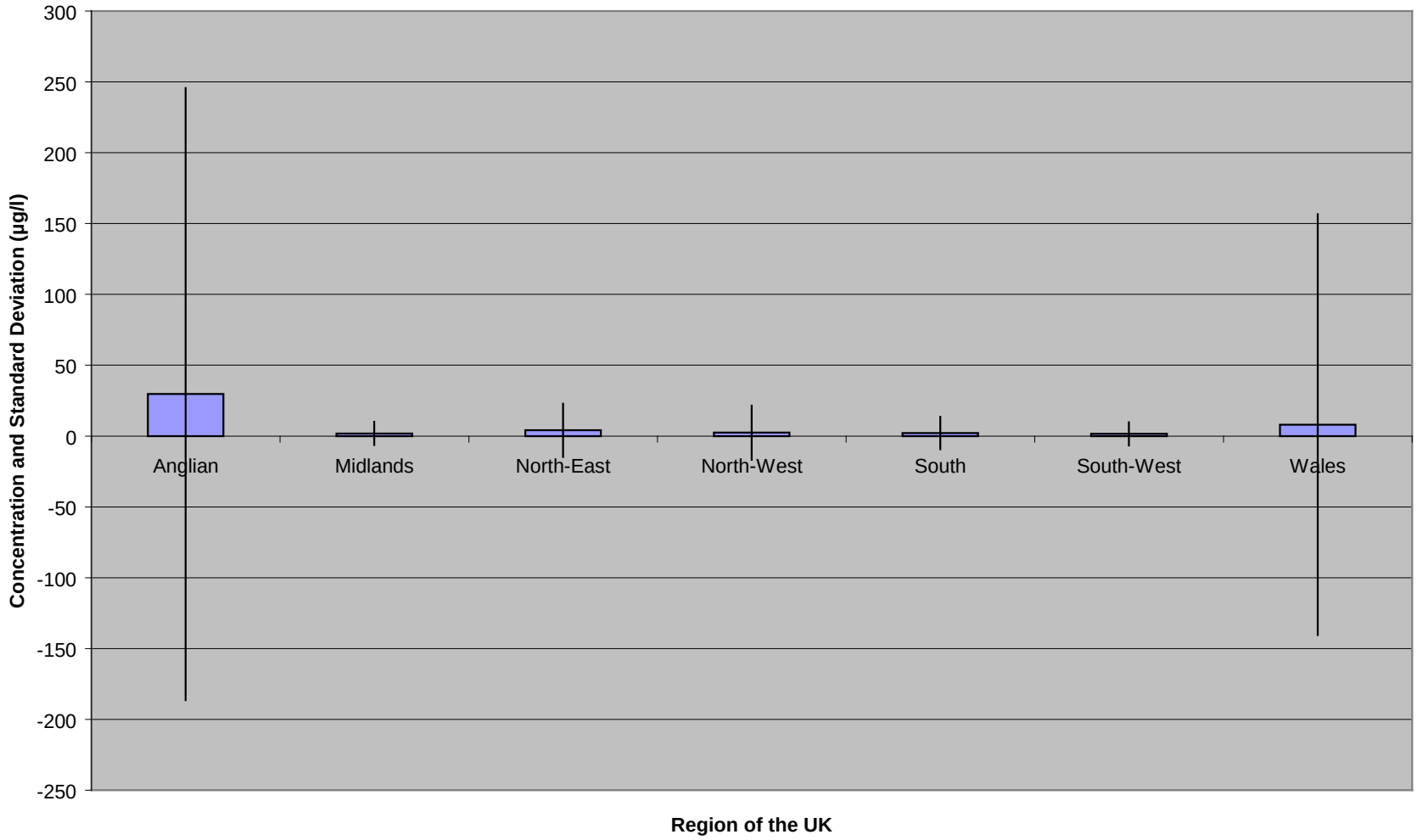


**Figure B3 Concentration of iodide in raw water in England and Wales (assuming values reported below the limit of detection are equal to 0 µg/l)**

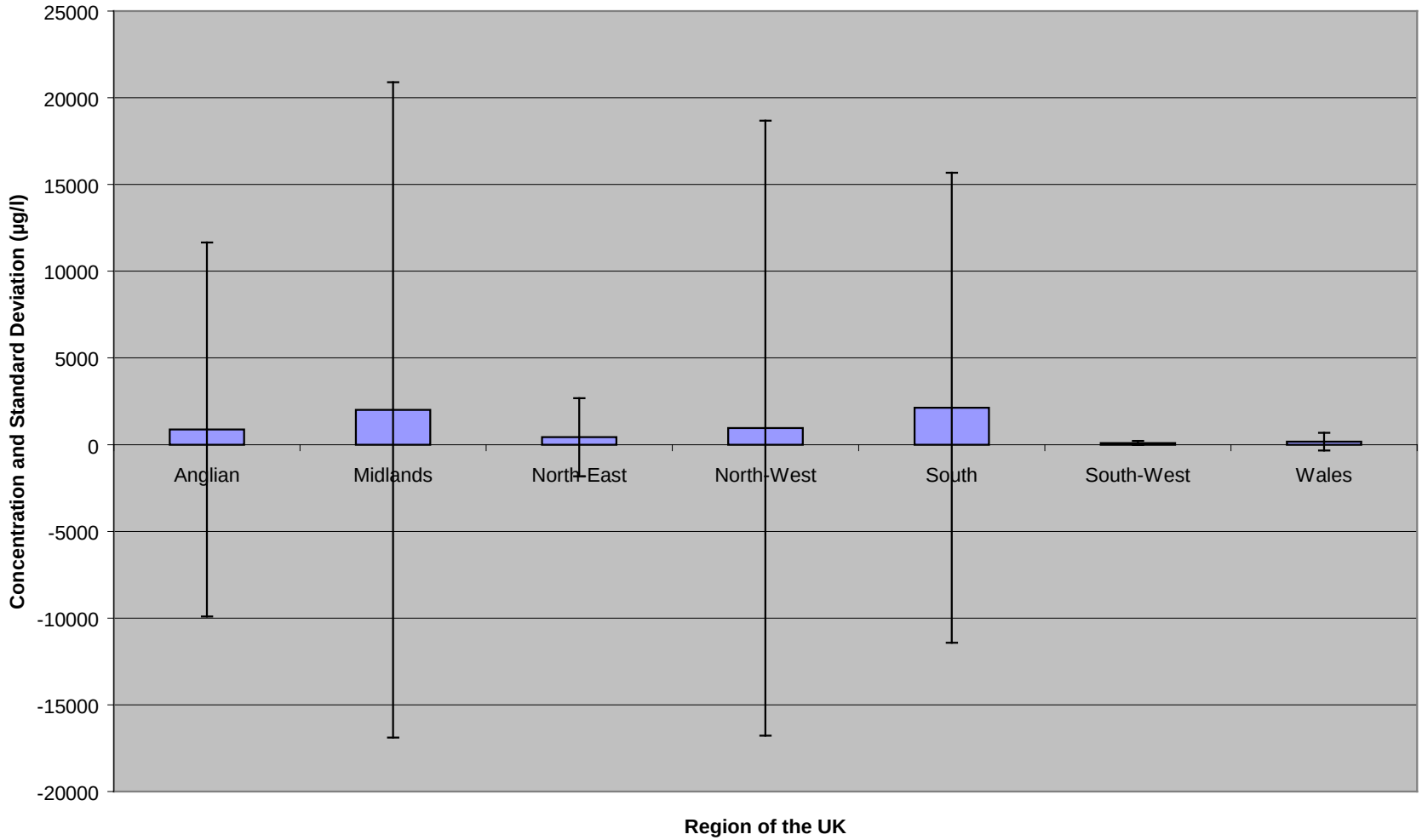


**Figure B4 Concentration of bromide in raw water in England and Wales (including samples detected below the limit of detection)**

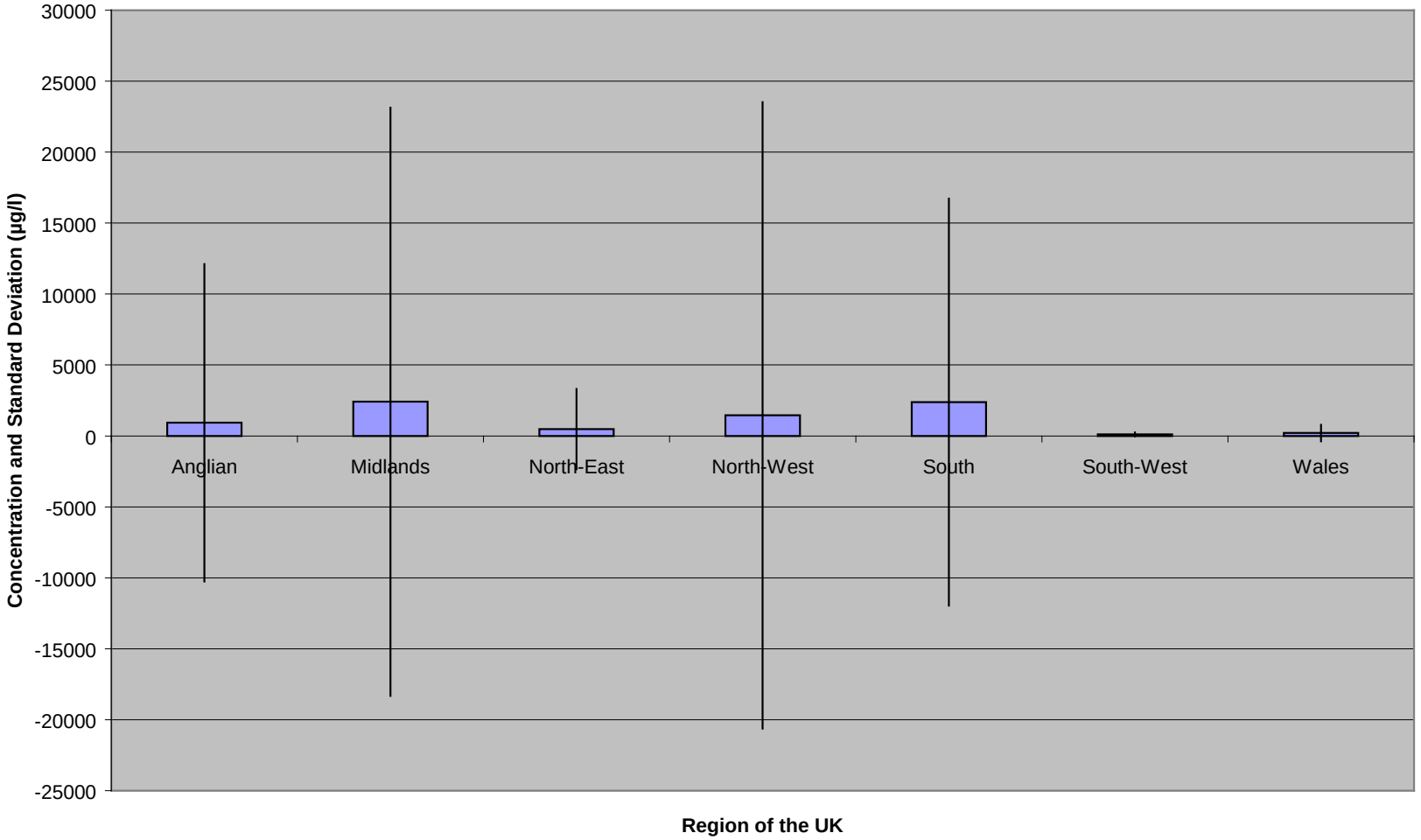


**Figure B5 Concentration of bromide in raw water in England and Wales (excluding samples detected below the limit of detection)**

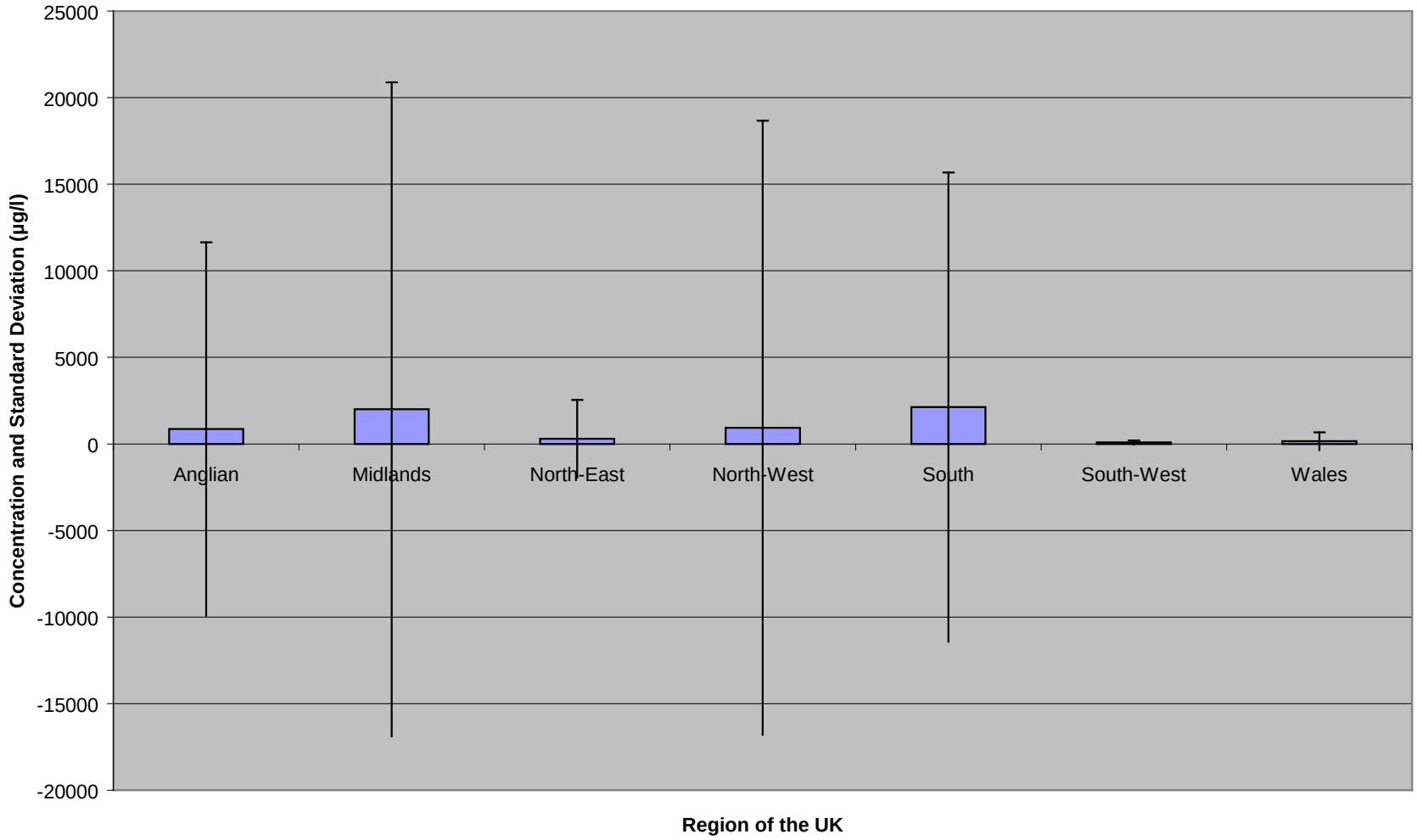


**Figure B6 Concentration of bromide in raw water in England and Wales (assuming values reported below the limit of detection are equal to 0 µg/l)**

**Table B1 Monitoring of iodide in raw water by Water Company C**

| | **Concentration (µg/l)** | | | | | |
|---|---|---|---|---|---|---|
| A1 | <100 | <100 | <2.5 | 2.5 | <3 | <3 |
| B1 | <100 | <100 | <100 | <2.5 | <3 | - |
| C1 | <100 | - | - | - | - | - |
| D1 | <100 | <100 | <2.5 | <3 | - | - |
| E1 | <100 | 4.9 | - | - | - | - |
| F1 | <100 | <100 | <2.5 | <3 | - | - |
| G1 | <100 | <100 | <2.5 | <3 | - | - |
| H1 | <100 | <100 | <2.5 | <3 | - | - |
| I1 | <100 | - | - | - | - | - |
| J1 | <100 | <100 | <100 | <2.5 | - | - |
| K1 | <100 | <100 | <3 | - | - | - |
| L1 | <100 | <100 | <3 | - | - | - |
| M1 | <100 | 10.1 | - | - | - | - |
| N1 | <100 | <100 | - | - | - | - |
| O1 | <100 | <100 | <3 | - | - | - |
| P1 | <100 | <100 | <2.5 | - | - | - |
| Q1 | <100 | <100 | <100 | <2.5 | <3 | - |
| R1 | <100 | - | - | - | - | - |
| S1 | <100 | - | - | - | - | - |
| T1 | <100 | <100 | - | - | - | - |
| U1 | <2.5 | - | - | - | - | - |
| V1 | 11.3 | - | - | - | - | - |
| W1 | <100 | <100 | <2.5 | - | - | - |
| X1 | <100 | <100 | <2.5 | - | - | - |
| Y1 | <100 | <100 | <100 | <3 | - | - |
| Z1 | 510 | <100 | <2.5 | <2.5 | - | - |
| A2 | <100 | <2.5 | <2.5 | <3 | - | - |
| B2 | <100 | - | - | - | - | - |
| C2 | <100 | <100 | <2.5 | - | - | - |
| D2 | <100 | <2.5 | - | - | - | - |
| E2 | <100 | <100 | <2.5 | <3 | - | - |
| F2 | <100 | <3 | - | - | - | - |
| G2 | <100 | <100 | <100 | <2.5 | <3 | - |

| | **Concentration (µg/l)** | | | | | |
|---|---|---|---|---|---|---|
| H2 | <100 | - | - | - | - | - |
| I2 | <100 | - | - | - | - | - |
| J2 | <100 | <2.5 | - | - | - | - |
| K2 | <100 | 4.4 | - | - | - | - |
| L2 | <100 | <100 | <3 | - | - | - |
| M2 | <100 | <100 | <100 | <2.5 | <2.5 | <3 |
| N2 | <100 | <100 | <100 | - | - | - |
| O2 | <100 | <100 | <2.5 | <2.5 | <3 | - |

**Table B2 Iodide concentrations detected above the limits of detection in raw water monitoring survey conducted by Water Company C**

| **Site** | **A1** | **E1** | **M1** | **V1** | **Z1** | **K2** |
|---|---|---|---|---|---|---|
| Number of samples above LoD | 1 | 1 | 1 | 1 | 1 | 1 |
| Number of samples below LoD | 5 | 1 | 1 | 0 | 3 | 1 |
| Concentration of sample above LoD | 2.5 | 4.9 | 10.1 | 11.3 | 510.0 | 4.4 |

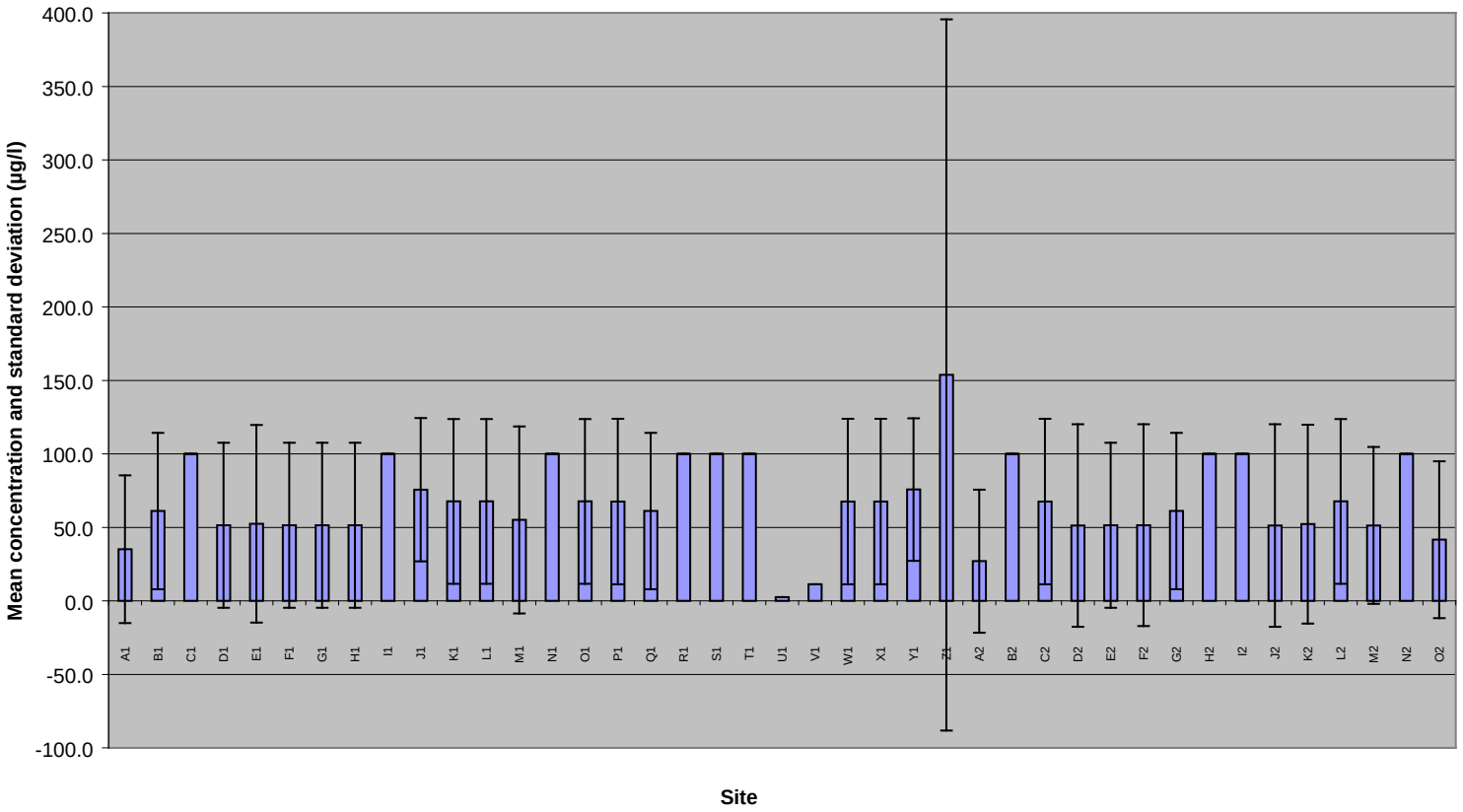


**Figure B7 Concentration of iodide in raw water in the Water Company C region (please note that single samples were taken at nine sites)**