Supplementary Information

**Inputs of disinfection by-products to the marine environment from various industrial activities: Comparison to natural production**

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Table S1: Overview of selected DBPs detected in power station effluents (extracted and amended from Jenner et al. (1997)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Power station** | **Chlorine dose [mg Cl2/L ]** | **Bromoform [µg/L]** | **DBAA  [µg/L]** | **DBAN [µg/L]** | **Tribromo- phenol [µg/L]** | **Reference** |
| Heysham 2 (UK) | 0.5 – 1.0 | 26.1 |  | 2.6 |  | a |
| Dungeness (UK) | 0.75 – 1.0 | 5.8 |  | 0.2 |  | a |
| Wylfa (UK) | 0.3 – 0.4 | 27.3 |  | 0.83 |  | a |
| Bradwell (UK) | 0.6 – 1.0 | 25 |  | 0.87 |  | a |
| Hartlepool (UK) | 0.5 – 1.0 | 3.5 |  | <0.1 |  | a |
| Sizewell A (UK) | 0.6 – 1.0 | 14.5 |  | <0.1 |  | a |
| Paluel (FR) | 0.37 | 3.1 |  | 0.1 |  | a |
|  | 0.82 | 9.6 |  | 1.05 |  | a |
|  | 0.2 | 26.8 | 10.3 | 2.8 | 0.14 | b |
| Penly (FR) | 0.62±0.1 | 13.4 |  | NA |  | a |
|  | 0.5±0.08 | 15.0 |  | NA |  | a |
|  | 0.57 | 7.4 | 7.4 | 0.94 | 0.10 | b |
| Gravelines (FR) | 0.64 | 6.4 |  | NA |  | a |
|  | 0.8 | 18.6 |  | NA |  | a |
|  | 0.77 | 26.8 | 9.5 | 3.6 | 0.37 | b |
| Maasvlakte (NL) | 0.8 – 1.5 | 11.5 |  | 0.83 |  | a |
|  | 0.8-1.5 | 8.4 |  | 0.94 |  | a |
| Madras (IND) | 1.0 | 28.3 |  |  |  | c |
| Youngkwang (ROK) | 1 | 124 |  |  |  | d |
| Ringhals (SWE) | 1.5 | 100 |  |  |  | e |
| Kori (ROK) |  |  |  |  | 0.02 | f |
| **All Data mean (range)** |  | **25.0  (3.1 – 100)** | **9.0  (7.4 – 10.3)** | **1.1  (<0.1 – 3.6)** | **0.16 (0.02 -0.37)** |  |

NA: not available; to increase readability, in some cases values were averaged and/or standard deviations omitted  
UK: United Kindom, FR: France, NL: Netherlands, IND: India, ROK: Republic of Korea, SWE: Sweden  
Data extracted from: a Jenner et al. (1997), b Allonier et al. (1999), c Padhi et al. (2012), d Yang (2001), e Fogelqvist et al. (1982), f Sim et al. (2009)

Table S2: Overview on DBP occurrences in thermal brines and reverse osmosis concentrates of desalination plants (extracted and amended from Kim et al. 2015).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source and location** |  | **TBM [μg/L]** | TBM [μg/L] | DBCM [μg/L] | DCBM [μg/L] | TCM [μg/L] | **HAAs [μg/L]** | MBAA [μg/L] | DBAA [μg/L] | TBAA [μg/L] | **HANs  [μg/L]** | DBAN [μg/L] | BCAN [μg/L] | **Other DBPs [μg/L]** |  |
| **Thermal Brine** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Red Sea coast, Saudi Arabia | Brine recycle | 9.5 | 9.0 | 0.36 | 0.13 | ND | 5.5 | 0.2 | 4.4 | 0.88 | 1.46 | 1.03 | 0.43 |  | a |
|  | brine blowout | 0.18 | 0.53 | 0.14 | 0.21 | ND | 4.5 | ND | 4.4 | ND | 0.50 | 0.50 | ND |  | a |
| Ruwais, UAE | brine blowout | <1.0 | <0.2 – 0.8 | <0.2 | <0.2 | <0.2 – 0.23 | <15.2 | <1.0 | <1.0 – 11.6 | ND |  |  |  |  | b |
| Doha West and  Al-Zor, Kuwait |  | 1.0 – 2.0 | 1.8 0.7 |  |  |  |  |  |  |  |  |  |  |  | c |
| Jeddah, Saudi Arabia |  | 12.7 – 17.8 | 12.4 – 17.4 | 0.3 – 0.4 |  |  |  |  |  |  |  |  |  |  | d |
| **RO concentrate** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Red Sea coast, Saudi Arabia | 1st pass conc. in plant 1 | 6.2 | 4.96 | 0.23 | 0.06 | ND | 0.78 | 0.17 | 0.61 | ND | ND | ND | ND |  | a |
|  | 1st pass conc. in plant 2 | 22.6 – 52.9 | 51.3 | 1.48 | 0.06 | ND | 5.7 – 7.2 | ND | 2.52 | 3.67 | 0.6 – 1.2 | 1.17 | 0.04 | 1.6 – 2.0  (I-THMs) | a |
| Carlsbad, USA | fall | 5.0 – 14 | 5 – 14 |  |  | 0.2 – 0.7 | 17 – 27 |  |  |  | 0.78 – 3.1 |  |  | 0.53 – 0.96 (Br-phenol) | e |
|  | winter | 29 – 61 | 10 – 20 |  |  | 20 – 41 |  |  |  |  |  |  |  |  | e |
| Ebara Corp, Japan |  | 24 – 39 |  |  |  |  |  |  |  |  |  |  |  |  | f |
| Nuweibaa, Egypt |  | 159 | 104 | 2.9 | 0.3 | 52 |  |  |  |  |  |  |  |  | g |
| **Mean\*** |  | **29.5** | **19.3** | **0.8** | **0.2** | **10.4** | **9.1** | **0.3** | **3.6** | **0.9** | **1.3** | **0.7** | **0.1** | **0.75 (Br-phenols)** |  |
| **Range** |  | **0.2** – **159** | **0.2** – **104** | **0.23** – **2.9** | **0.06** – **0.3** | **ND** – **52** | **0.78** – **27** | **ND** – **0.17** | **0.6** – **11.6** | **ND** – **3.67** | **0.5** – **3.1** | **ND** – **1.2** | **ND** – **0.4** | **0.53** – **0.96** |  |

Data extracted from: (a) Le Roux et al. (2015), (b) Elshorbagy and Abdulkarim (2006), (c) Saeed et al. (1999), (d) Mayankutty et al. (1991), (e) Agus and Sedlak (2010), (f) Kojima et al. (1995), (g) calculated mean THM concentration from three outlets from Hamed et al. (2017), ND: not detected.

\* calculated from all values provided. If rages are given, the mean value was used for the calculation. ND was set to 0 for purpose of calculation.

Table S3: Most frequently identified disinfection by-products in ballast water management systems (extracted from David et al. (2018)\*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **DBP** | **Frequency of detection§** | **Discharge concentration in [µg/L]** | | | | |
|  |  | **Min** | **Max** | **Median** | **Mean** | **SD** |
| Bromate | 20 | 6.85 | 920 | 33.5 | 119.7 | 245.8 |
| Bromochloroacetic acid | 27 | 0.10 | 246.7 | 5.6 | 15.1 | 46.6 |
| Bromoform | 36 | 0.08 | 890 | 229 | 247.1 | 213.7 |
| Dibromoacetic acid | 34 | 0.14 | 230 | 32.8 | 48.7 | 50.9 |
| Dibromoacetonitrile | 17 | 0.28 | 133 | 12.9 | 23.3 | 32.5 |
| Dibromochloroacetic acid | 18 | 1.50 | 32.7 | 8.7 | 10.8 | 8.2 |
| Dibromochloromethane | 33 | 0.03 | 120 | 16 | 22.1 | 28.2 |
| Dibromomethane | 10 | 0.06 | 9.6 | 1.6 | 2.8 | 3.4 |
| Dichloroacetic acid | 21 | 0.10 | 77.5 | 2.96 | 11 | 18 |
| Dichloroacetonitrile | 11 | 0.01 | 9.2 | 0.19 | 1.9 | 3.1 |
| Dichlorobromoacetic acid | 19 | 0.10 | 27.7 | 3.4 | 5.9 | 7.8 |
| Dichlorobromomethane | 27 | 0.04 | 70.5 | 4.4 | 9.5 | 14.5 |
| Monobromoacetic acid | 30 | 0.20 | 191 | 3.1 | 15.5 | 37.8 |
| Monochloroacetic acid | 21 | 0.08 | 495 | 2.9 | 36.3 | 110.2 |
| Tribromoacetic acid | 26 | 0.10 | 970 | 19.3 | 103.4 | 197.8 |
| Trichloroacetic acid | 18 | 0.50 | 150 | 9.7 | 26.3 | 41.0 |
| Trichloromethane | 21 | 0.10 | 257 | 3.9 | 29.8 | 61.1 |
| 2,4,6-Tribromophenol | 5 | 0.10 | 0.45 | 0.21 | 0.27 | 0.14 |

\* The selection of DBPs is limited to findings in 36 Final Approval dossiers as the test conditions are relatively close to a realistic operational ballast water treatment. § Number of dossiers listing the respective disinfection by-product. Means refer to samples where compounds were detected.

Table S4: Concentrations of DBPs reported in wastewater effluents (extracted from Krasner et al. (2009))

|  |  |  |
| --- | --- | --- |
| **Disinfectant** | **DBP** | **Level in wastewater effluent** |
| Chloramine (chlorine added to poorly nitrified wastewater) | THMs | Median = 2 *μ*g/L |
| HAAs | Median = 8.9 *μ*g/L |
| HANs | ND to 12 *μ*g/L (median and 75th percentile levels of 0.3 and 0.8 *μ*g/L, respectively) |
| Chlorine (chlorine added to well nitrified wastewater) | THMs | 11 to 92 *μ*g/L (median = 57 *μ*g/L) |
| HAAs | 13 to 136 *μ*g/L (median = 70 *μ*g/L |
| HANs | 0.9 to 30 *μ*g/L (median = 16 *μ*g/L) |

ND: not detected

Table S5: Concentrations of DBPs in chlorinated saline sewage effluents in Hong Kong.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Primary effluent** | | **Secondary effluent** | | **Reference**\* |
| **Chlorine dose and contact time** | **Levels**  **[μg/L]** | **Chlorine dose and contact time** | **Levels**  **[μg/L]** |
| Bromochloroacetic acid | 15 mg/L NaOCl as Cl2 for 2 h | 4.2 | 6 mg/L NaOCl as Cl2 for 2 h | 1.4 | a |
| Bromodichloroacetic acid | 2.2 | 0.0 | a |
| Bromoform | 26.5 | 31.8 | a |
| Chloroform | 8.0 | 5..0 | a |
| Dibromoacetic acid | 6.0 | 8.6 | a |
| Dibromochloroacetic acid | 0.0 | 0.0 | a |
| Dibromochloromethane | 15.6 | 2.5 | a |
| Dichloroacetic acid | 6.8 | 3.3 | a |
| Dichlorobromomethane | 11.6 | 4.9 | a |
| Tribromoacetic acid | 8.0 | 2.8 | a |
| Trichloroacetic acid | 5.0 | 5.7 | a |
| 2,4,6-Tribromophenol |  |  | 6 mg/L NaOCl as Cl2 for 30 min | 0.97 | b |

\*Chlorination of the primary and secondary effluents was conducted in batch tests in the laboratory. Data extracted from (a) Yang et al. (2005); (b) Ding et al. (2013);

**Estimate on annual discharge of cooling water from coastal thermal power stations**

In 2016, approximately 25,000 TWh of electricity were produced worldwide (IEA 2018) with the annual global thermal electricity production relying on cooling systems for heat dissipation amounts to 18,900 TWh (16,300 TWh by fossil fuel, 2 600 TWh by nuclear power). Maas et al. (2020) identified that one fourth of the power plant capacities are located at the coast. Assuming an equal distribution between fossil fuel and nuclear power production between coastal and inland production and an average heating of water (ΔT) by 12.5°C, an annual discharge of 4.7 x 1011 m3 is estimated (Table S6).

Table S6: Overview on global cooling water use in electricity production

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Production**  **[TWh]** | | **Estimated discharge of cooling**  **water in the sea at different water heating temperatures (m3)** | | |
|  | **Global** | **Coastal power plants** | **ΔT = 10 °C** | **ΔT = 12.5 °C** | **ΔT = 15 °C** |
| Fossil Fuel | 16,300 | 4 080 | 4.51 x 1011 | 3..76 x 1011 | 3.01 x 1011 |
| Nuclear | 2 600 | 650 | 1.18 x 1011 | 9.47 x 1010 | 7.82 x 1010 |
| Total | 18,900 | 4 730 | 5.69 x 1011 | 4.70 x 1011 | 3.79 x 1011 |

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