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# Global assessment of chemical quality of drinking water: The case of trihalomethanes

Cristina M Villanueva [a,b,c,d,*], Iro Evlampidou [a], Fathelrahman Ibrahim [a], Carolina Donat-Vargas [a,b,c], Antonia Valentin [a,b,c], Anca-Maria Tugulea [e], Shinya Echigo [f], Dragana Jovanovic [g], Albert T Lebedev [h], Mildred Lemus-Pérez [i], Manuel Rodriguez-Susa [i], Arben Luzati [j], Telma de Cássia dos Santos Nery [k], Pablo A Pastén [l,m], Marisa Quiñones [n], Stig Regli [o], Richard Weisman [o], Shaoxia Dong [p], Mina Ha [q], Songkeart Phattarapattamawong [r], Tarek Manasfi [s], Shaibu-Imodagbe Egbenya Musah [t], Amanda Eng [u], Karel Janák [v], Samantha C. Rush [w], David Reckhow [x], Stuart W. Krasner [y], Paolo Vineis [z], Susan D. Richardson [w], Manolis Kogevinas [a,b,c,d]

[a] ISGlobal, Doctor Aiguader, 88, Barcelona 08003, Spain
[b] CIBER epidemiología y salud pública (CIBERESP), Av. Monforte de Lemos, 3-5, Madrid 28029, Spain
[c] Universitat Pompeu Fabra (UPF), Doctor Aiguader 88, Barcelona 08003, Spain
[d] IMIM (Hospital del Mar Medical Research Institute), Doctor Aiguader 88, Barcelona 08003, Spain
[e] Environmental Health Science and Research Bureau, Health Canada, Ottawa, ON K1A 0K9, Canada
[f] Graduate School of Global Environmental Studies, Kyoto University, Rm252, Research Building 3, Yoshidahonmachi, Sakyo, Kyoto 606-8501, Japan
[g] Department on Drinking Water Quality, Institute of Public Health of Serbia, Dr Subotica 5, Belgrade 11000, Serbia
[h] Organic Chemistry Department, M.V. Lomonosov Moscow State University, Moscow 119991, Russia
[i] Departamento de Ingeniería Civil y Ambiental, Universidad de los Andes, Cra. 1 Este #19a-40, Edificio Mario Laserna - Piso6 Bogotá, 111711, Colombia
[j] Environmental Health Department, Institute of Public Health, Alexander Moisiu Nr. 80, Tirana, Albania
[k] Divisão de Pneumologia, Instituto do Coração - InCor - Hospital das Clínicas, Faculdade de Medicina, Universidade de São Paulo, Av. Dr. Enéas de Carvalho Aguiar, 44, São Paulo (SP) 05403-900, Brazil
[l] Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna, Macul, Santiago 4860, Chile
[m] Centro de Desarrollo Urbano Sustentable (CEDEUS), Av. Vicuña Mackenna, Macul, Santiago 4860, Chile
[n] Quiñones Consulting, Colón 110-1301, Miraflores, Lima 15074, Peru
[o] Office of Ground Water and Drinking Water, U.S. Environmental Protection Agency, 1200 Pennsylvania Ave, N.W., Washington, DC 20460, USA
[p] Department of Water Quality and Health Monitoring, National Institute of Environmental Health, China CDC, 29# Nanwei Road, Xicheng District, Beijing 100050, PR China
[q] Department of Preventive Medicine, Dankook University College of Medicine, 119 Dandae-ro Cheonan-si, Chungnam-do 31116, South Korea
[r] Department of Environmental Engineering, King Mongkut's University of Technology Thonburi, 126 Pracha-Utit Rd., Bangmod, Tungkru, Bangkok 10140 Thailand
[s] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf CH-8600, Switzerland
[t] Ahmadu Bello University, Samaru Campus, Zaria, Kaduna State, Nigeria
[u] Research Centre for Hauora and Health, Massey University, Wellington Campus, PO Box 756, Wellington 6140, New Zealand
[v] Norwegian Institute of Public Health, P.O. Box 4404 Nydalen, Oslo NO-0456, Norway
[w] Department of Chemistry and Biochemistry, University of South Carolina, Columbia, SC 29208, USA
[x] Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA 01062, USA
[y] Metropolitan Water District of Southern California, Water Quality Laboratory, 700 Moreno Ave La Verne, California 91750, USA
[z] MRC Centre for Environment and Health, School of Public Health, Imperial College London, Michael Uren Biomedical Engineering Hub, White City Campus, Wood Lane, London W12 0BZ, UK

* Corresponding author at: ISGlobal, Doctor Aiguader, 88, Barcelona 08003, Spain.
*E-mail address:* cristina.villanueva@isglobal.org (C.M. Villanueva).

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ABSTRACT

*Background:* Trihalomethanes (THM), a major class of disinfection by-products, are widespread and are associated with adverse health effects. We conducted a global evaluation of current THM regulations and concentrations in drinking water.

*Methods:* We included 120 countries (~7000 million inhabitants in 2016), representing 94% of the world population. We searched for country regulations and THM routine monitoring data using a questionnaire addressed to referent contacts. Scientific and gray literature was reviewed where contacts were not identified or declined participation. We obtained or estimated annual average THM concentrations, weighted to the population served when possible.

*Results:* Drinking water regulations were ascertained for 116/120 (97%) countries, with 89/116 (77%) including THM regulations. Routine monitoring was implemented in 47/89 (53%) of countries with THM regulations. THM data with a varying population coverage was obtained for 69/120 (58%) countries consisting of ~5600 million inhabitants (76% of world's population in 2016). Population coverage was ≥90% in 14 countries, mostly in the Global North, 50–89% in 19 countries, 11–49% among 21 countries, and ≤10% in 14 countries including India, China, Russian Federation and Nigeria (40% of world's population).

*Discussion:* An enormous gap exists in THM regulatory status, routine monitoring practice, reporting and data availability among countries, especially between high- vs. low- and middle-income countries (LMICs). More efforts are warranted to regulate and systematically assess chemical quality of drinking water, centralize, harmonize, and openly report data, particularly in LMICs.

## 1. Introduction

Humanity is facing a global water crisis of growing water scarcity, along with quality issues. This is largely caused by a steep increase in the world's population and in fresh water demand since the 1950′s, including unsustainable extraction of ground water and poor infrastructure in water supply systems, especially in low- and middle- income countries (LMICs) (Bouabid and Louis, 2015; Whitmee et al., 2015). Climate change crisis is expected to exacerbate water stress through decline of renewable surface water and ground water resources projected in most dry subtropical regions (IPCC, 2014). This leads to unprecedented and urgent pressures to ensure sustainable drinking water access for the present and future generations in many parts of the world.

Chemical pollution of drinking water is a global growing problem that has received limited attention (Damania et al., 2019) compared to water access, sanitation, and hygiene (WASH) issues, which are routinely monitored by the WHO/UNICEF since 1990. The United Nations (UN) Sustainable Development Goal (SDG) #6 urges to guarantee universal access to safe drinking water free from pollution by 2030 (SDG target#6.3), mainly through improved drinking water sources and disinfection. However, there is a general lack of knowledge about the occurrence of chemicals in drinking water, particularly in LMICs.

Chemical hazards in drinking water are multiple and from many origins, e.g., nitrate from intensive agriculture and farming, arsenic or fluoride from natural sources, industrial chemicals from untreated effluents, as well as chemical by-products formed during disinfection processes to inactivate pathogens. Disinfection of drinking water is unquestionably necessary to provide microbiologically safe drinking water. However, disinfection by-products (DBPs) are unintentionally generated (Richardson et al., 2007). Virtually the entire population in developed countries is exposed to DBPs through ingestion, inhalation, or dermal absorption when drinking or using municipal tap water for showering, washing dishes, or swimming in pools (Villanueva et al., 2015). Based on animal data, the International Agency for Research on Cancer (IARC) classifies chloroform and other DBPs as possible human carcinogens (IARC, 2012). Likewise, bladder cancer has been consistently associated with long-term DBPs exposure in epidemiologic studies (Costet et al., 2011b; Villanueva et al., 2004).

Trihalomethanes (THMs) are generally the most abundant DBP class formed in water treated with chlorine, the most widely used water disinfectant, and are used as a DBP marker. The extent of DBP formation is impacted by precursor levels (i.e., the amount of organic and inorganic materials occurring in the raw water that are transformed by the disinfectants to DBPs), the nature of the treatment/disinfection processes, and the DBP regulations. WHO guidelines for individual THMs are 300 μg/L for chloroform, 100 μg/L for bromoform, 100 μg/L for dibromochloromethane, and 60 μg/L for bromodichloromethane (WHO, 2022a). The maximum contaminant level (MCL) established by the European Union (EU) is 100 μg/L for total THMs (i.e., the sum of chloroform, bromodichloromethane, dibromochloromethane, and bromoform) (EC, 2020), although a few member states may have more stringent regulations. Prior to 2001, in the United States (US), the MCL for total THMs was 100 μg/L and after 2006, it is currently 80 μg/L (DeMarini, 2020). In the period 2010–2014 following the implementation of the current THM regulatory levels, there has been a reduction of 20 μg/L in the average total THM occurrence for the highest 5% of systems serving >100,000 people across 44 US states compared to 1997–1998 (Seidel et al., 2017). Worldwide centralized information on regulation, monitoring, and THM measurements in drinking water is missing or is scarce and scattered, and beyond Europe (Evlampidou et al., 2020) and the US (Weisman et al., 2022), there are no systematic studies reporting these data.

In this context and expanding a preceding EU-based THM assessment (Evlampidou et al., 2020), we conducted a global evaluation of chemical quality of drinking water, focusing on THMs, and including the most populated countries worldwide. We report the current state of knowledge on the regulatory status and routine monitoring practice of THMs, as well as THM occurrence data worldwide.

## 2. Methods

### 2.1. Study design and population

During 2017–2020 we performed a worldwide ecological descriptive study using existing and available data on regulations and data on THM concentrations from 1997 to 2020. We included countries presented in the EU-based THM assessment (Evlampidou et al., 2020) and expanded on the missing European countries. We additionally selected the most populated countries within each of the UN regions (2015 revision) in descending order until 75% coverage for the specific UN region was achieved (UN, 2015). This initial list was expanded to include countries mentioned in the WHO report on drinking water standards and THM regulations worldwide (WHO, 2021) and countries where we had personal contacts or encountered relevant information during the literature review. Countries with active war at the time of data collection were not included. We finally targeted 120 countries (Tables 1–4), accounting for 6,993,800,182 inhabitants and representing approximately 94% of the world population in 2016 (IHME, 2016).

**Table 1**
Summary information on total trihalomethane (THM) regulations maximum contaminant level (MCL), routine monitoring practice, percentage of country population covered, reporting period, annual average, and standard deviation (SD) for countries in the African continent ordered by descending population.

| | | | | Drinking water regulation | | | THM data | | | | | THM data source | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | UN region | Country | Population (GBD 2016)[17] | THM regulations | MCL, total THMs (μg/L) | THMs routinely monitored | Population coverage (%) | Reporting years | Mean (μg/L) | Population weighted | SD (μg/L) | PC | LR | PR | OD |
| 1 | Western Africa | Nigeria | 184,740,841 | yes | 1[a] | no | 7 | 2008–2015 | 491.9 | yes | – | x | x | – | – |
| 2 | Eastern Africa | Ethiopia | 102,321,708 | no | – | no | 0·3 | 2013–2017 | 92.2 | yes | – | – | x | – | – |
| 3 | Northern Africa | Egypt | 91,682,301 | yes | 100 | unknown | 0 | – | – | – | – | – | – | – | – |
| 4 | Middle Africa | Dem. Rep. Congo | 79,547,445 | unknown | unknown | unknown | 0 | – | – | – | – | – | – | – | – |
| 5 | Eastern Africa | Tanzania | 54,512,129 | no | – | no | 2 | 2008 | 31.8 | no | 33.7 | – | x | – | – |
| 6 | Southern Africa | South Africa | 51,770,560[e] | yes | 1[a] | yes | 55 | 2008–2018 | 59.5 | yes | 104 | x | x | x | – |
| 7 | Eastern Africa | Kenya | 46,574,907 | no | – | no | 11 | 2003–2012 | 10.1 | yes | – | – | x | – | – |
| 8 | Eastern Africa | Uganda | 40,387,030 | yes | 100 | no | 1 | 2009, 2017 | 140.3 | no | 2.4 | – | x | – | – |
| 9 | Northern Africa | Algeria | 40,312,224 | yes | 100 | unknown | 6 | 2012–2017 | 77.4 | yes | – | – | x | – | – |
| 10 | Northern Africa | Sudan | 39,330,050 | yes | [b] | unknown | 0 | – | – | – | – | – | – | – | – |
| 11 | Northern Africa | Morocco | 33,659,387 | yes | 1[a] | unknown | 0 | – | – | – | – | – | – | – | – |
| 12 | Eastern Africa | Mozambique | 28,800,876 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 13 | Western Africa | Ghana | 28,238,371 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 14 | Middle Africa | Angola | 25,901,596 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 15 | Eastern Africa | Madagascar | 24,939,825 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 16 | Middle Africa | Cameroon | 24,002,465 | unknown | Unknown | unknown | 0 | – | – | – | – | – | – | – | – |
| 17 | Western Africa | Ivory Coast | 23,053,614 | unknown | Unknown | unknown | 0 | – | – | – | – | – | – | – | – |
| 18 | Western Africa | Niger | 20,081,505 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 19 | Western Africa | Burkina Faso | 18,629,543 | yes | 1[a] | unknown | 0 | – | – | – | – | – | – | – | – |
| 20 | Eastern Africa | Zambia | 16,647,858 | yes | 30 | no | 0 | – | – | – | – | – | – | – | – |
| 21 | Eastern Africa | Zimbabwe | 15,955,587 | no | – | no | 17 | 2008, 2015 | 17.7 | yes | 19.4 | – | x | – | – |
| 22 | Eastern Africa | Rwanda | 12,075,093 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 23 | Eastern Africa | Burundi | 11,571,157 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 24 | Northern Africa | Tunisia | 11,209,073 | yes | [b] | unknown | 0 | – | – | – | – | – | – | – | – |
| 25 | Western Africa | Sierra Leone | 6,622,608 | unknown | – | unknown | 0 | – | – | – | – | – | – | – | – |
| 26 | Southern Africa | Botswana | 2,297,411 | yes | 1000 | unknown | 0 | – | – | – | – | – | – | – | – |

PC - Personal communication; OD - Open data; PR - Public Report; LR - Literature review (see references in the supplementary material).

[a] The sum of the ratio of the concentration of each trihalomethane to its respective guideline should not exceed 1, where guidelines for chloroform are 200 µg/L except in China (60 µg/L), Uruguay (150 µg/L), South Africa, Iran, Saudi Arabia, Thailand, and Singapore (300 µg/L), and New Zealand (400 µg/L); bromodichloromethane guideline=60 µg/L, dibromochloromethane=100 µg/L except in Peru (50 µg/L) and New Zealand (150 µg/L), and bromoform guideline = 100 µg/L.

[b] Total THMs are not regulated, but chloroform (300 µg/L), bromodichloromethane (60 µg/L), dibromochloromethane (100 µg/L), and bromoform (100 µg/L) are regulated separately.

[c] Total THMs are not regulated, but chloroform (200 µg/L), bromodichloromethane (60 µg/L), dibromochloromethane (100 µg/L), and bromoform (100 µg/L) are regulated separately.

[e] Source of the population data according to National statistics (Albania, India, Republic of Korea, Serbia, South Africa, Thailand, Vietnam), Wikipedia (Brazil, Canada, Haiti, Peru, Venezuela) and reported in the questionnaire by national contacts (US) for the corresponding THM reporting years.

### 2.2. Data collection

*Questionnaire used in personal communications.* We designed a questionnaire to collect data on THM regulations and monitoring practice, water source, and disinfection methods (Supplementary Material Fig. 1). The questionnaire also ascertained the institution/person providing the information, reporting year and geographic region, population served, and maximum permissible level for THMs according to the country's regulation (Maximum Concentration Level – MCL, or guidelines). We created a template database to compile data for any year between 2010 and 2016 on an annual average, standard deviation (SD), and number of water samples tested for total THMs, chloroform, bromodichloromethane, chlorodibromomethane, and bromoform. Between October 2017 and February 2018, we sent the study questionnaire to experts in national agencies (Ministries of Health, Institutes of Public Health, Water Agencies, etc.), universities, and research centres with responsibilities in the maintenance or generation of data on drinking water quality. Where possible, the raw THM data was requested and the template database provided.

*Literature review and gray literature.* For countries where experts were not identified or declined to participate, we explored other data sources such as online open data and public reports, and by personal communications. We performed a literature review according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and expanded the study period to 1997–2020. We aimed to identify drinking water regulations and open online monitoring reports with THM measurements at the tap, distribution systems, or water treatment plants from official websites (e.g., Ministry of Health, municipality, etc.), water companies, and/or private laboratories. Secondly, we performed a literature search for published peer-reviewed scientific articles and gray literature, including Masters or PhD theses using the online databases PubMed, Google Scholar, Mendeley, and Google. We used no restriction to any language and used these keywords in English language: [country name] AND [[drinking water] OR [potable water] OR [water quality]] AND [[Trihalomethanes] OR [THMs] OR [disinfection by-products] OR [chlorination by-products] OR [chloroform]]. When performing this search in Google, we also used the French, Spanish, and Portuguese translation of the keywords. When encountering websites in the local language, we used the Google automatic translation service to translate the relevant text or page into English when necessary. The literature review on China was conducted by a native-Chinese speaker. We included articles and reports when THM data were based on actual measurements, but we excluded them when only modelled THM data were provided. For the data extraction and entry, we used an adapted extended version of the template THM database and created separate country-based datasets.

We looked for drinking water regulations in a broad sense, i.e. including either guidelines (non-binding recommendations), or binding maximum contaminant levels. In addition to the above, we used the keywords [[Guidelines] OR [Legislation] OR [Law] OR [Regulations] OR [Order]]. For information extraction and entry, we created a THM country regulation database.

Due to the ecological design of the study and the anonymity of data, ethics approval was not sought.

### 2.3. Data analysis to estimate country THM indices and population coverage

*Based on data from questionnaires.* For the estimation of THM descriptive statistics and population coverage, we used data as provided or performed additional analysis, including application of population weights whenever possible. The procedure was as follows:

When only country-wide average THM concentrations and population size were available through our data sources, we used the country average THM and population served coverage data as was. When raw data were available and measurements were below the detection limit

**Table 2**

Summary information on total trihalomethane (THM) regulations maximum contaminant level (MCL), routine monitoring practice, percentage of country population covered, reporting period, annual average, and standard deviation (SD) for countries in the American continent and Oceania by descending population.

| # | UN region | Country | Population (GBD 2016)[17] | Drinking water regulation | | | THM data | | | | | THM data source | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | THM regulations | MCL, total THMs (μg/L) | THMs routinely monitored | Population coverage (%) | Reporting year(s) | Mean (μg/L) | Population weighted | SD (μg/L) | PC | LR | PR | OD |
| 27 | North America | United States | 310,000,000[e] | yes | 80 | yes | 65 | 2011 | 33.6 | no | 32.5 | x | – | – | – |
| 28 | South America | Brazil | 207,660,929[e] | yes | 100 | partially | 15 | 2004–2018 | 58.5 | yes | 33.6 | x | x | – | – |
| 29 | Central America | Mexico | 128,669,838 | yes | 200 | unknown | 15 | 1999–2000 | 47.4 | yes | – | – | x | – | – |
| 30 | South America | Colombia | 48,515,490 | yes | 200 | partially | 36 | 2003–2017 | 31.3 | yes | 30.7 | x | x | – | – |
| 31 | South America | Argentina | 43,692,698 | yes | 100 | unknown | 1 | 1998–1999 | 4.6 | no | – | – | x | – | – |
| 32 | North America | Canada | 35,702,908[e] | yes | 100 | yes | 90 | 2015 | 27.0 | yes | 33.0 | x | – | – | – |
| 33 | South America | Venezuela | 26,432,000[e] | no | – | unknown | 18 | 2001–2008 | 64.6 | yes | 13.8 | – | x | – | – |
| 34 | South America | Peru | 25,983,588[e] | yes | 1[a] | partially | 40 | 1997–2017 | 31.7 | yes | 13.9 | x | – | – | – |
| 35 | South America | Chile | 18,168,131 | yes | 1[a] | yes | 88 | 2016 | 16.5 | yes | 15.6 | x | – | – | – |
| 36 | South America | Ecuador | 16,562,619 | yes | 500 | unknown | 0 | – | – | – | – | – | – | – | – |
| 37 | Central America | Guatemala | 16,526,042 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 38 | Caribbean | Cuba | 11,409,748 | yes | 1[a] | unknown | 0 | – | – | – | – | – | – | – | – |
| 39 | South America | Bolivia | 11,068,133 | yes | 100 | unknown | 0 | – | – | – | – | – | – | – | – |
| 40 | Caribbean | Dominican Republic | 10,530,348 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 41 | Caribbean | Haiti | 8,578,000[e] | no | – | no | 0·3 | 2001 | 48.1 | no | 17.7 | – | x | | – |
| 42 | Central America | Honduras | 8,327,052 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 43 | South America | Paraguay | 6,684,414 | yes | 100 | unknown | 0 | – | – | – | – | – | – | – | – |
| 44 | Central America | El Salvador | 6,164,537 | yes | 1[a] | unknown | 0 | – | – | – | – | – | – | – | – |
| 45 | Central America | Nicaragua | 6,161,901 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 46 | Central America | Costa Rica | 4,815,802 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 47 | Central America | Panama | 3,967,868 | yes | 100 | unknown | 0 | – | – | – | – | – | – | – | – |
| 48 | South America | Uruguay | 3,441,934 | yes | 1[a] | unknown | 0 | – | – | – | – | – | – | – | – |
| 49 | South America | Suriname | 546,054 | unknown | – | unknown | 0 | – | – | – | – | – | – | – | – |
| 50 | Australia/N. Zealand | Australia | 24,101,585 | yes | 250 | yes | 76 | 2012–2018 | 71.7 | no | 28.7 | – | – | x | x |
| 51 | Australia/N. Zealand | New Zealand | 4,551,506 | yes | 1[a] | yes | 38 | 2010–2017 | 18.4 | yes | – | x | – | – | – |
| 52 | Melanesia | Fiji | 861,865 | unknown | unknown | unknown | 0 | – | – | – | – | – | – | – | – |
| 53 | Polynesia | Samoa | 198,584 | no | – | no | 0 | – | – | – | – | – | – | – | – |

PC - Personal communication; OD - Open data; PR - Public Report; LR - Literature review (see references in the supplementary material).

[a] The sum of the ratio of the concentration of each trihalomethane to its respective guideline should not exceed 1, where guidelines for chloroform are 200 μg/L except in China (60 μg/L), Uruguay (150 μg/L), South Africa, Iran, Saudi Arabia, Thailand, and Singapore (300 μg/L), and New Zealand (400 μg/L); bromodichloromethane guideline=60 μg/L, dibromochloromethane=100 μg/L except in Peru (50 μg/L) and New Zealand (150 μg/L), and bromoform guideline = 100 μg/L.

[c] Total THMs are not regulated, but chloroform (200 μg/L), bromodichloromethane (60 μg/L), dibromochloromethane (100 μg/L), and bromoform (100 μg/L) are regulated separately.

[e] Source of the population data according to National statistics (Albania, India, Republic of Korea, Serbia, South Africa, Thailand, Vietnam), Wikipedia (Brazil, Canada, Haiti, Peru, Venezuela) and reported in the questionnaire by national contacts (US) for the corresponding THM reporting years.

**Table 3**
Summary information on total trihalomethane (THM) regulations maximum contaminant level (MCL), routine monitoring practice, percentage of country population covered, reporting period, annual average, and standard deviation (SD) for countries in the Asian continent by descending population.

| | | | | THM regulation | | | THM data | | | | | THM data source | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | UN region | Country | Population (GBD 2016)[17] | THM regulations | MCL, total THMs (μg/L) | THMs routinely monitored | Population coverage (%) | Reporting year (s) | Mean (μg/L) | Population weighted | SD (μg/L) | PC | LR | PR | OD |
| 54 | Eastern Asia | China | 1,367,028,506 | yes | 1[a] | yes | 10 | 1997–2016 | 39.8 | yes | – | x | x | – | – |
| 55 | Southern Asia | India | 1,210,854,977[e] | yes | [c] | unknown | 1.9 | 2006–2015 | 531 | yes | – | – | x | – | – |
| 56 | South-Eastern Asia | Indonesia | 257,916,568 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 57 | Southern Asia | Pakistan | 190,959,485 | no | – | no | 12 | 2007–2012 | 118 | yes | – | – | x | – | – |
| 58 | Southern Asia | Bangladesh | 161,892,212 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 59 | Eastern Asia | Japan | 125,683,487 | yes | 100 | yes | 98 | 2016 | 11.9 | yes | 7.4 | x | – | – | – |
| 60 | South-Eastern Asia | Philippines | 102,453,788 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 61 | South-Eastern Asia | Vietnam | 85,789,573[e] | yes | [c] | no | 18 | 1998–2014 | 66.0 | yes | 51.4 | – | x | – | – |
| 62 | Southern Asia | Iran | 81,329,586 | yes | 1[a] | unknown | 23 | 2008–2018 | 22.3 | yes | – | – | x | – | – |
| 63 | Western Asia | Turkey | 79,322,758 | yes | 100 | yes | 20 | 2006–2018 | 24.5 | yes | – | – | x | x | – |
| 64 | South-Eastern Asia | Thailand | 65,980,000[e] | yes | [a] | partially | 37 | 2002–2017 | 34.3 | yes | 29.5 | x | x | – | – |
| 65 | Eastern Asia | Rep.of Korea | 48,580,293[e] | yes | 100 | yes | 48 | 2000–2015 | 20.4 | yes | 10.4 | x | | – | – |
| 66 | Western Asia | Iraq | 39,396,098 | yes | 150 | unknown | 22 | 2005–2014 | 62.7 | yes | – | – | x | – | – |
| 67 | Western Asia | Saudi Arabia | 31,521,065 | yes | 1[a] | unknown | 1 | 2003–2015 | 12.0 | yes | – | – | x | – | – |
| 68 | South-Eastern Asia | Malaysia | 30,753,604 | yes | 1[a] | unknown | 76 | 2003–2005 | 30.7 | no | – | – | x | – | – |
| 69 | Central Asia | Uzbekistan | 30,433,047 | yes | [d] | yes | 0 | – | – | – | – | – | – | – | – |
| 70 | Southern Asia | Nepal | 30,076,834 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 71 | Western Asia | Yemen | 28,141,448 | yes | 150 | unknown | 0 | – | – | – | – | – | – | – | – |
| 72 | Southern Asia | Sri Lanka | 20,719,796 | no | – | no | 0.5 | 2014 | 15.7 | no | 7.5 | – | x | – | – |
| 73 | Western Asia | Syria | 18,214,567 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 74 | Central Asia | Kazakhstan | 17,867,814 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 75 | South-Eastern Asia | Cambodia | 15,941,371 | yes | 250 | unknown | 14 | 2013 | 25.6 | no | – | – | – | x | – |
| 76 | Central Asia | Tajikistan | 8,591,322 | yes | [d] | yes | 0 | – | – | – | – | – | – | – | – |
| 77 | Western Asia | Israel | 8,185,202 | yes | 100 | unknown | 0 | – | – | – | – | – | – | – | – |
| 78 | Western Asia | Jordan | 7,716,860 | yes | 150 | unknown | 0 | – | – | – | – | – | – | – | – |
| 79 | South-Eastern Asia | Laos | 7,211,163 | no | – | no | 0 | – | – | – | – | – | – | – | – |
| 80 | Western Asia | Lebanon | 5,827,434 | no | – | no | 53 | 2003–2004 | 8.2 | yes | – | x | x | – | – |
| 81 | Western Asia | Palestine | 5,163,946 | yes | 100 | unknown | 0 | – | – | – | – | – | – | – | – |
| 82 | Western Asia | Oman | 4,696,202 | yes | 1[a] | unknown | 0 | – | – | – | – | – | – | – | – |
| 83 | South-Eastern Asia | Singapore | 3,931,006 | yes | 1[a] | yes | unknown | 2017 | 35.8 | no | – | – | – | – | x |
| 84 | Eastern Asia | Mongolia | 3,037,242 | yes | [c] | unknown | 0 | – | – | – | – | – | – | – | – |
| 85 | Western Asia | Cyprus | 910,587 | yes | 100 | yes | 64 | 2012–2013 | 66.2 | yes | 33·2 | x | – | – | – |

PC - Personal communication; OD - Open data; PR - Public Report; LR - Literature review (see references in the supplementary material).

[a] The sum of the ratio of the concentration of each trihalomethane to its respective guideline should not exceed 1, where guidelines for chloroform are 200 μg/L except in China (60 μg/L), Uruguay (150 μg/L), South Africa, Iran, Saudi Arabia, Thailand, and Singapore (300 μg/L), and New Zealand (400 μg/L); bromodichloromethane guideline=60 μg/L, dibromochloromethane=100 μg/L except in Peru (50 μg/L) and New Zealand (150 μg/L), and bromoform guideline = 100 μg/L.

[c] Total THMs are not regulated, but chloroform (200 μg/L), bromodichloromethane (60 μg/L), dibromochloromethane (100 μg/L), and bromoform (100 μg/L) are regulated separately.

[d] Total THMs are not regulated, only chloroform is regulated. MCL=60 μg/L in Russian Federation, and 200 μg/L in Tajikistan and Uzbekistan.

[e] Source of the population data according to National statistics (Albania, India, Republic of Korea, Serbia, South Africa, Thailand, Vietnam), Wikipedia (Brazil, Canada, Haiti, Peru, Venezuela) and reported in the questionnaire by national contacts (US) for the corresponding THM reporting years.

**Table 4**
Summary information on total trihalomethane (THM) regulations maximum contaminant level (MCL), routine monitoring practice, percentage of country population covered, reporting period, annual average, and standard deviation (SD) for countries in the European continent by descending population.

| | | | | Drinking water regulation | | | THM data | | | | | THM data source | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| id | UN region | Country | Population (GBD 2016)( IHME, 2016) | THM regulations | MCL, total THMs (μg/L) | THMs routinely monitored | Population coverage (%) | Reporting year(s) | Mean (μg/L) | Population weighted | SD (μg/L) | PC | LR | PR | OD |
| 86 | Eastern Europe | Russian Federat. | 146,055,091 | yes | [d] | yes | 9 | 1999–2019 | 16.8 | yes | – | x | x | – | – |
| 87 | Western Europe | Germany | 82,048,579 | yes | 50 | yes | 90 | 2011–2013 | 0.5 | no | – | x | – | – | – |
| 88 | Northern Europe | United Kingdom | 65,375,433 | yes | 100 | yes | 44 | 2010–2015 | 24.2 | yes | 7.1 | x | – | – | – |
| 89 | Western Europe | France | 64,939,098 | yes | 100 | yes | 100 | 2005–2011 | 11.7 | yes | – | – | – | x | |
| 90 | Southern Europe | Italy | 60,501,702 | yes | 30 | yes | 22 | 2012–2017 | 3.1 | yes | 3.6 | x | – | – | x |
| 91 | Southern Europe | Spain | 46,481,496 | yes | 100 | yes | 85 | 2013 | 28.8 | yes | 28.6 | – | – | x | – |
| 92 | Eastern Europe | Ukraine | 45,635,692 | yes | 100 | yes | 0 | – | – | – | – | – | – | – | – |
| 93 | Eastern Europe | Poland | 38,641,788 | yes | 100 | yes | 81 | 2017 | 5.7 | yes | 6.7 | x | | – | – |
| 94 | Eastern Europe | Romania | 19,364,092 | yes | 100 | yes | 7 | 2006–2013 | 91.8 | yes | 64.2 | x | x | – | – |
| 95 | Western Europe | Netherlands | 17,141,153 | yes | 25 | yes | 99 | 2015 | 0.2 | no | – | x | – | – | – |
| 96 | Western Europe | Belgium | 11,367,990 | yes | 100 | yes | 93 | 2011–2014 | 13.2 | yes | 4.0 | x | – | – | – |
| 97 | Southern Europe | Greece | 10,868,170 | yes | 100 | yes | 41 | 2007–2017 | 26.3 | yes | 9.2 | x | – | – | x |
| 98 | Eastern Europe | Czech Republic | 10,631,077 | yes | 100 | yes | 79 | 2015 | 12.8 | yes | 9.6 | x | – | – | – |
| 99 | Southern Europe | Portugal | 10,474,821 | yes | 100 | yes | 96 | 2015 | 23.8 | yes | 19.3 | x | – | – | – |
| 100 | Eastern Europe | Hungary | 9,909,325 | yes | 50 | yes | 96 | 2015 | 10.0 | no | 20.0 | x | – | – | – |
| 101 | Northern Europe | Sweden | 9,887,967 | yes | 100 | yes | 100 | 2011–2013 | 10.0 | no | – | x | – | – | – |
| 102 | Southern Europe | Serbia | 7,114,393[e] | yes | 100 | yes | 71 | 2015 | 10.5 | yes | 10.8 | x | – | – | – |
| 103 | Western Europe | Austria | 8,692,636 | yes | 30 | yes | 100 | 1997 | 1.1 | no | 5.9 | – | x | – | – |
| 104 | Western Europe | Switzerland | 8,377,856 | yes | 50 | yes | 100 | 2020 | 1.1 | no | – | x | – | – | – |
| 105 | Eastern Europe | Bulgaria | 7,239,052 | yes | 100 | yes | 0 | – | – | – | – | – | – | – | – |
| 106 | Northern Europe | Denmark | 5,724,401 | yes | 25 | yes | 98 | 2014–2016 | 0.02 | no | 0.1 | x | – | – | – |
| 107 | Northern Europe | Finland | 5,507,289 | yes | 100 | yes | 80 | 2015 | 7.6 | no | – | x | – | – | – |
| 108 | Eastern Europe | Slovakia | 5,456,895 | yes | 100 | yes | 87 | 2015 | 10.0 | no | – | x | – | – | – |
| 109 | Northern Europe | Norway | 5,253,197 | yes | 100 | yes | 36 | 2014 | 7.0 | yes | 7.0 | x | – | – | – |
| 110 | Northern Europe | Ireland | 4,641,095 | yes | 100 | yes | 83 | 2014 | 47.3 | yes | 25.4 | – | – | – | x |
| 111 | Southern Europe | Croatia | 4,221,725 | yes | 100 | yes | 85 | 2015 | 10.2 | no | 5.9 | x | – | – | – |

(*continued on next page*)

**Table 4** (*continued*)

| id | UN region | Country | Population (GBD 2016)( IHME, 2016) | Drinking water regulation THM regulations | MCL, total THMs (µg/L) | THMs routinely monitored | THM data Population coverage (%) | Reporting year(s) | Mean (µg/L) | Population weighted | SD (µg/L) | THM data source PC | LR | PR | OD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 112 | Northern Europe | Lithuania | 2,895,874 | yes | 100 | yes | 99 | 2015 | 1.0 | yes | 5.9 | x | – | – | – |
| 113 | Southern Europe | Albania | 2,891,851[e] | yes | 100 | no | 20 | 2002–2006 | 3.9 | yes | 1.9 | x | x | – | – |
| 114 | Southern Europe | North Macedonia | 2,075,547 | unknown | unknown | unknown | 3 | 2011 | 21.1 | no | 10.9 | – | x | – | – |
| 115 | Southern Europe | Slovenia | 2,064,986 | yes | 100 | yes | 89 | 2015 | 2.9 | yes | 4.5 | x | – | – | – |
| 116 | Northern Europe | Latvia | 1,981,699 | yes | 100 | yes | 71 | 2015 | 7.2 | yes | 2.6 | x | – | – | – |
| 117 | Northern Europe | Estonia | 1,317,494 | yes | 100 | yes | 64 | 2015 | 13.7 | yes | 12.8 | x | – | – | – |
| 118 | Western Europe | Luxembourg | 579,190 | yes | 50 | yes | 59 | 2011–2018 | 7.5 | yes | 3.0 | – | – | – | x |
| 119 | Southern Europe | Malta | 420,113 | yes | 100 | yes | 100 | 2017 | 49.4 | no | – | x | – | – | – |
| 120 | Northern Europe | Iceland | 330,652 | yes | 100 | yes | 0 | – | – | – | – | – | – | – | – |

PC - Personal communication; OD - Open data; PR - Public Report; LR - Literature review (see references in the supplementary material).

[d] Total THMs are not regulated, only chloroform is regulated. MCL=60 µg/L in Russian Federation, and 200 µg/L in Tajikistan and Uzbekistan.

[e] Source of the population data according to National statistics (Albania, India, Republic of Korea, Serbia, South Africa, Thailand, Vietnam), Wikipedia (Brazil, Canada, Haiti, Peru, Venezuela) and reported in the questionnaire by national contacts (US) for the corresponding THM reporting years.

(DL), we assigned half the value of the reporting laboratory's DL. When only data for the four THMs was available, we calculated total THMs by summing the individual components. We used the mean values of THMs instead of median values, despite the skewedness of some data, because many countries provided mean values and published literature commonly reports means. For the minimum and maximum values, we used the non-weighted THM levels to show the actual range.

We calculated the country population-weighted average THM level and standard deviation (SD) when area-specific (e.g., localities, municipalities, regions, etc.) THM data were available, which we then assigned to the whole country. For the calculation of the individual weights, the country population-weighted THM average, and the population served coverage, we used the country and reporting areas' population figures provided either by the national experts or from census data for the reporting year or – if more than one year, data was available – closest to the mid-point reporting period.

Additionally, for the estimation of the population served coverage, we primarily used country-level population size in 2016 from the Global Burden of Disease 2016 study (IHME, 2016) and secondarily either information from specific country request or from the National Statistical offices or from Wikipedia using the search term "Demographics of [country name]" (13 countries).

*Based on data from literature review.* We obtained or calculated average THM estimates for specific reporting areas from data available in the literature (online open data, public reports, scientific research articles). Firstly, all identified articles and reports were entered into an Excel sheet with the following information: country name, authors, publication date, article title, journal, reporting year, study area, population covered, type of water (e.g., surface water, ground water, mixed), and disinfection method. Secondly, the full text of the article was assessed and information was extracted and entered in another Excel sheet, including reported mean, standard deviation (SD), range (minimum, maximum), and median for total THMs, chloroform, bromodichloromethane, dibromochloromethane, and/or bromoform in each study area. In a third step, THM indices were entered in a table to summarize the final THM indices per country, province, or city. If more than one study was conducted in the area and in the same water network, the more recent published THM mean values were included, and the average THM value was calculated for the area from all studies published in the same year. Articles that did not report THM mean values were excluded in the third step. The extraction steps were checked by two authors to assess whether the information in the papers was accurately extracted and the articles met the inclusion criteria. Population-weighted averages were calculated in a similar way as previously described for data from questionnaires.

Individual country and master databases were created from the template databases, and data were entered in Microsoft Excel 2010. We performed the statistical analysis in STATA 12.0 (Stata Corp, Texas, USA). Global maps with country specific THM concentrations were produced using ArcGIS (version 10.3.1; Esri.)

## 3. Results

*Regulatory status.* Out of the 120 targeted counties, we obtained information on drinking water quality regulations for 116 (97%) (Supplementary Fig. 2 and Supplementary Table 1). THMs were regulated in 89 (77%) countries and the rest did not include THMs in the drinking water regulations (Fig. 1, Tables 1–4). The MCL of total THMs ranged from 25 µg/L in Denmark and the Netherlands to 1000 µg/L in Botswana. Other countries with low MCLs were Austria, Zambia, and Italy (30 µg/L), followed by Hungary, Luxembourg, and Germany (50 µg/L). By contrast, countries with high MCLs besides Botswana were Ecuador (500 µg/L), Australia (250 µg/L), Mexico (200 µg/L), and Colombia (200 µg/L). Reported MCL were between 50 and 150 µg/L in 48 countries, and among these, the MCL was 100 µg/L in 40 countries. In 15 countries total THMs MCL was set as 1 for the sum of the ratios of the

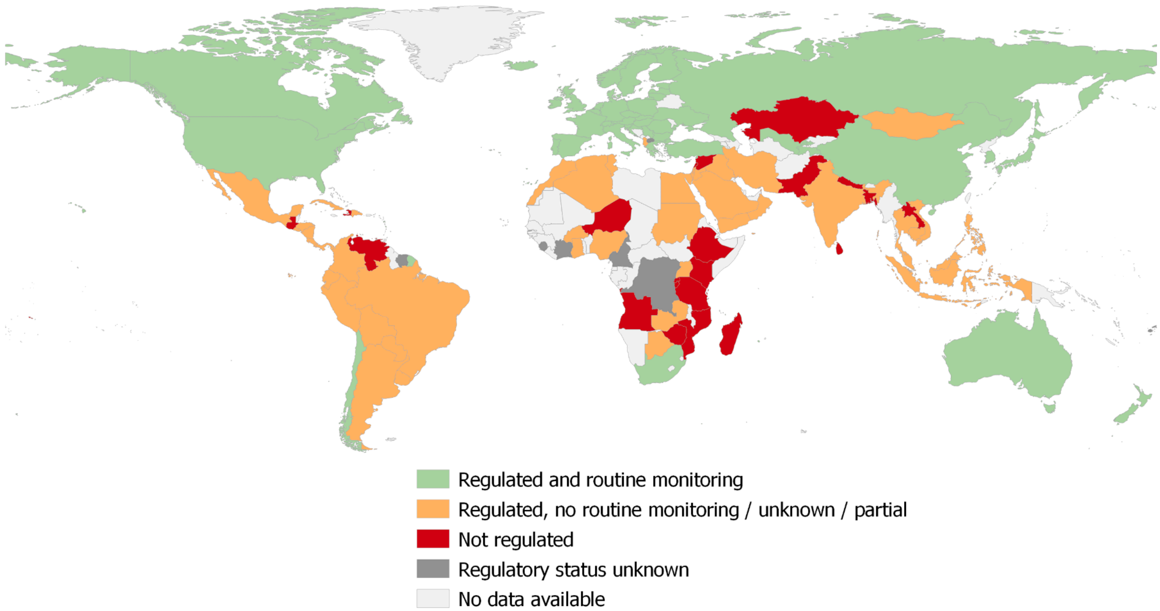


**Fig. 1.** Regulatory and routine monitoring status of trihalomethanes in the world in 2016.

concentration of each individual trihalomethane (chloroform, bromodichloromethane, dibromochloromethane, and bromoform) to its respective maximum prescribed quantity. Five of these countries used WHO standards for individual THMs. Finally, only individual THMs were regulated in 16 countries, of which 3 countries used WHO standards (Tables 1–4).

*Routine monitoring.* Of 89 countries with THM regulations, 47 (53%) conducted routine monitoring. In contrast, five countries (Albania, Nigeria, Uganda, Vietnam, and Zambia) did not routinely monitor THMs, while routine THM monitoring in Brazil, Colombia, Peru, and Thailand was not systematic. Finally, despite THM regulations, the routine monitoring practice was unknown in 33 countries (37%), Tables 1–4).

*Source of THM data.* Data were obtained exclusively through personal communications for 28 countries, which include North America (Canada, US), Chile and Peru from South America, Japan, Republic of Korea, New Zealand, all Northern European countries, 5 Southern European countries (Croatia, Malta, Portugal, Serbia, and Slovenia), 4 Western European countries (Belgium, Germany, the Netherlands, and Switzerland) and 4 Eastern European countries (Czech Republic, Hungary, Poland, and Slovakia). We used personal contacts complemented with literature review for Albania, Brazil, China, Colombia, Lebanon, Nigeria, Romania, Russian Federation, and Thailand. We used personal contacts and open data for Greece and Italy. For South Africa we used personal contacts, literature review, and public reports. To obtain data for Turkey, we used scientific literature and public reports. Data for Australia, Cambodia, France, Luxemburg, and Spain was obtained exclusively through public reports. Data for Singapore and Ireland was based entirely on open data publicly available. For the remaining countries, data on average THM levels was acquired exclusively from the scientific literature (Tables 1–4). The name of contacts providing Personal Communications are in Supplementary Table 2. Bibliographic references used when literature review, or open data was used are shown in the Supplementary Table 3.

*Population coverage of THM data.* Among 120 countries, THM data with a varying population coverage were obtained from 69 countries (58%) (Tables 1–4, Fig. 2), accounting for 5,643,439,493 inhabitants (75.6% of the world population in 2016) (IHME 2016). THM concentrations corresponded to water supplied to at least 90% of the country's population in 14 countries, including 12 European countries, Canada, and Japan. Data from 19 countries including the US, South Africa, Australia, Chile, Malaysia, Lebanon, Cyprus, and 12 European countries, corresponded to 50 to 89% of the population. THM data corresponded to 11–49% of country population among 21 countries, and ≤10% in 14 countries including India, China, Russian Federation, and Nigeria (which represents 40% of world's population), where data corresponded

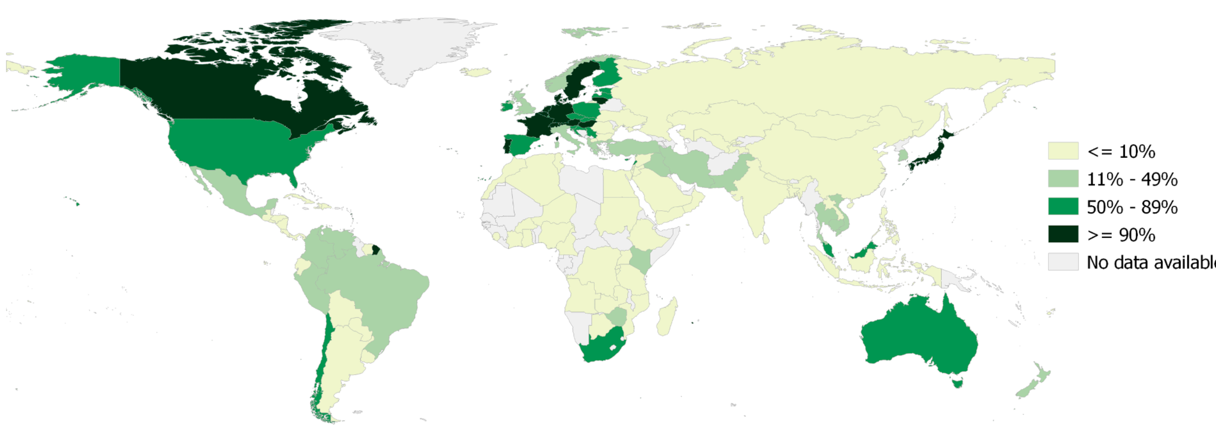


**Fig. 2.** Proportion of country population with trihalomethane data obtained in the present study, 1997–2016.

to specific regions/cities based on literature review or personal communications. Population coverage was undisclosed in Singapore.

*THM concentrations.* Among 33 countries with >50% coverage (963,433,844 inhabitants, 13% of world population in 2016), annual average THM concentrations were highest in Australia (72 μg/L), Cyprus (66 μg/L), South Africa (60 μg/L), Malta (49 μg/L), and Ireland (47 μg/L). Lowest levels were in Denmark, Netherlands, Germany, Lithuania, Switzerland, and Austria (≤1 μg/L). Annual THM average concentrations for countries with more than 10% coverage (55 countries) are shown in Fig. 3, corresponding to the reporting years indicated in Tables 1–4.

## 4. Discussion

Findings from this global assessment highlight the unbalanced regulatory status, routine monitoring practice, and data availability on THM occurrence among countries and regions. There is an enormous gap between high income countries (e.g., Europe, Australia, Canada, Japan, New Zealand, US) vs. low income countries (e.g., Sub-Saharan Africa, Southeast Asia) (UNCTAD, 2022). Regulation, routine monitoring, measurement data, and higher population coverage was concentrated in high income countries, where surveillance data were centralised in some. In contrast, most low-income countries lack any data or the population coverage was very limited, partly due to lack of regulation, routine monitoring, and reporting to a central database. Limited data coverage is remarkable for large countries such as China, which has a vast influence on environmental impacts at the planetary scale, where urgent action is needed to reduce pollution and related harm (Persson et al., 2022).

DBPs form complex mixtures (Richardson et al., 2007), which constitute a methodological research challenge (Villanueva et al., 2014). Since the first identification of chloroform in drinking water in the 1970′s (Bellar et al., 1974; Rook, 1974), total THMs have been typically used as a DBP surrogate, particularly when the disinfectant is chlorine. Other widespread by-products of chlorination are haloacetic acids, which are regulated in a few countries (Poleneni, 2020). We focused our assessment on total THMs, since they have shown consistent associations with human health effects (bladder cancer), and an exposure-response relationship exists (Costet et al., 2011a; Villanueva et al., 2004). However, the use of total THMs as a DBP surrogate has some limitations. Alternative disinfectants such as chloramines, chlorine dioxide, or ozone, are increasingly being used to lower THM formation. In turn, alternative disinfectants increase the formation of other DBPs (mostly unregulated), such as chlorite, chlorate, bromate, nitrosamines, organic nitrogenous DBPs, iodinated DBPs, and haloaldehydes, which can also be of health concern (Richardson et al., 2007). For example, ozone and/or chlorine dioxide are used instead of chlorine (or to a much greater extent) in many European countries to comply with THM regulations (Lenntech, 2022), and many drinking water treatment plants in the US have switched to using chloramination to lower regulated THMs and haloacetic acids (Bloodgood et al., 2022). DBP classes differ in physico-chemical characteristics and toxic properties, and THMs is the most characterised DBP class in terms of toxicity and human epidemiology (Richardson et al., 2007). THM species (chloroform, bromodichloromethane, dibromochloromethane, and bromoform) have different toxic properties, with brominated species more lipophilic and genotoxic (Richardson et al., 2007). As a consequence, the use of total THMs may hide disparities in composition and toxicity (Richardson et al., 2007). Finally, THMs may not necessarily be the drivers for the adverse health outcomes reported (Allen et al., 2022; Li and Mitch, 2018; Richardson and Plewa, 2020). In summary, although the use of total THMs has limitations as a DBP surrogate, given the complexity of DBPs, they constitute a valid DBP indicator for monitoring in case of chlorine-based disinfection, which is the most common worldwide.

The difficulties in THM data generation and sharing in low-income settings can be explained by multiple reasons including technical, financial, and human resources constraints. A substantial part of the population does not have access to piped water or other improved sources and chlorination frequently occurs -if any- at the end-user level, in which case the collection point for THM monitoring is not obvious or not easily accessible. Water sample collection, processing, and THM analysis is expensive and resource demanding. Sample collection has to follow a specific protocol, e.g. avoid bubble formation and air cavities in the vial to avoid head space, use of quenching agent, refrigeration until the analysis within a week, etc. Laboratory analysis requires appropriate sample preparation and the use of gas chromatography with electron capture or mass spectrometry detection run by trained personnel. Lack of laboratories, equipment, and human resources, and transport issues e.g. inaccessibility of roads to send the samples to the laboratory is common in many LMICs explain the difficulties to conduct routine THM monitoring. The reasons underlying the difficulties in reporting and data sharing are complex and multiple. The political dimension of water access (e.g. private vs. public), that can be understood as a common good or as merchandise can be present and generate tensions in the provision of safe water. At least part of the data are generated by private drinking water supply operators, where data access is not usually or easily made public. The lack of a centralised information system at the national level hampers the accessibility to data, since primary

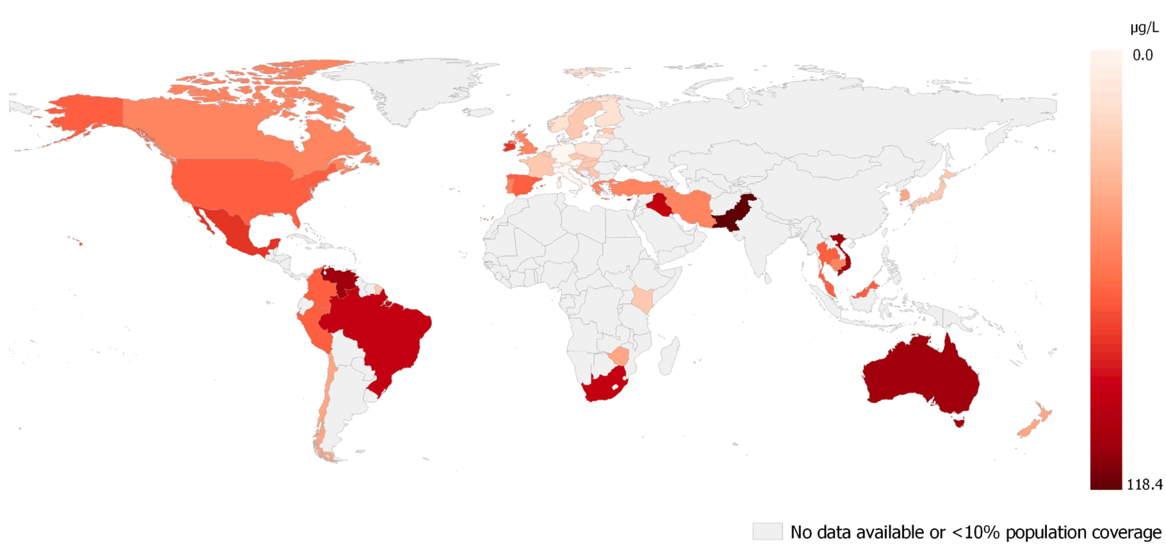


**Fig. 3.** Average trihalomethane levels in countries with >10% population coverage, 1997–2016.

information is scattered among numerous water utilities and agencies. Finally, the regulatory context can also influence routine monitoring practice and reporting, as non-binding guidelines are less likely to end up in routine monitoring and reporting compared to binding legislation.

Our study was subject to certain limitations. A main challenge has been the identification and compilation of data from multiple sources and languages. Reported data from most LMICs were from published research studies, while data from high-income countries were mostly from routine monitoring records. Centralised data was only available in a few countries. The personal communications that provided routine monitoring data was dependent on the extent of the network of relationships. Although the steering committee of the study included professionals from different countries with a long track record in DBP research and a worldwide network of international contacts, it is plausible to have missed key referents leading to underrepresentation of certain countries. The study period was extended back to the late 1990′s in order to incorporate data from literature review from low- and middle-income countries, but not only these (see Austria). Assuming that water sources and treatment practices have not likely experienced major changes which critically affect THM formation in these settings, we considered that reporting old data was more informative than omitting such data completely. Presented data is indicative, although not necessarily representive of current levels.

We combined measurements at the tap with measurements at the treatment plant and monitoring with research data, which constitutes a source of uncertainty. The use of country-average concentrations disregards disparities within country (e.g., among regions or cities within a country), thus leading to potentially biased country estimates (e.g., under- or overestimation). However, a global assessment requires the use of simple metrics such as the average, to easily allow comparison among a large number of countries. In this worldwide effort, inaccuracies in terms of regulatory status, routine monitoring, or specific THM figures (coverage, average, etc.) may have occurred. Information for some countries may have been available online but missed during the literature review due to the use of the specific keywords, search engines, and languages. In addition, we used the available THM data provided or identified in the literature or public reports, and we did not evaluate reliability or made any expert judgment concerning the reliability of measurements. Validation studies comparing existing data with ad-hoc measurements are warranted in future studies to assess the reliability of routine monitoring data or published data. The authors consider this as an initial effort open to corrections, improvements, updates, and to be expanded to other widespread chemical contaminants in drinking water, such as nitrate or arsenic, among others. In addition, lessons learned can be applied to emerging chemical contaminants of concern such as per- and polyfluoroalkyl substances (PFAS), which constitute persistent and mobile contaminants widespread in the water cycle, and which are objectives of new regulatory actions (EC, 2020; WHO, 2022b).

Among countries with more than 50% THM data coverage, we observed highest average levels in Australia, and lowest in Central and Northern Europe. The reasons for the low levels achieved in some countries include the use of mostly ground water sources (Austria, Germany), advanced treatment and distribution without the application of chlorine (The Netherlands, Switzerland) (Smeets et al., 2009; von Sonntag and von Gunten, 2012), or a combination of both (Denmark, Lithuania) (Hunkeler et al., 2012). Of note, the THM MCL in drinking water in Australia is 250 μg/L, which is one of the highest reported MCLs for total THMs. As another example of how regulatory standards modulate occurrence concentrations, average THMs were 34 μg/L in the US, with a SD of 33 μg/L. Thus, the average plus one SD was 67 μg/L. The regulatory limit is 80 μg/L, where it was expected that utilities would try to stay below 64 μg/L, which includes a 20% safety factor.

## 5. Conclusions

Chemical quality of drinking water is a growing global problem that needs to be addressed. The existence of national guidelines and country legislation can help ensure the safety of drinking water, particularly when binding legislation exists. The need for disinfection of drinking water to provide microbiologically safe water is unquestionable to prevent diarrhoeal diseases and death, but measures to minimize DBP formation exist. Wherever possible or applicable, individual countries where THM regulations do not exist need to create new binding regulations, set MCLs, and allocate budget. Capacity building may be necessary to ensure regular THM monitoring through specific training and equipment. Additionally, Public Health and Water agencies in countries with available monitoring data should coordinate to create a centralized database and make it publicly available to allow for their public or scientific use. Efforts comparable to the UNICEF/WHO Joint Monitoring Programme for Chemical Quality of Drinking Water (WHO/UNICEF, 2021), including widespread contaminants such as THMs, among others, are warranted and need to be further strengthened in order to provide open, harmonised, and centralised data to monitor chemical quality of drinking water accessible for all.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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## *Disclaimer*

The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2023.119568.

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