ENVIRONMENTAL RESEARCH
WATER

PURPOSE-LED PUBLISHING™

Part of the ENVIRONMENTAL RESEARCH SERIES

TOPICAL REVIEW • OPEN ACCESS

On the value of indicators for large-scale water quality assessments

To cite this article: Stijn H Peeters *et al* 2025 *Environ. Res.: Water* **1** 042002

View the article online for updates and enhancements.

You may also like

- A review and synthesis of post-wildfire shifts in hydrologic processes and streamflow generation mechanisms
Brian A Ebel, John C Hammond, Michelle A Walvoord et al.

- Post-wildfire water quality and aquatic ecosystem response in the U.S. Pacific Northwest: science and monitoring gaps
Sara Wall, Jana E Compton, Ashley A Coble et al.

- Beyond one-size-fits-all: a path toward region-specific flash drought monitoring and management
Gabriela Gesualdo and Antonia Hadjmichael

This content was downloaded from IP address 84.113.107.231 on 16/02/2026 at 08:17

ENVIRONMENTAL RESEARCH
WATER

Check for updates

TOPICAL REVIEW

On the value of indicators for large-scale water quality assessments

OPEN ACCESS

RECEIVED
1 July 2025

REVISED
17 November 2025

ACCEPTED FOR PUBLICATION
9 January 2026

PUBLISHED
2 February 2026

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Stijn H Peeters[1,*], **Floris S R Teuling**[1], **Rohini Kumar**[4], **Albert Nkwasa**[2,3], **Simon N Gosling**[5], **Keerthana Suresh**[2,6], **Ilaria Micella**[1] and **Nynke Hofstra**[1]

[1] Earth Systems and Global Change, Wageningen University and Research, Droevendaalsesteeg 3a, Wageningen, 6708 PB, The Netherlands
[2] Water Security Research Group, Biodiversity and Natural Resources Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria
[3] Department of Water and Climate, Vrije Universiteit Brussel (VUB), 1050 Brussel, Belgium
[4] Department Computational Hydrosystems, Helmholtz Centre for Environmental Research GmbH—UFZ, Leipzig 04318, Germany
[5] School of Geography, University of Nottingham, Nottingham, United Kingdom
[6] Department of Physical Geography, Utrecht University, 3584 CB Utrecht, The Netherlands
[*] Author to whom any correspondence should be addressed.

E-mail: stijn1.peeters@wur.nl and rohini.kumar@ufz.de

Keywords: indicator, water quality, roadmap, parameter, model

Abstract

Global efforts to improve water quality under UN SDG 6.3.2 are undermined by disparate national monitoring standards that prevent coherent assessment. Additionally, water quality modeling can help to provide spatially continuous monitoring data for a set of water quality constituents, but not for all relevant indicators. This inconsistency hinders accountability in supply chains, management of biogeochemical cycles, and mitigation of transboundary pollution. To address this inconsistency, we evaluate and propose a core set of water quality indicators. We compare this proposed set against the against water quality constituents currently included in major international monitoring frameworks (e.g. nutrients, heavy metals, and microbial contaminants) and modeling projects, which simulate outputs like nutrient concentrations and pollutant loads, to identify key areas where modeling efforts could focus. Finally, we propose a tiered roadmap designed to achieve implementation of these core metrics, focusing on harmonizing existing outputs, filling model gaps, and incorporating emerging indicators.

1. Introduction

Ensuring water quality is central to environmental health and human well-being. The United Nations' sustainable development goals (SDGs, United Nations 2015) provide an actionable framework for tracking progress, with indicator 6.3.2 specifically monitoring the proportion of water bodies with good ambient water quality as compared to national or subnational standards (UN Water 2021, UNESCO 2024). The UN tracks progress towards SDG 6.3.2 by having participating state actors and authorities report on several core water quality constituent groups i.e. oxygen, salinity, nitrogen, phosphorus and acidification, as well as a set of elective parameters that each participant can choose to include but is not obliged to provide (UN-Water SDG 6 Monitoring Guide).

While the core indicator set prima facie supports cross-country comparisons as they report on the same parameters, these parameters can be qualitatively different, as each participant potentially focuses its monitoring on different sets of water quality constituents and uses different thresholds to evaluate whether concentration levels meet its specific water quality objectives. See for example the World Health Organization (WHO) review on drinking water quality standards across the globe (WHO 2018c). This reflects a known challenge in global environmental monitoring, limiting direct comparability despite standardized indicators (Srebotnjak *et al* 2012). Consequently, when stakeholders from different regions discuss 'water quality', they may appear to be addressing a unified concept, while their understanding is

© 2026 The Author(s). Published by IOP Publishing Ltd

shaped by disparate, locally derived definitions and priorities (as also discussed specifically for the EU Water Framework Directive (WFD) by Hering *et al* 2010). The tension between local importance and global standards poses a barrier to universally applicable quantitative standards (thresholds).

The inconsistency can have serious consequences in areas of environmental, economic, and geopolitical concern, creating blind spots for accountability within global supply chains. While the grey water footprint concept exists to quantify pollution, the disparate national standards for water quality monitoring make its consistent and transparent calculation difficult, staging barriers to track and manage the grey water footprint of internationally traded goods (Aldaya *et al* 2012). The inconsistency also prevents us from fully understanding and managing disruptions to biogeochemical cycles, as that requires consistent data from all involved systems (Seitzinger *et al* 2005). As the cumulative impact from multiple nations cannot be assessed as a coherent whole, the absence of shared standards facilitates unchecked export of pollutants to oceans and international ocean basins.

A collaborative approach to overcome this challenge is to focus global consensus-building efforts on which parameters should be consistently monitored worldwide that provide a common descriptive language for water quality. Model-based simulations can complement *in situ* observations by providing a means to spatially continuous monitor progress toward SDG target 6.3 and to project future water quality outcomes through 2030 and beyond (Bouwman *et al* 2024). This is particularly valuable in regions with limited or no data (see for example Nkwasa *et al* (2024)).

Significant community efforts are already underway to harmonize models to improve intercomparability. A key example is the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; www.isimip.org/), a broad research framework that coordinates impact modeling groups across multiple sectors—such as water, agriculture, permafrost, fire, terrestrial biodiversity, lakes, and human health—to simulate climate change impacts under consistent scenarios. The water quality analysis in this paper is part of a specific workstream within this larger project, known as the ISIMIP—water quality sector, some analysis results of which are featured in this special issue.

A large set of models simulating the same water quality constituent enables the use of ensembles, providing more robust estimates of water quality (Van Vliet *et al* 2016). However, the constituents included in the ISIMIP WQ MIP (Strokal *et al* 2025) are sometimes covered by only a small number of models, reflecting the same challenge seen in the SDG monitoring. We therefore need to focus on a core set of water quality indicators that the ISIMIP WQ-MIP should endeavor to include.

To bridge the gap between monitoring needs and modeling capabilities, this paper proposes a pathway toward a harmonized core set of water quality indicators specifically for use in large-scale models like those in ISIMIP. The primary aims are therefore:

1. To review major pollutant categories and, for each, recommend the most suitable indicator(s) for large-scale modeling based on scientific validity and current modeling potential.
2. To benchmark current global water quality modeling capabilities (using the ISIMIP WQ MIP as a case study) against major international monitoring frameworks to identify critical gaps and opportunities.
3. To propose a concrete roadmap for the modeling community, outlining steps to harmonize existing outputs and incorporate new, essential indicators.

This proposed core set is intended to complement and provide detail for SDG indicator 6.3.2, moving beyond its broad parameter groups to indicators that are more mechanistically insightful and policy-relevant. While this paper focuses on selecting *parameters*, it does not propose universal *thresholds*, as these must remain tailored to specific water uses (Cash and Wright 2001)

2. Review of water quality indicators

To develop a comprehensive core set of indicators, we review four major categories of water quality constituents. These categories were chosen to encompass both traditional parameters included in frameworks like the UNEP SDGs as well as emerging threats that require urgent attention, such as pharmaceuticals and plastics. The outcome of this review has been summarized in table 1.

2.1. Biological (microbiological water quality)

The largest threat to global water quality in terms of micro-organisms is human and animal feaces (Prüss-Ustün *et al* 2019), and an indicator for fecal contamination is therefore often used. However, any singular indicator is a poor representative for all pathogens from a fecal source, as pathogens have different rates of persistence and survival (Savichtcheva and Okabe 2006, Holcomb and Stewart 2020). An ensemble of microbiological indicators should therefore be the aim.

While this review focuses on bacterial and viral indicators commonly used in large-scale assessments, other contaminants of concern exist. These include bacteriophages (often proposed as viral indicators), fungi, and the growing threat of antimicrobial resistance (AMR) genes and bacteria. While important, a full review is beyond the scope of this paper.

2.1.1. Bacterial indicators of fecal contamination

The most common modeled microbiological indicator is the presence or absence of fecal coliforms, which are used as a proxy for fecal contamination (Kroeze *et al* 2016). The premise of this indicator is that the organism in question has several qualities (facultatively anaerobic, rod-shaped, Gram-negative and non-sporulating), and that those qualities are enough to confidently state that the *fecal coliform* could only have come from an animal/human host, hence the name *fecal* coliform. However, several genera of bacteria can meet these demands, can grow in water, and are common contaminants of non-fecal sources, as reviewed by Doyle and Erickson (2006). It is likely for this reason that several meta-reviews on the link between gastrointestinal illness and microbial indicators of water quality found that the presence of fecal coliforms in surface water is a poor predictor for illness in those who are exposed to surface water (Wade *et al* 2006, Gruber *et al* 2014). As Fecal coliforms correlate poorly with disease and are often themselves contaminated with non-fecal sources, they are not well suited as an indicator for fecal contamination. *Enterococci* (Wade *et al* 2006) and *Escherichia coli* (Wade *et al* 2006, Gruber *et al* 2014) however, do adequately predict gastrointestinal illness.

2.1.2. Viral indicators of fecal contamination

There are two major types of viral indicators of fecal contamination: (1) bacteriophages capable of infecting enteric bacteria whose presence points to the presence of enteric bacteria (e.g. *E. coli*) and thus fecal contamination and (2) viral strains capable of infecting humans and/or animals, the presence of which points to fecal contamination.

Case 2 is in function similar to detecting the bacterial strains—detecting a pathogen directly and as proxy for fecal contamination—however fecal indicator bacteria are often inadequate in predicting the presence or health risks of human enteric viruses (Savichtcheva and Okabe 2006, Gerba *et al* 2018) due to for example differences in persistence in the environment (Dean and Mitchell 2022). The seasonality and zoonotic status are of major importance in selecting a viral indicator of fecal contamination: some viruses show strong seasonality, while others do not, and the ability of a virus to infect either human, animal or both means that the presence of a virus can indicate the presence of human feaces, animal feaces, or a combination of both (Sinclair *et al* 2012). Farkas *et al* (2020) review viral indicators for tracking domestic wastewater contamination, and suggest the use of enteric viral indicators (AdV, PyV, AiV) as they are human specific, easy to detect and show low seasonal variability.

2.1.3. Specific indicators of microbial water quality

Some pathogens like *Cryptosporidium*'s oocytes are highly resistant and can persist for months (Fayer 2004, King and Monis 2007) long after general fecal indicators have disappeared. This means that important, highly persistent pathogens may need to serve as separate indicators.

2.1.4. Recommendation for a core modeling set

While fecal coliforms have a modeling legacy, the evidence shows they are poor health risk indicators. To improve policy relevance, the core set should prioritize *E. coli* or *Enterococci*. For viral risk, a human-specific virus like AdV should be considered. Models like GloWPa show this is feasible for *Rotavirus* and *Cryptosporidium* (Vermeulen *et al* 2019), and thus persistent pathogens like *Cryptosporidium* should be retained where possible.

2.2. Indicators of bulk organic pollution

Assessing organic pollution requires more than quantifying the total organic material.

- Biochemical oxygen demand (BOD) quantifies the oxygen consumed by microorganisms metabolizing the *biodegradable* fraction of organics (APHA 2017). Its limitation is that it can underestimate the total organic load, especially in effluent with complex industrial chemicals (Monje-Ramirez *et al* 2004).
- Chemical oxygen demand (COD) and total organic carbon (TOC) (Geerdink *et al* 2017) use chemical oxidation or combustion to measure the *total* organic content, both biodegradable and non-biodegradable (APHA 2017). Their limitation is that they provide little information on the immediate impact on environmental oxygen levels.

Table 1. Recommended core modeling indicator based on the above review.

Water quality constituent	Water quality indicators	Recommended water quality modeling indicator	Rationale
Microbiological	Fecal coliforms, *E. coli, Enterococci*, human adenovirus (AdV), *Cryptosporidium*	• *E. coli* OR *Enterococci* • Human adenovirus (AdV) • *Cryptosporidium* // other persistent pathogens.	Fecal coliform is a poor health risk indicator. *E. coli* and *Enterococci* show a better correlation with gastrointestinal illness. Bacteria are poor proxies for viruses, so a specific viral indicator (like AdV) is needed for viral risk. Highly persistent pathogens like *Cryptosporidium* need to be included separately as they can outlast other indicators.
Bulk organic	Biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC)	• BOD and COD (or TOC) • BOD/COD ratio	Relying only on BOD is insufficient as it misses non-biodegradable industrial waste. Using both BOD and COD provides a complete picture of organic pollution. The BOD/COD ratio is a powerful diagnostic for assessing the biodegradability and nature of the pollution source.
Pharmaceuticals	Substance-by-substance indicators	One representative compound from each of the largest classes (e.g. an antibiotic, an NSAID, a hormone, etc)	The chemical diversity makes a single indicator for all pharmaceuticals impossible. The recommendation is a pragmatic, class-based approach: modeling one key substance from each major therapeutic group to serve as an indicator for that class of risk.
Persistent organic pollutants (POPs)	PCBs, dioxins, pesticides, flame retardants, PFAS	None	POPs are explicitly excluded from the core set. The rationale is that their complex chemical partitioning behavior and data requirements make them too difficult to implement in broad-scale models.
Inorganic	Acidity (pH), EC/TDS, nutrients (N, P), heavy metals, radionuclides	• pH & EC • Total nitrogen (TN) & total phosphorus (TP) • One or two priority heavy metals (e.g. lead, arsenic)	pH and EC represent essential 'master variables' that control fundamental water chemistry. TN and TP are the key indicators for nutrient pollution and eutrophication, a widespread global issue. Modeling all heavy metals is too complex for a core set, so a pragmatic approach is to model a few high-priority ones as representatives of toxic metal risk. Radionuclides are explicitly excluded as their risk is highly localized, not a 'common pressure' suitable for a global core set.
Plastic Pollution	Macroplastics (>5 mm), Microplastics (<5 mm), nanoplastics (<100 nm)	A suite of indicators, including: • Riverine macroplastic loads • Concentration of specific, high-risk microplastic polymers	Included as it is an important emerging pollutant. A single universal indicator is not feasible due to the multifaceted nature of plastic (different sizes, polymer types, impacts). The recommended path is to use a suite of indicators that address different size fractions and associated risks.

BOD and COD/TOC are complementary as the ratio of BOD/COD is a powerful measure of biodegradability. A low ratio indicates persistent industrial waste that may pose risks beyond oxygen depletion (Eckenfelder 2000), such as toxicity and bioaccumulation.

2.2.1. Recommendation for a core modeling set

Relying solely on BOD is insufficient. To capture both readily biodegradable and persistent organic pollution, a robust core set requires both BOD and COD (or TOC). The BOD/COD ratio represents a powerful diagnostic that models could provide to assess the nature and risk of organic pollution.

2.3. Indicators of specific organic pollution

Note that while BOD and COD are essential for assessing bulk organic pollution and oxygen depletion, neither captures the specific toxicological risks from organic micropollutants, which each require separate considerations.

2.4. Indicators of pharmaceuticals

Pharmaceuticals are contaminants of emerging concern defined by their intrinsic biological activity at low concentrations (Larsson 2014). Their widespread human and veterinary use, bioactivity as well as a persistent nature can create an environment of continuous low-level exposure, leading to risks like AMR (Pruden *et al* 2006) and thus serve as 'agents of subtle, insidious change' (Daughton *et al* 1999). The diverse nature of the compounds in question means we cannot have a simple indicator for pharmaceuticals but have to turn to indicators of each substance.

2.4.1. Recommendation for a core modeling set

Given the large number of pharmaceutical compounds, we will have to be pragmatic when it comes to a core set and add one of each of the largest classes pharmaceuticals: antimicrobials (antibiotics, antifungals), anti-inflammatory drugs (NSAIDs), analgesics, hormones, psychiatric medications (antidepressants, antiepileptics), beta-blockers, lipid-regulating agents, and cytostatica. Care must be taken to select representative compounds based not only on therapeutic class, but also on their environmental behavior (e.g. one highly soluble and mobile compound, one that strongly sorbs to sediment, and one that is highly persistent, etc), see for example a comparison of various methods/prioritization schemes by Roos *et al* (2012).

2.5. Persistent organic pollutants (POPs)

POPs are defined by their resistance to degradation, their capacity to bioaccumulate in food webs, and their potential for long-range environmental transport (Breivik *et al* 2004, Ashraf 2017). POPs include substances such as polychlorinated biphenyls (PCBs), dioxins, PFASs, and many organochlorine pesticides. Their danger is globally recognized through the Stockholm convention (UNEP 2009). The complex chemical properties governing their partitioning between water, sediment, and biota require highly specialized models that are difficult to implement at a global scale, especially since validation data is scarce.

2.5.1. Recommendation for a core modeling set

The complex chemical properties of POPs require specialized models such as multifate models (Wania and Mackay 1995, Klasmeier 2006, Falakdin *et al* 2022), due to various factors: (1) POPS are not just spread through water, but also by air (Scheringer 2009) or through biota (Armitage and Gobas 2007). (2) Estimates of emissions, degradation and physical-chemical properties can be subject to large uncertainty (Jones 2021), which has a knock-down effect when simulating loads, fate and concentrations (Meyer *et al* 2005). While this makes POPs impractical for inclusion in broad ensembles like ISIMIP currently, their environmental importance is undeniable. Therefore, we recommend that progress in this area should be pursued by specialized modeling groups, and a key focus for the broader community should be on improving global monitoring and emission inventories to support future modeling efforts.

2.6. Indicators of inorganic pollution

This category includes heavy metals, nutrients (N, P, S), acids, and salts. The inorganic constituents in surface water can originate from both natural (geogenic) and human (anthropogenic) sources. However, this distinction is often blurred, as the two are not independent and their influences frequently overlap (Hyslop and Trowsdale 2012). Human impacts can significantly alter local geochemical conditions, thereby mobilizing naturally occurring pollutants (as discussed for Arsenic by Smedley and Kinniburgh

(2002)). For example, increased organic matter from wastewater can change redox conditions, leading to the dissolution of minerals or the desorption of geogenic substances like arsenic from soil (Lawson *et al* 2013). This is further complicated by substances that have more than one origin, such as arsenic which is a natural component of bedrock but is also used as a pesticide (WHO 2018a), and while lithium is found naturally in minerals it is also used as a pharmaceutical (Bratt 2010) and can be released by mining/mineral processing (Kaunda 2020). The classification of a pollutant source as either 'geogenic' or 'anthropogenic' is therefore context dependent.

A few inorganics and indicators of dissolved inorganics include:

- Acidity (pH) is a master variable influencing the solubility, mobility, and toxicity of many other substances, such as heavy metals (Bourg and Loch 1995, Sintorini *et al* 2021).
- Electrical conductivity (EC), salinity, total suspended solids and total dissolved solids (TDSs) are related measures of the total amount of dissolved inorganic material. EC is the easiest to measure and is strongly correlated with the others (Hem 1985).
- Phosphorus (P), nitrogen (N), and sulfur (S) are key nutrients whose speciation determines their environmental role (Schlesinger 1997), with the first two being characterized in biogeochemical flow and currently exceeding planetary boundary limits (Rockström *et al* 2009). Indicators often include total forms (Total nitrogen—TN, total phosphorus—TP) and various dissolved and reactive species (Terrel 1989, Walsh and Milon 2016). N and P are the primary limiting nutrients in many aquatic ecosystems (Elser *et al* 2007), excess input of N and P from sources like agriculture and wastewater are the leading cause of eutrophication (Smith *et al* 1999), which in turn can lead to harmful algal blooms (Glibert *et al* 2001, Granéli *et al* 2008) and extended oxygen minimum zones (Rabalais *et al* 2014).
- Heavy metals (e.g. Pb, Hg, As) are elements that are never degraded. Their impact depends heavily on their chemical speciation, which is controlled by pH, redox state, and the presence of other chemicals (as reviewed by Tack *et al* 1995). This is a broad category, and some heavy metals, such as Uranium, are also radioactive and are discussed further below.
- Radionuclides are unstable atoms whose presence poses a risk even at low concentrations (ICRP 2007, WHO 2018b). Elements from the decays series of uranium (U) thorium (Th), radium (Ra) and radon (Rn) can dissolve from rocks and soils into groundwater, and subsequently into surface waters. This is the primary pathway for natural radionuclides to enter surface waters (Sohrabi 1998). Anthropogenic sources of radionuclides include the mining of natural occurring radioactive materials, (mismanaged) waste from the nuclear fuel cycle and nuclear weapons testing (Salvatores and Palmiotti 2011).

2.6.1. Recommendation for a core modeling set

For a core set, fundamental parameters like pH and EC are essential. For nutrients, models should center on TN (particulate AND dissolved) and TP for their importance as limiting nutrients, while also providing key species (like nitrate) where possible to improve diagnostic power. Given the complexity of heavy metals, a pragmatic approach would be to start by modeling one or two high-priority metals (e.g. lead, arsenic) as representatives of toxic metal risk. Significant radionuclide contamination is a highly regional and localized problem. It is primarily linked to specific geology or specific anthropogenic point sources. The purpose of the core set is to create a common language for common pressures on global water quality. Radionuclides, while posing a severe risk, do not fit this profile.

2.7. Indicators of plastic pollution

Plastics are classified by size: macroplastics (>5 mm), microplastics (<5 mm), and nanoplastics (<100 nm) (GESAMP 2015). Each class has unique sources, impacts, and monitoring challenges. Macroplastics can cause direct physical harm (van Bijsterveldt *et al* 2021), but they also act as a long-term source for smaller plastics and also degrade into smaller particles (Andrady 2011). Standardized indicators vary across these classes, from measuring riverine flux for macroplastics (van der Wal *et al* 2015) to using spectroscopy for identifying microplastic and nanoplastic polymer types (Huang *et al* 2022) although due to their extremely small size this remains challenging for nanoplastics (Gigault *et al* 2018).

2.7.1. Recommendation for a core modeling set

Due to the emerging nature of this pollutant, its inclusion in a core set of water quality indicators is important. However, the multifaceted nature of plastic pollution and the yet unclear impacts of different plastic types and sizes make defining a single, universal indicator difficult (Hartmann *et al* 2019). A path forward may require a suite of indicators that address the different size fractions, such as riverine macroplastic loads and the loads and concentrations of specific, high-risk microplastic polymers in water bodies.

3. Benchmarking current capabilities (where is the gap?)

As a first step, we compared the indicators in our review against those in major monitoring frameworks and the current ISIMIP WQ MIP (table 2). These include legally binding directives within the European Union, such as the WFD, and federal laws in the United States like the Safe Drinking Water Act (SDWA). National standards from China and Canada are also included, alongside the international guidelines for drinking-water quality from the WHO and UNEP's GEMS/Water data program (GEMStat).

The benchmarking exercise highlights several areas where there are large overlaps between monitoring frameworks and large-scale modeling. For example, nutrients such as TN and TP are not only core water quality constituents within the SDG monitoring framework but are also well-represented in the ISIMIP modeling ensemble (Strokal *et al* 2025). Similarly, salinity, another core SDG water quality constituent, is widely monitored and simulated by several large-scale models. These existing successes demonstrate that the potential for unification has already been realized and provide a foundation upon which we can build.

This analysis, however, also reveals a disconnect between other monitoring priorities and current large-scale modeling capabilities. Essential indicators like pH, COD, heavy metals, *E. coli*, and *Enterococci* are standard in most global monitoring frameworks but are absent or underrepresented in the current ISIMIP multi-model ensemble (table 2). This highlights an opportunity for the modeling community to increase its policy relevance by addressing these gaps.

4. A roadmap for a core set of modeled water quality indicators

Based on our review and gap analysis, we propose a tiered approach to developing a core set for the water quality modeling community.

Tier 1: harmonize existing outputs; the most immediate progress can be made by harmonizing outputs for water quality constituents already modeled. For example, models simulating fecal contamination (DynQual, WorldQual) should align their reporting by providing outputs for *E. coli* or *Enterococci,* which are more robust health indicators than fecal coliform. Models simulating nutrients (SWAT+, MARINA, etc.) should all endeavor to provide TN and TP to create consistent ensembles for assessing eutrophication risk.

Tier 2: fill critical gaps. The modeling community should prioritize adding capacity for key missing indicators identified in the gap analysis. Some examples of critical gaps that when filled would increase relevance for real-world water management are:

- pH: A fundamental master variable that controls most chemical processes.
- COD: To be provided alongside BOD, allowing for a comprehensive assessment of organic pollution.
- A pragmatically chosen heavy metal representative.

Tier 3: address emerging and complex indicators. For emerging threats like pharmaceuticals and microplastics, a single indicator is challenging. We propose starting with pragmatic solutions:

- For pharmaceuticals/toxic organics, models can use an integrated risk metric like msPAF (already modeled by WFLOW-DELWAQ (Deltares 2023, van Verseveld *et al* 2024) and select one or two high-priority, widely detected compounds (e.g. a common antibiotic or pesticide) with varied patterns of behavior as initial tracer indicators.
- For plastics, models should follow a dual-indicator approach as recommended above, focusing on macroplastic flux and microplastic concentration.

Table 2. Water quality indicator inclusion in the monitoring frameworks and the water quality parameters/indicators discussed in this paper. *Potential*: not core to the framework, but may be monitored under specific conditions. *Limited*: Monitoring does happen, but only for a subset (WHO GDWQ for example). *Guidance*: The organization sets guidelines and/or recommendations but does not operate monitoring networks or enforce binding standards. *Yes*: indicates routine or mandated monitoring for this specific parameter or closely related indicators. No: the parameter is generally not included. *No* (*some text*); indicates that while the constituent is not monitored, they are part of for example research or advocacy. *MS Specific*: monitoring and/or standards are determined at the member state level within the EU framework. *Related indicators*: used for fecal coliforms where the primary indicators monitored are *E. coli* and/or total coliforms/*Enterococci*. Abbreviations are explicated in table 3. All ISIMIP models as described in by Strokal *et al* (2025).

Parameter/indicator	EU	USA	China	Canada	WHO	UNEP	ISIMIP inclusion
Heavy metals	Yes (WFD PS, GWD, DWD)	Yes (SDWA, USGS NAWQA)	Yes (Drinking water std, surface water std)	Yes (ECCC FWQMS, CCME/HC guidelines)	Yes (GDWQ)	Potential (GEMStat)	No
Radionuclides	Yes (DWD)	Yes (SDWA)	Yes (Drinking water std)	Yes (HC drinking water guidelines)	Yes (GDWQ)	Potential (GEMStat)	No
Pharmaceuticals	Yes (WL, DWD WL, PS proposal)	Yes (USGS NAWQA, UCMR potential)	Yes (Priority control)	Yes (ECCC targeted, CMP)	Limited (GDWQ—specific chemicals)	Potential (GEMStat, WWQA)	Some (TCS,DCL -> MARINA)
Antibiotics	Yes (WL, PS proposal)	Yes (USGS NAWQA, UCMR potential)	Yes (Priority control))	Yes (ECCC targeted, CMP)	No	Potential (GEMStat, WWQA)	No
Sulfate (SO_4^{2-})	Potential/MS specific (GWD allows MS thresholds)	Yes (SDWA secondary std)	Yes (Drinking water standards)	Yes (ECCC FWQMS—major ions, HC guidelines)	No (No health guideline)	Potential (GEMStat)	No
Nitrogen (N) (Nitrate, nitrite, ammonia, total N)	Yes (WFD, GWD, UWWTD)	Yes (USGS NAWQA, CWA/NARS, SDWA)	Yes (Surface Water std, drinking water std)	Yes (ECCC FWQMS, HC guidelines)	Yes (Nitrate, nitrite—GDWQ)	Yes (Core SDG—nitrogen/nitrate)	Yes (TN -> IMAGE—GNM/SWAT+/GREEN)
Total dissolved nitrogen (TDN)	Potential/MS specific	Potential (USGS NAWQA)	Potential	Potential	No	Potential (GEMStat)	Yes (TDN -> MARINA/mQM)

(Continued.)

Table 2. (Continued.)

Phosphorus (P) (Total P, phosphates)	Yes (WFD, UWWTD)	Yes (USGS NAWQA, CWA/NARS)	Yes (Surface water std-TP)	Yes (ECCC FWQMS)	No	Yes (Core SDG—Phosphorus)	Yes (TP -> WorldQual/ WaterGAP3/ IMAGE—GNM/SWAT+/ GREEN)
Total dissolved phosphorus (TDP)	Potential/MS specific	Potential (USGS NAWQA)	Potential	Potential	No	Potential (GEMStat)	Yes (TDS ->MARINA)
Acidity (pH)	Yes (WFD Phys-chem)	Yes (USGS NAWQA, CWA/NARS, SDWA)	Yes (Surface water std, drinking water std)	Yes (ECCC FWQMS, HC guidelines)	No (No health guideline)	Yes (Core SDG)	No
Biochemical oxygen demand	Yes (UWWTD, WFD support)	Yes (NPDES)	Yes (Surface water std)	Potential	No	Potential (GEMStat)	Yes (Dynqual/ WorldQual/ WaterGAP3)
Chemical oxygen demand	Yes (UWWTD, WFD support)	Yes (NPDES)	Yes (Surface water std)	Potential	No	Potential (GEMStat)	No
Total organic carbon (TOC)	Potential (Research/advanced)	Yes (NPDES, SDWA potential)	Potential	Yes (ECCC FWQMS)	No	Potential (GEMStat)	No
Total dissolved solids (TDS)	Potential/MS specific	Yes (NPDES, SDWA Secondary std, USGS NAWQA)	Potential	Potential (via conductivity/ions)	Guidance (No health guideline)	Potential (via conductivity)	Yes (WorldQual/ WaterGAP3)
Cryptosporidium	Potential/risk-based (DWD)	Yes (SDWA)	No	Yes (HC drinking water guidelines)	Yes (Guidance—GDWQ)	Potential (GEMStat)	Yes (GloWPa)
E. coli	Yes (BWD, DWD)	Yes (SDWA—RTCR)	Yes (Drinking water std)	Yes (HC drinking water guidelines)	Yes (Guidance—GDWQ)	Potential (GEMStat)	No

(Continued.)

Table 2. (Continued.)

Parameter/indicator	EU	USA	China	Canada	WHO	UNEP	ISIMIP inclusion
Enterococci	Yes (BWD, DWD)	Yes (Recreational WQC, NARS)	No	Potential/guidance (Recreational waters)	Guidance (Recreational waters)	Potential (GEMStat)	No
Fecal Coliforms	Yes (Related indicators—BWD/DWD)	Yes (Related indicators—SDWA/RTCR)	Yes (Related indicators—drinking water std)	Yes (Related indicators—HC guidelines)	Yes (Guidance—GDWQ)	Potential (GEMStat)	Yes (Dynqual/ WorldQual/ WaterGAP3)
Microplastics	Yes (DWD methodology/WL potential)	No (Research)	Yes (EOC prioritization, standards planned)	No (Research)	Guidance (GDWG)	Advocacy (WWQA)	Yes (MARINA)
Macroplastics	No	No	No	No	No	No	Yes (MARINA)
msPAF (Multi-substance potentially affected fraction)	Yes (WFD key factor toxicity)	No	No	No	No	No	Yes (WFLOW-DELWAQ)

Table 3. Frameworks and directives used in our benchmark.

Region/organization	Abbreviation	Program	Reference
European Union (EU)	WFD	Water Framework Directive	EU Water Framework Directive 2000/60/EC
	GWD	Groundwater Directive	EU Groundwater Directive 2006/118/EC
	DWD	Drinking Water Directive	EU Drinking Water Directive (EU) 2020/2184
	WL	Watch List	Commission implementing decision (EU) 2025/439
United States (USA)	SDWA	Safe Drinking Water Act	EPA—Safe Drinking Water Act (SDWA, 40 CFR 141)
	USGS NAWQA	National Water-Quality Assessment	USGS National Water-Quality Assessment (NAWQA) Project
	UCMR	Unregulated Contaminant Monitoring Rule	EPA-Fifth Unregulated Contaminant Monitoring Rule (UCMR)
China		Surface Water Standard	GB 3838-2002
		Drinking Water Standard	GB 5749-2006
		Priority Control	2022-00530
Canada	ECCC FWQMS	Freshwater Quality Monitoring and Surveillance	Environment and Climate Change Canada (ECCC) monitors freshwater quality.
	CCME	Canadian Council of Ministers of the Environment	CCME—Canadian environmental quality guidelines water
	HC	Health Canada Guidelines	Health Canada—guidelines for Canadian drinking water quality
	CMP	Chemicals management plan	Chemicals management plan
World Health Organization	GDWQ	Guidelines for drinking-water quality	WHO—guidelines for drinking-water quality, 4th edition
United Nations Environmental Program	GEMStat	Global environment monitoring system for freshwater	UNEP—GEMS/water program

5. Conclusion

This paper summarizes the literature, existing policy documents, and available models and identifies a roadmap for the large-scale modeling community to provide a more consistent dataset of water quality that directly supports and enhances SDG indicator 6.3.2. Water quality model outputs have no role yet in monitoring SDG 6.3.2. However, there is potential to include model outputs in monitoring overviews, as they provide spatially continuous data in areas and constituents with sparse *in-situ* monitoring data available. To complement monitoring already done within standardized monitoring frameworks, the large-scale water quality community can focus on aligning existing outputs, for instance for microorganisms, TN and TP. Afterwards, critical gaps in missing indicators can be filled, for instance by focusing on pH, COD and heavy metals. Further into the future, emerging indicators can be incorporated. As soon as the first steps on the roadmap are taken, the model outputs provide a great additional source of information for the evaluation of progress towards SDG 6.3.2.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

SHP has been supported by UNEP/WWQA (Grant No. SSFA/2024/7523). AN was supported by the SOS-Water project (Grant Agreement No. 101059264), the EUROLakes project (Grant Agreement No. 101157482) and the ACT4CAP27 project (Grant Agreement No. 101134874), all funded by the European Union's Horizon Europe Research and Innovation Programme.

ORCID iDs

Stijn H Peeters 0000-0003-1354-8334
Floris S R Teuling 0000-0002-7436-3096
Rohini Kumar 0000-0002-4396-2037
Albert Nkwasa 0000-0002-8685-8854
Simon N Gosling 0000-0001-5973-6862
Keerthana Suresh 0000-0003-1930-9318
Ilaria Micella 0000-0003-0442-5121
Nynke Hofstra 0000-0002-0409-5145

References

Aldaya M M, Chapagain A K, Hoekstra A Y and Mekonnen M M 2012 *The Water Footprint Assessment Manual: Setting the Global Standard* (Routledge)

Andrady A L 2011 Microplastics in the marine environment *Mar. Pollut. Bull.* **62** 1596–605

APHA 2017 *Standard Methods for the Examination of Water and Wastewater* 23rd edn (American Public Health Association, American Water Works Association, Water Environment Federation)

Armitage J M and Gobas F A 2007 A terrestrial food-chain bioaccumulation model for POPs *Environ. Sci. Technol.* **41** 4019–25

Ashraf M A 2017 Persistent organic pollutants (POPs): a global issue, a global challenge *Environ. Sci. Pollut. Res.* **24** 4223–7

Bourg A C M and Loch J G 1995 Mobilization of heavy metals as affected by pH and redox conditions *Biogeodynamics of Pollutants in Soils and Sediments: Risk Assessment of Delayed and Non-linear Responses* (Springer Berlin Heidelberg) pp 87–102

Bouwman A F *et al* 2024 Multimodel and multiconstituent scenario construction for future water quality *Environ. Sci. Technol. Lett.* **11** 1272–80

Bratt J 2010 The use of lithium as a medication *The Neurobiology of the Mood Disorders* (Cambridge University Press) pp 589–93

Breivik K, Alcock R, Li Y-F, Bailey R E, Fiedler H and Pacyna J M 2004 Primary sources of selected POPs: regional and global scale emission inventories *Environ. Pollut.* **128** 3–16

Cash K and Wright R 2001 *Canadian Water Quality Guidelines for the Protection of Aquatic Life* (CCME)

Daughton C G and Ternes T A 1999 Pharmaceuticals and personal care products in the environment: agents of subtle, insidious change? *Environ. Health Perspect.* **107** 907–38

Dean K and Mitchell J 2022 Identifying water quality and environmental factors that influence indicator and pathogen decay in natural surface waters *Water Res.* **211** 118051

Deltares 2023 *D-Water Quality, User Manual* (Deltares)

Doyle M P and Erickson M C 2006 Closing the door on the fecal coliform assay *Micro Mag.* **1** 162–3 (available at: https://s3.us-west-002.backblazeb2.com/agp-video-web-app/media/meetings/calspan/rwqcb-laho/rwqcb-laho_20210513-20210513/rwqcb-laho_20210513/document/public/item-8---public-comment---kenneth-tate---closing-the-door-on-fecal-coliform-2006.pdf)

Eckenfelder W W Jr. 2000 *Industrial Water Pollution Control* 3rd edn (McGraw-Hill)

Elser J J, Bracken M E, Cleland E E, Gruner D S, Harpole W S, Hillebrand H and Smith J E 2007 Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems *Ecol. Lett.* **10** 1135–42

Falakdin P, Terzaghi E and Di Guardo A 2022 Spatially resolved environmental fate models: a review *Chemosphere* **290** 133394
Farkas K, Walker A, Adriaenssens E M, McDonald J E, Hillary L S, Malham S K and Jones D L 2020 Viral indicators for tracking domestic wastewater contamination in the aquatic environment *Water Res.* **181**
Fayer R 2004 Cryptosporidium: a water-borne zoonotic parasite *Vet. Parasitol.* **126** 37–56
Geerdink R B, van den Hurk R S and Epema O N 2017 Chemical oxygen demand: historical perspectives and future challenges *Anal. Chim. Acta* **961** 1–11
Gerba C P, Betancourt W Q and Kitajima M 2018 The challenges of monitoring for emerging viral pathogens in wastewater *Yale J. Biol. Med.* **91** 245–52
GESAMP 2015 *Sources, fate and effects of microplastics in the marine environment: a global assessment P J* Kershaw ed (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Rep. Stud. GESAMP No. 90 p 96
Gigault J, ter Halle A, Baudrimont M, Pascal P Y, Gauffre F, Phi T L and Grassl B 2018 Current opinion: what is a nanoplastic? *Environ. Pollut.* **235** 1030–4
Glibert P M, Magnien R, Lomas M W, Alexander J, Tan C, Haramoto E and Kana T M 2001 Harmful algal blooms in the Chesapeake and coastal bays of Maryland, USA: comparison of 1997, 1998, and 1999 events *Estuaries* **24** 875–83
Granéli E, Weberg M and Salomon P S 2008 Harmful algal blooms of allelopathic microalgal species: the role of eutrophication *Harmful Algae* **8** 94–102
Gruber J S, Ercumen A and Colford J M Jr 2014 Coliform bacteria as indicators of diarrheal disease in drinking water: a systematic review and meta-analysis *PLoS One* **9** e107429
Hartmann N B, Huffer T, Thompson R C, Hassellov M, Verschoor A, Daugaard A E and Wagner M 2019 Are we speaking the same language? Recommendations for a definition and categorization framework for plastic debris
Hem J D 1985 *Study and Interpretation of the Chemical Characteristics of Natural Water* vol 2254 (US Government Printing Office)
Hering D, Borja A, Carstensen J, Carvalho L, Elliott M, Feld C K and van de Bund W 2010 The European Water Framework Directive at the age of 10: a critical review of the achievements with recommendations for the future *Sci. Total Environ.* **408** 4007–19
Holcomb D A and Stewart J R 2020 Microbial indicators of fecal pollution: recent progress and challenges in assessing water quality *Curr. Environ. Health Rep.* **7** 311–24
Huang Z, Hu B and Wang S 2022 Analytical methods for microplastics in the environment: a review *Environ. Chem. Lett.* **21** 383–401
Hyslop E and Trowsdale S 2012 Differentiating between natural and anthropogenic sources of metals in the environment *Environmental Forensics* (Wiley) pp 95–122
ICRP 2007 The 2007 recommendations of the International Commission on Radiological Protection. ICRP Publication 103 *Ann. ICRP* **37(2-4)**
Jones K C 2021 Persistent organic pollutants (POPs) and related chemicals in the global environment: some personal reflections *Environ. Sci. Technol.* **55** 9400–12
Kaunda R B 2020 Potential environmental impacts of lithium mining *J. Energy Nat. Resour. Law* **38** 237–44
King B J and Monis P T 2007 Critical processes affecting Cryptosporidium oocyst survival in the environment *Parasitology* **134** 309–23
Klasmeier J *et al* 2006 Application of multimedia models for screening assessment of long-range transport potential and overall persistence *Environ. Sci. Technol.* **40** 53–60
Kroeze C *et al* 2016 Global modelling of surface water quality: a multi-pollutant approach *Curr. Opin. Environ. Sustain.* **23** 35–45
Larsson D G J 2014 Pollution from drug manufacturing: a neglected risk for public health and the environment *Rev. Environ. Contam. Toxicol.* **230** 1–22
Lawson M, Polya D A, Boyce A J, Bryant C, Mondal D, Shantz A and Ballentine C J 2013 Pond-derived organic carbon driving changes in arsenic hazard found in Asian groundwaters *Environ. Sci. Technol.* **47** 7085–94
Meyer T, Wania F and Breivik K 2005 Illustrating sensitivity and uncertainty in environmental fate models using partitioning maps *Environ. Sci. Technol.* **39** 3186–96
Monje-Ramirez I and De Velasquez M O 2004 Removal and transformation of recalcitrant organic matter from stabilized saline landfill leachates by coagulation–ozonation coupling processes *Water Res.* **38** 2359–67
Nkwasa A, Chawanda C J, Nakkazi M T, Tang T, Eisenreich S J, Warner S and Van Griensven A 2024 One third of African rivers fail to meet the' good ambient water quality'nutrient targets *Ecol. Indic.* **166** 112544
Pruden A, Pei R, Storteboom H and Carlson K H 2006 Antibiotic resistance genes as emerging contaminants: studies in northern Colorado *Environ. Sci. Technol.* **40** 7445–50
Prüss-Ustün A, Wolf J, Bartram J, Clasen T, Cumming O, Freeman M C, Gordon B, Hunter P R, Medlicott K and Johnston R 2019 Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low-and middle-income countries *Int. J. Hyg. Environ. Health* **222** 765–77
Rabalais N N, Cai W J, Carstensen J, Conley D J, Fry B, Hu X and Zhang J 2014 Eutrophication-driven deoxygenation in the coastal ocean *Oceanography* **27** 172–83
Rockström J, Steffen W, Noone K, Persson Å, Chapin F S III, Lambin E and Foley J 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** 32
Roos V, Gunnarsson L, Fick J, Larsson D G and Rudén C 2012 Prioritising pharmaceuticals for environmental risk assessment: towards adequate and feasible first-tier selection *Sci. Total Environ.* **421–422** 102–10
Salvatores M and Palmiotti G 2011 Radioactive waste partitioning and transmutation within advanced fuel cycles: achievements and challenges *Prog. Part. Nucl. Phys.* **66** 144–66
Savichtcheva O and Okabe S 2006 Alternative indicators of fecal contamination: relations with pathogens and conventional indicators, and an assessment of the correlation with human health risk *Water Res.* **40** 2463–76
Scheringer M 2009 Long-range transport of organic chemicals in the environment *Environ. Toxicol. Chem.* **28** 677–90
Schlesinger W H 1997 *Biogeochemistry: An Analysis of Global Change* (Academic Press)
Seitzinger S P, Harrison J A, Dumont E, Beusen A H W and Bouwman A F 2005 Sources and delivery of carbon, nitrogen, and phosphorus to the coastal zone: an overview of global NEWS, a new model *Glob. Biogeochem. Cycles* **19**
Sinclair R G, Rose J B, Hashsham S A, Gerba C P and Haas C N 2012 Criteria for selection of surrogates used to study the fate and control of pathogens in the environment *Appl. Environ. Microbiol.* **78** 1969–77
Sintorini M M, Widyatmoko H, Sinaga E and Aliyah N 2021 Effect of pH on metal mobility in the soil *IOP Conf. Ser.: Earth Environ. Sci.* **737** 012071
Smedley P L and Kinniburgh D G 2002 A review of the source, behaviour and distribution of arsenic in natural waters *Appl. Geochem.* **17** 517–68

Smith V H, Tilman G D and Nekola J C 1999 Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems *Environ. Pollut.* **100** 179–96
Sohrabi M 1998 The state-of-the-art on worldwide studies in some environments with elevated naturally occurring radioactive materials (NORM) *Appl. Radiat. Isot.* **49** 169–88
Srebotnjak T, Carr G, de Sherbinin A and Rickwood C 2012 A global water quality index and hot-deck imputation of missing data *Ecol. Indic.* **17** 108–19
Strokal M *et al* 2025 Advancing water quality model intercomparisons under global change: perspectives from the new ISIMIP water quality sector *Environ. Res. Water* **1** 035002
Tack F M G and Verloo M G 1995 Chemical speciation and fractionation in soil and sediment heavy metal analysis: a review *Int. J. Environ. Anal. Chem.* **59** 225–38
Terrell C R 1989 *Water Quality Indicators Guide: Surface Waters* vol 161 (US Department of Agriculture, Soil Conservation Service)
UN-Water 2021 *Annual report 2020* (United Nations) (available at: https://unsceb.org/sites/default/files/2021-08/Annual-Report-2020.pdf)
UNEP 2009 *Stockholm Convention on Persistent Organic Pollutants (Pops)* (United Nations Environment Programme)
United Nations 1945 *Charter of the United Nations*
United Nations 2015 *Transforming our world: the 2030 Agenda for Sustainable Development*
UNSECO 2024 The United Nations world water development report 2024: water for prosperity and peace (UNESCO) (available at: https://unesdoc.unesco.org/ark:/48223/pf0000388948)
van Bijsterveldt C E J, van der Ploeg M, van der Wal A, van der Schalie M and de Vries T A 2021 The effects of macroplastic on the salt marsh establishment on a tidal flat *Mar. Pollut. Bull.* **169** 112558
van der Wal A, van der Meulen M D, Tweehuijsen G, Peterlin M, Palatinus A, Kovač Viršek M and van der Graaf S 2015 Identification and assessment of riverine input of (marine) litter *Final Report for Project* DG-ENV-B1-2012-001
van Verseveld W J *et al* 2024 Wflow_sbm v0.7.3, a spatially distributed hydrological model: from global data to local applications *Geosci. Model Dev.* **17** 3199–234
Van Vliet M T H, Van Beek L P H, Eisner S, Flörke M, Wada Y and Bierkens M F P 2016 Multi-model assessment of global hydropower and cooling water discharge potential under climate change *Glob. Environ. Change* **40** 156–70
Vermeulen L C, Hofstra N and van der Hoek W 2019 Global-scale modeling of human and animal pathogens in surface water *Global Water Security* (American Geophysical Union (AGU)) pp 99–113
Wade T J, Calderon R L, Sams E, Beach M, Brenner K P, Williams A H and Dufour A P 2006 Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness *Environ. Health Perspect.* **114** 24–28
Walsh P J and Milon J W 2016 Nutrient standards, water quality indicators, and economic benefits from water quality regulations *Environ. Resour. Econ.* **64** 643–61
Wania F and Mackay D 1995 A global distribution model for persistent organic chemicals *Sci. Total Environ.* **160** 211–32
WHO 2018a *Arsenic* (World Health Organization)
WHO 2018b *Guidelines for Drinking-water Quality: Radiological Aspects* (World Health Organization)
World Health Organization 2018c A global overview of national regulations and standards for drinking- water quality

TABLE 3 REFERENCES IN ORDER OF APPEARANCE
Europe

Commission Implementing Decision 2025 (EU) 2025/439 establishing a watch list of substances for Union-wide monitoring in the field of water policy pursuant to Directive 2008/105/EC of the European Parliament and of the Council (notified under document C(2025) 1244)
Directive W F 2003 Common implementation strategy for the water framework directive (2000/60/EC) *Guidance document, 7*
Directive (EU) 2020/2184, on the quality of water intended for human consumption
EU 2006 EU Directive 2006/118/EC of the European Parliament and of the Council of the 12 December 2006 on the Protection of Groundwater against Pollution and Deterioration

US

Environmental Protection Agency 2025 *40 CFR Part 141: National Primary Drinking Water Regulations* (U.S. Government Publishing Office)
National Water-Quality Assessment (NAWQA) 2024 (USGS) (available at: https://www.usgs.gov/mission-areas/water-resources/science/national-water-quality-assessment-nawqa)
U.S. Environmental Protection Agency 2021 Revisions to the Unregulated Contaminant Monitoring Rule (UCMR 5) for public water systems and announcement of public meetings. *Federal Register* **86** 73126-73160. And specifically (is covered by NAWQA, see above):
U.S. Geological Survey Contaminants of Emerging Concern (CEC) (available at: https://www.usgs.gov/mission-areas/water-resources/science/emerging-contaminants)

China

GB 3838-2002 2002 *Environmental Quality Standards for Surface Water* (China Environment Publishing House)
GB 57460-2006 2006 *Standards for Drinking Water Quality* (China Environment Publishing House)
2022-00530 2022 *List of New Pollutants for Priority Control* (China Environment Publishing House)

Canada

Canada, E. a. C. C. 2017 Overview of freshwater quality monitoring and surveillance. Canada.ca (available at: https://www.canada.ca/en/environment-climate-change/services/freshwater-quality-monitoring/overview.html)

Canada, E. a. C. C. 2018 Water quality issues: subtances of emerging concern. Canada.ca (available at: https://www.canada.ca/en/environment-climate-change/services/freshwater-quality-monitoring/substances-emerging-concern.html)

Canadian Council of Ministers of the Environment | Le Conseil canadien des ministres de l'environment (available at: https://ccme.ca/en/current-activities/canadian-environmental-quality-guidelines)

Health Canada 2024 *Guidelines for Canadian Drinking Water Quality*

Health Canada 2022 Chemicals Management Plan. Canada.ca (available at: https://www.canada.ca/en/health-canada/services/chemical-substances/chemicals-management-plan.html) Also used (although it is covered by the above references):

WHO

World Health Organization 2022 *Guidelines for drinking-water quality: incorporating the first and second addenda* (World Health Organization)

UN

United Nations Environment Programme 2023 Quality Assurance for Freshwater Quality Monitoring - Technical Guidance Document (available at: https://wedocs.unep.org/20.500.11822/42666)