

Review

Drinking Water Standards and Their Implementation—A Critical Assessment

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Abstract: Diminishing clean water resources and their pollution (due to human activities and climatic change) are of great concern on a global basis. Under such conditions, the adequacy of drinking water (DW) standards and their meticulous implementation are issues of utmost importance in safeguarding human health. Unfortunately, the significant number of disease outbreaks (and of other suspected/potential health effects) related to DW, even in developed countries, attests to the fact that these issues require vigilance and continuous re-appraisal, particularly considering the assorted emerging contaminants and the ever-improving technological tools to cope with them. Therefore, the present comprehensive assessment addresses the main issues and concerns regarding DW standards and implementation thereof. Emphasis is placed on identifying the *inherent deficiencies* of standards (due to neglect of potential toxic contaminants and to debatable specifications/limit values) and regulations for their implementation and the monitoring of DW quality (due to weaknesses of available analytical/measurement techniques and inadequacies of tools and protocols). Rather serious deficiencies on these aspects are evident regarding the main categories of contaminants, i.e., synthetic chemicals and biological species. In regard to addressing these issues, progress made in recent years at the scientific/technical level and the main challenges are outlined toward the goal of an improvement in standards and their implementation.

Keywords: drinking water quality; contaminants; chemical; microbiological; radiological; standards; regulations; implementation; monitoring; analytical techniques



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1. Introduction

Drinking water (DW) contaminants are a major threat to public health. Therefore, the provision of safe DW has been one of humanity's most successful public health interventions, constituting a defining aspect of a developed country [1] as well as a major target in developing parts of the world. Progress in this direction has certainly been made in recent decades. In a survey carried out in 2006 [2], it was found that the proportion of the world population consuming DW from certified and controlled water sources was 87%, which was significantly greater than the corresponding proportion (77%) recorded in 1990.

To provide safe potable water for consumers, suppliers need to manage and control/monitor the produced DW quality using existing/appropriate tools and methods [2,3]. A decisive role in these activities is played by *standards and regulations*, which stipulate the acceptable limit values of various potential DW contaminants as well as the obligations and means regarding DW quality monitoring [2,3]. For the sake of clarity, it is noted that "*standard*" is a document, commonly approved through consensus by a recognized (standardization) body, providing guidelines or characteristics for products or related processes, with which compliance is not mandatory. "*Regulation*" is a document issued by governments/authorities that specifies product characteristics and related processes, including the applicable administrative provisions, with which compliance is mandatory [4]. Consequently, standards/standardization provide the basis for technical regulations. Well known in this respect are the World Health Organization (WHO) guidelines/standards for DW

quality [5], which are broadly accepted internationally and discussed herein. Additionally, in the context of this critical review, an assessment is made of the new European Union (EU) DW Directive (DWD) published in December 2020 [6] and of the Safe DW Act (SDWA) of the United States Environmental Protection Agency (USEPA) [7]. These documents are considered advanced and representative of conditions prevailing in technologically developed countries. It is noted that all acronyms are defined in Table A2.

The SDWA requires USEPA to determine the level of contaminants in DW at which no adverse health effects are likely to occur. These non-enforceable health goals, based on possible health risks from exposure over a lifetime, are called *maximum contaminant level goals* (MCLGs). The enforceable standard, in most cases, is known as a *maximum contaminant level* (MCL), i.e., the maximum permissible level of a contaminant in water, which is delivered to any user of a public water system (PWS). MCLs are set as close to the health goals as possible after considering costs, benefits, and the capability of PWS to detect and remove contaminants using suitable treatment technologies [7].

Despite significant progress made in the last decades, on standards/regulations as well as in contaminant detection techniques [8] and in developing water treatment technologies (e.g., [9–14]), the situation regarding DW-related problems is not satisfactory worldwide. According to the WHO, each year, 3.4 million people, mostly children, die from water-related diseases (WRD), whereas it is estimated that improving water quality can reduce the global disease burden by approximately 4% [15]. It is noted that WRD is commonly defined [16] as “any significant adverse effect on human health, such as death, disability, illness or disorders, caused directly or indirectly by the condition, or changes in the quantity or quality, of any waters”.

The occurrence of incidents related to DW quality, aside from their direct human health effects, tends to reduce public confidence in water supply systems [3], even in developed countries. The multitude of causes of such incidents is a matter of concern, requiring investigation. In studies about water governance in 13 Latin America and Caribbean (LAC) countries and 17 countries of the Organisation for Economic Co-operation and Development (OECD), there is evidence of governance failures that handicap water policy design and implementation measures [17]. Furthermore, the 24 waterborne disease outbreaks that have been recorded for the period 2000–2016 in developed countries, suggest that DW management needs particular attention to prevent disastrous consequent effects on human populations [18]. Interestingly, it is estimated that 65 million EU citizens (approx. 8% of EU population), are served by relatively small water suppliers, considered to implement inferior water quality control compared to that of large water suppliers, whereas two million are without water service [19].

The issues of DW quality standards and regulations have to be addressed also in the broader context of overall water management, which should take into account various impacting factors, including system/infrastructure conditions, contingency planning, status and improvements of analytical techniques, monitoring tools [17], water treatment technology, and (above all) the emergence of new or heretofore neglected potential contaminants. It should be noted here that this review will not assess quality standards used for monitoring the surface water resources, utilized for DW production. Such typical standards, expressed in the form of water quality indices (WQI)s, are used worldwide (e.g., [20]) and are based on the National Science Foundation WQI (index referred to as NSF-WQI [21]). This index is a single number comprised of weighted contributions from eight significant water quality parameters.

For all the above reasons, even in cases where an adequate regulatory framework exists, there is a need to frequently review and revise regulations to ensure that the required flexibility exists to adapt to newly perceived or even unforeseen challenges. In the USA, the 1996 SDWA amendments require USEPA to review and revise as appropriate National Primary DW Regulations (NPDWR) no less often than every six years [7,22]. The SDWA also requires that a contaminant must occur “or likely occurs” in DW to be regulated, presuming that the contaminant is either naturally occurring or could occur as a result

of natural, human-caused, or industrial pollution [23]. However, this approach does not necessarily include potential chemical or biological contaminants that could be *accidentally released* or *purposefully/maliciously* introduced into a water supply to harm consumers. For example, the contamination of groundwater, surface water and finally DW of the Veneto Region of Italy, with perfluoroalkylated substances (PFAS), detected in 2013, was attributed to a local chemical plant. This is a typical case of a complex threat that required, among other measures (legal work, enhanced scientific collaboration, installation of special filters etc.), the rapid establishment of standards for synthetic chemicals in DW for humans, which were quickly extended to cover water for livestock and irrigation [24].

This paper aims to provide a comprehensive assessment of DW quality standards/regulations and of their implementation, considering the aforementioned serious concerns, including the frequently occurring DW-related incidents, the emerging (and/or heretofore neglected) potentially toxic contaminants, and the pressure to recycle (often inadequately) treated effluents due to the diminishing clean water resources. Based on the overarching goal of human health protection, the inadequacies of standards and regulations and the implementation thereof are identified, and priorities are suggested to address them through research and development (R&D) and other relevant actions.

2. Contaminant Categories—Regulated Parameters

DW can contain physical, biological, and chemical constituents that should be monitored in order to evaluate potential risks to human health [10]. According to the WHO, the major aspects of DW quality are *chemical*, *microbiological*, and *radiological* and those affecting water acceptability in appearance, taste, and odor [5].

Chemicals comprise the largest group of regulated pollutants [5,6,22]. Approaches to the management of chemical hazards in DW vary between those where the source water is considered a significant contributor and those focusing on materials and chemicals used in the treatment and distribution of DW [5]. While there is limited knowledge on the toxicity profiles of many of these chemicals, large databases are available on the toxicity mechanisms for some of those substances [25]. Particularly important are contaminants from industrial and agricultural activities (Table 1), despite efforts and legislation to control them at their source, e.g., [26].

Table 1. Categorization of source/origin of chemical compounds contaminating DW [5].

Source of Chemical Constituents	Examples of Sources
Naturally occurring	Rocks, soils, and the effects of the geological setting and climate; eutrophic water bodies (also influenced by sewage inputs and agricultural runoff)
Industrial sources and human dwellings	Mining (extractive industries) and manufacturing and processing industries, sewage (including a number of contaminants of emerging concern), solid wastes, urban runoff, fuel leakages
Agricultural activities	Manures, fertilizers, intensive animal practices, and pesticides
Water treatment or materials in contact with DW	Coagulants, disinfection byproducts (DBPs), piping materials
Pesticides used in water for public health	Larvicides used in the control of insect vectors of disease

Microbiological contaminants in DW, unlike chemical substances, can cause rapid symptoms of infection and disease outbreaks [27]. Even at low concentrations, these microorganisms are worrisome, posing high risk of infection [28]. The practical approach, which is taken worldwide in setting DW system performance targets for microbiological hazards, is the identification of *reference organisms*. This practice is based on the assumption

that there is a quantifiable relationship between an indicator density and the potential health risks involved [27]. The aforementioned indicators are grouped in three major categories [29]:

1. **General (process) microbial indicators**, which characterize the efficacy of a process, e.g. *Pseudomonas aeruginosa*, *Giardia lamblia*, and *Cryptosporidium* [5,6,22].
2. **Fecal indicators**, evincing the presence of fecal contamination, only inferring that pathogens may be present, e.g., *Escherichia coli* (*E. coli*), *Enterococci* and *Clostridium perfringens* [5,6,22], Bacteriophages, and Coliforms [29].
3. **Index organisms and model organisms**, suggestive of pathogen presence and behavior, respectively, such as *Clostridium perfringens*, an index for enteric viruses.

Typically, different reference pathogens are identified to represent bacteria, viruses, protozoa and helminths [5], including at least one of each group [3]. These indicators are considered easier to measure than the full range of microorganisms that pose health risks [30]. The limit values of indicator pathogens set out by the EU and USEPA are presented in Parts A and C of Annex I and Part A.3 of Annex II of the DWD 2020/2184 [6], and in § 141.52 of NPDWR [22], respectively.

Radiological hazards (also called *radionuclides*) can be present in different amounts in DW with those of natural origin usually released from rocks and minerals [31]. Common natural radioelements are those from the uranium-238 chain, with the most relevant being uranium-238 (^{238}U), uranium-234 (^{234}U), radium-226 (^{226}Ra), and radon-222 (^{222}Rn). Many radionuclides tend to lodge for long periods of time in bone, and since bone marrow plays a critical role in immune system function, there are concerns that these substances could cause immune system damage [32].

3. Assessment of Standards and Regulated Parameters

3.1. Chemical Contaminants

3.1.1. Overview of Standards and Regulations

The EU DWD and the USEPA NPDWR (i.e. Part B and C, Annex I of DWD 2020/2184 [6] and §141.50–51, §141.53–54 of NPDWR [22], respectively) contain parametric limit values for several chemical substances, which follow, in general, the recommended values of Table A3.3, Annex 3 of the WHO guidelines [5]. It is noted that there are chemical substances included in DWD and NPDWR that have lower limit values than those suggested by the WHO; however, for quite a few chemical contaminants, listed in Table 2, the limit values set by the above standards are higher than those of the WHO.

In natural waters, the chemicals of the greatest health concern are usually excess *fluoride*, *nitrate/nitrite*, and *arsenic* [5]. Nitrate, one of the most common groundwater contaminants in rural areas, is primarily regulated in DW, since brief exposure to a level at or just above the standard of 10 mg/L nitrate-N is a potential health problem, mainly for infants [33]. In contrast to other water contaminants, contaminants such as arsenic or synthetic chemicals do not change water color, odor or taste; thus, exposed populations may continue to consume contaminated water (unsuspected, if there is no warning). Inorganic contaminants, such as *chromium*, and *perchlorate* (ClO_4^-), are significant DW quality issues in DW sources [34]; e.g., in USA river systems, the toxic form of hexavalent Cr(VI) has been detected in concentrations from <1 to 30 mg/L [35]. The third Unregulated Contaminant Monitoring Regulation (UCMR 3) of USEPA required (many, but not all) PWS to implement Cr(VI) monitoring, along with 28 chemicals and two viruses [36], with the specification for Cr(VI) to be controlled for one year. *Perchlorate* is another example of a detected, hazardous substance that remains unregulated by USEPA [37,38]. The following section deals with groups of emerging contaminants, widely studied in the literature due to their identified presence in water (raw and/or treated), that are partially regulated or not regulated at all.

Table 2. Comparison of parametric limit values for some DW chemical contaminants as set by the EU, USEPA, and WHO [5,6,22]. The standard values of the listed contaminants (set either by USEPA’s NPDWR, the EU DWD, or both) are *higher* than those of WHO guidelines.

Chemical	WHO Guideline Value, mg/L	EU DWD Limit Value, mg/L	USEPA NPDWR MCL, mg/L
Barium	1.3	-	2
Cadmium	0.003	0.005	0.005
Carbofuran	0.007	-	0.040
Carbon tetrachloride	0.004	-	0.005
Chlordane	0.0002	-	0.002
Chlorite	0.7	0.25	1
Chromium (total) *	0.05	0.05	0.1
2,4-Dichloro- phenoxy-acetic acid (2,4-D)	0.03	-	0.07
Endrin	0.0006	-	0.002
Ethylbenzene	0.3	-	0.7
Fluoride	1.5	1.5	4
Lead	0.01	0.005	0.015
Methoxychlor	0.02	-	0.04
Selenium	0.04	0.02	0.05
Simazine	0.002	-	0.004
Styrene	0.02	-	0.1
Vinyl chloride	0.0003	0.0005	0.002
Xylenes	0.5	-	10

* Trivalent and hexavalent chromium.

3.1.2. Contaminants of Emerging Concern (CEC)

In most cases, the source of DW is surface water around the cities or upstream of agricultural watershed [39]. The contaminants of emerging concern (CECs), i.e., “any synthetic or naturally occurring chemical or any microorganism that is not commonly monitored in the environment but has the potential to enter the environment and cause known or suspected adverse ecological and/or human health effects” [40], have gained special attention in the last decade. Significant categories of CECs are those of endocrine-disrupting compounds (EDCs), pharmaceuticals (PhACs)/personal care products (PPCPs), industrial and commercial compounds (ICCs), and current-use pesticides (CUPs) [41].

CECs have been detected in surface waters (i.e., rivers, streams, and lakes) as well as in groundwater and DW [42,43]. The recent study of Tröger, Ren, Yin et al. (2021) addressed the issue of CECs behavior in full-scale DW treatment plants via target and suspect screening in order to investigate the relationship between treatment efficiency of target substances and the presence of unknown CECs in water [44]. The results of this significant survey reported that 58 out of the 177 target compounds were detected in at least one DW sample, compared with 115 in the raw water.

In order to identify potential health risks and prioritize chemicals for abatement or monitoring, toxicological risk assessment of CEC in DW (or DW-sources) is required [45]. In such assessments, concentrations of chemicals in DW/sources are compared to one of the following guidelines/targets [45]:

- Statutory DW guideline values;
- Provisional guideline values based on recent toxicity data in absence of DW guidelines;
- Generic DW target values in absence of toxicity data.

CECs are generally put on “priority pollutant” lists since they are substances for which there is new evidence of harmfulness but no definitive conclusions about their detrimental effect on human health. These lists form the basis for research and for review of DW

standards [46]. The priority pollutant list of USEPA is the *Contaminant Candidate List (CCL)* with contaminants that are currently not subject to any proposed or promulgated NPDWR but are known or anticipated to be present in PWS. The Final CCL 4 was announced in November 2016 and included 97 chemicals or chemical groups (i.e., commercial chemicals, pesticides, and pharmaceuticals) and 12 microbial contaminants (i.e., waterborne pathogens) [46,47]. However, *currently, only a few EDCs and PPCPs, are listed in the USEPA's DW CCL 4*. Although CECs are a recognized potential risk in direct potable reuse (DPR) projects, with reported effects on human health (e.g., damage to the nervous system, liver, kidney, and possible cancer risks) [35], most of them have no regulatory limits in DW. Some states in the USA, such as California, have started to fill this gap with regulations that specifically address CECs [48].

EU has developed the “List of priority substances in the field of water policy” (latest update in November 2014) [49], which contains 45 substances, or groups thereof, with some of them (i.e., polyaromatic hydrocarbons (PAHs), perfluorooctane sulfonic acid (PFOS), and heptachlor) included in the latest DWD of 2020 with parametric limit values [6]. Human and veterinary medicinal products are not yet defined as priority substances in the EU region [50], although proposals for Environmental Quality Standards (EQS) are drafted at EU and at national levels for some compounds. The mandatory environmental risk assessment and other pieces of EU legislation relevant to the degradation of pharmaceuticals seem inadequate to ensure the complete elimination of their risk to the environment [51] and, evidently, to water and DW [52].

3.1.3. Per- and Poly-fluoroalkyl Substances (PFAS)

Per- and poly-fluoroalkyl substances (PFAS) are a group of man-made chemicals found in a variety of products including firefighting foams, household products, food packaging, and stain and water repellants [53]. PFAS are sometimes referred to as “forever chemicals”, because they are not readily degraded in the environment and can lead to long-term contamination of soil and water supplies [54], resulting in significant presence in DW [55]. They are included in the European DWD (Part B.3 of Annex III of DWD 2020/2184 [6]) as a regulated parameter, with the limit value of 0.5 µg/L *for the totality of PFAS* and 0.1 µg/L for a subset of PFAS, while the corresponding recommended (not legally binding) value by the Swedish Food Agency is 0.09 µg/L for the sum of eleven PFAS in DW [56]. Targeting such chemical subgroups is advantageous because the toxicological endpoints are often assumed to be similar, which allows for extrapolation from well-studied chemicals to those less studied. However, assessing only small subgroups systematically ignores the majority of PFAS and underestimates the overall risk, particularly when many of the chemicals are unknown [54].

Despite the fact that PFAS may contaminate systems that serve approximately 19 million people living in the USA [57], there are no federal enforceable standards. USEPA has established a health advisory level of 70 parts per trillion (ppt) for the sum of perfluorooctanoic acid (PFOA) and PFOS, the two most widely studied PFAS [58]. However, there are some states (e.g., New Hampshire, Michigan, and New Jersey) that have decided to set a lower advisory level, while others have implemented enforceable MCLs for specific PFAS [53]. For instance, the New Hampshire limit value is 12 ppt for PFOA and 15 ppt for PFOS [57].

Researchers of the Environmental Working Group (EWG) [59] suggest the health-based standards of 1 ppt *for the sum of PFAS in DW* and 1 ppt of the total concentration for the sum of all PFAS in groundwater and cleanup of contaminated sites. The EWG proposal raises some serious questions on the provided safety level by the EU DWD, as even the lowest limit of 0.1 µg/L (100,000 ppt) is far above the EWG recommended values. Meanwhile, the coalition of trade associations of the USA comment that PFAS are a diverse family of chemical materials used across a wide cross-section of industries, propounding that the approach of establishing standards should consider regulations based on the characteristics of individual chemicals and not as a single class [60]. However, a class-based

approach is considered feasible and could facilitate more frequent testing, thus improving compliance and detection of emerging risks [54].

3.1.4. Disinfection Byproducts (DBP)

Chemical disinfection, a typical process in DW treatment for the deactivation of pathogens, using agents such as chlorine, ozone, chloramine, and chlorine dioxide, can form hazardous disinfection byproducts (DBPs) [61]. Trihalomethanes (THMs), haloacetic acids, and haloacetaldehydes (HALs) are principal DBP classes typically varying from several to a few hundreds of milligrams per liter in treated water [62].

Anthropogenic contaminants, originally present in raw water [62] and natural organic matter (NOM) consisting of terrestrial and microbially derived material, are the main precursors of DBPs that have been linked to an observed risk of bladder cancer [61,63], early-term miscarriage, and birth defects [64]. Due to advances in analytical chemistry, more than 600 DBPs have been identified, although less than 20 are currently regulated worldwide. In particular, together with bromate, total THM concentrations and HAAs are the DBPs regulated in the EU, with a maximum contaminant level of 100 µg/L and 60 µg/L, respectively [6]. Similarly, the MCLGs set by USEPA for DBPs include the nine substances presented in § 141.53 of NPDWR [22].

Considering that disinfection is commonly the last process in a water treatment plant, once formed, DBPs can be readily delivered to consumers [64]. Ding et al. [62] have reviewed the unintended effects of DW treatment reagents and treatment/piping materials on the DBP formation, including alternative DBP precursors, the transformation of DBPs into more toxic species, and the catalytic processes responsible for DBP generation. Moreover, as recently reported, many unregulated DBPs are apparently more toxic than those currently regulated. Despite the fact that the WHO, USEPA, and EU (along with several other countries) have set limit values for a small number of DBPs in DW, there is significant discussion as to whether the right DBPs are currently controlled. For instance, DBPs considered as carcinogenic in animals do not cause the same type of cancer in humans, and the increased wastewater impacts on fresh-water sources could result in new DBPs not previously envisaged [37].

Other relevant issues are reviewed by Diana et al. [61] who pointed out potential difficulties in the identification of DBPs in water, such as unsuitable quenching agents in the sampling and analytical procedure, along with poor characterization of non-halogenated compounds in comparison to the halogenated DBPs. Nevertheless, new approaches for determining toxicity drivers [65] allow for the determination of important groups of such substances in DW through the identification of forcing agents of DBP-induced toxicity.

3.2. Microbiological Contaminants

3.2.1. Indicator Microorganisms

The regulations of USEPA and EU have selectively included some pathogen indicators that represent the three groups of microbial indicators outlined in Section 2 [29]. The monitored indicators have been used in water quality management and health risk assessments because they are much easier and less costly to detect and quantify than the individual pathogenic microorganisms [30]. Nevertheless, for more than 100 years, there has been debate among microbiologists and public health practitioners concerning the adequacy of DW monitoring that is commonly practiced, which involves indicators as opposed to individual/specific pathogens [8,66]. For instance, the concentration of fecal bacteria in water (e.g. *E. coli*) can provide an indicative level of enteric viruses when the contamination originates from human sources [30] but may not be representative if the pollution is of animal origin [67].

Enteric viruses

The consumption of contaminated water is associated with disease outbreaks, mostly caused by enteric viruses and protozoan parasites [68]. Enteric viruses affect the digestive system and present a serious health risk if ingested [69]. The vast majority of studies

on the presence and fate of viruses in municipal wastewater have focused on enteric viruses [16,70], including a large number of available methods for detecting those species in complex environmental matrices [71].

Adenoviruses (AdVs), a sub-group of enteric viruses, have been detected in various water environments worldwide, including DW [72], and have been suggested as possible indicators for viral pathogens [68]. Human AdVs features have led to their inclusion in USEPA's CCL, while the EU DWD disregards them, suggesting the detection of somatic coliphages as a viral indicator and making a general statement for the addition of enteric pathogens in the regulated parameters [6]. Somatic coliphages, viruses that use bacteria as hosts for replication, are considered useful models or surrogates to assess the behavior of enteric viruses in water and their sensitivity to treatment and disinfection processes [5]. Somatic coliphages also exhibit the advantage of being detectable by simple, inexpensive and rapid techniques [30]. However, factors such as water temperature or the fluctuation of microorganism concentration in surface water might affect the correlation among microbial parameters [73]. The specific association between somatic coliphages and human enteric viruses is therefore a matter of discussion either due to difficulties in differentiating between human and animal fecal contamination [30] or because of reported environmental conditions that present variable effects on adenovirus stability [72]. The recent study of Truchado et al. [74] regarding the monitoring of human enteric viruses and coliphages in two water reuse systems proved that the absence of coliphages does not mean a negative sample for norovirus, a human enteric virus.

Pseudomonas

Pseudomonas aeruginosa is no longer a parameter to be monitored in DW, according to the latest DWD of the EU [6]. USEPA includes *Pseudomonas* in the pathogenic bacteria potentially present in untreated wastewater, with no limit value for PWS [75]. *Pseudomonas* are a large group of free-living bacteria that are frequently found in home and medical settings and can even grow in distilled water, as clearly shown in the study by Mena and Gerba [76]. Contamination of tap water has been associated with outbreaks of *Pseudomonas* that can cause eye, ear, and skin infections in healthy individuals and even bacteremia in immunocompromised patients [75,76]. *P. aeruginosa* has been detected in samples with free residual chlorine concentrations between 0.2 and 2.0 mg/L [77], confirming this species' resistance to conventional water treatment processes [78].

Cryptosporidium and Giardia lamblia

Cryptosporidium parvum (Crypto) and *Giardia lamblia* (Giardia) are parasites broadly associated with water [79] but absent from the European DW quality criteria. The MCLG set by USEPA for each pathogen is at zero, along with the requirement for filtered systems to remove 99% of *Cryptosporidium* and/or 99.9% of *Giardia* [22]. During the period of 1954–2016, *Giardia* was responsible for ~40% of all documented water-related outbreaks of protozoan parasites [80]. Both parasites can be transferred through water in environments where there are poor sanitation systems, a lack of hygiene, an inadequate water management system, and wastewater reuse practices [81]. Major waterborne cryptosporidiosis and giardiasis outbreaks have been associated with observed suboptimal water treatment [18,82]. DW sources in rural areas have also been reported to be contaminated with these parasites, which is a matter of serious concern at present [83].

Despite the fact that *Cryptosporidium parvum* oocysts are more resistant than *Giardia lamblia* cysts to removal and inactivation by conventional water treatment [82], both pathogens have been detected in treated water samples [28] and eventually in DW [18,80,81]. Nakada et al. [80] remark that bacteria could be suitable surrogates to predict the occurrence of *Giardia* cysts in raw water but may not be appropriate to predict the disinfection of *Giardia* cysts, as they found no correlation between indicator bacteria and *Giardia* cysts in treated water. *E. coli* and coliforms are rapidly inactivated by disinfection processes, whereas more resistant pathogens, such as *Giardia* cysts, *Cryptosporidium* oocysts, and human enteric viruses, are almost unaffected for several hours, constituting a major public health risk if the integrity of the distribution system (DS) is breached [19,84].

Legionella

Although the leading cause of reported waterborne disease outbreaks in the USA has been confirmed to be Legionnaires' disease, a pneumonia caused by the *Legionella* bacterium [85], there is no limit value for *Legionella*'s presence in USA's DW regulations. USEPA suggests that if *Giardia lamblia* and viruses are removed/inactivated, then DW is likely to be free of *Legionella* [22]. In 1989, EPA enacted the Surface Water Treatment Rule (SWTR), which requires PWS using a surface water supply, or a groundwater supply under the direct influence of surface water, to filter and disinfect the water (the latter intended to control microbial contamination, including *Legionella*). Nevertheless, *Legionella* species have been detected in disinfected DW distribution systems [86]. Lu et al. [87] examined large volume (90 L) ultrafiltration concentrates from six sites within a DS in Georgia, USA, and frequently (57%) detected *Legionella* spp. Despite the absence of US federal regulations that could broadly control the presence of *Legionella* in water systems, there are local and state regulations carry this out [85].

Regarding the EU region, although *Legionella* is responsible for the highest health burden of all waterborne pathogens (according to WHO), there is no obligation for Member States to monitor its presence in private and public premises unless the risk assessment indicates so [6].

Emerging infectious diseases

At present, neither the SDWA nor the EU DWD include indicators for all pathogens in DW quality parameters, raising serious questions about consumers' safety. Moreover, apart from the well-known diseases, the WHO has defined emerging infectious diseases as those that "have appeared in the population for the first time, or that may have existed previously but there is rapidly increasing incidence or geographic range" [88,89], adding further concern regarding the transmission of new microbiological hazards via water. The Centers for Disease Control and Prevention (CDC), an agency of USA Public Health Service, responsible for disease prevention and health promotion, define emerging infectious diseases as follows [90]:

- New infections resulting from changes in, or evolution of, existing organisms.
- Known infections spreading to new geographic areas or populations.
- Previously unrecognized infections appearing in areas undergoing ecologic transformation.
- Old infections re-emerging as a result of antibiotic resistance in known agents or breakdowns in public health measures.

The current pandemic of COVID-19, caused by the coronavirus SARS-CoV-2, is a typical example of an emerging infectious disease. Coronaviruses are enveloped single-stranded RNA viruses with crown-like spikes on their surfaces that can remain infectious for days in sewage and for long periods in DW, rendering contaminated water a potential vehicle for human exposure if aerosols are generated [88,91]. Enveloped viruses (EBOV, SARS-CoV, influenza A, etc.) are wrapped in bilipid membranes and demonstrate various environmental behaviors, persistence, and fates [92]. Most DW treatment plants, including those used to produce DW from wastewater, were designed using microbial risk assessments and process performance data with non-enveloped enteric viruses [92]. Methods to concentrate and recover non-enveloped enteric viruses from wastewater and other environmental matrices may not be suitable for enveloped viruses [73]. Despite the health impacts caused by outbreaks of these viruses, the investigation of their presence in DW is not mandatory in many countries, including the USA and the EU region. This is partly due to lack of consensus regarding the following issues [93]:

- Which viruses could be used as biological markers;
- Which volume or amount of sample is ideal for virus detection;
- Which method is best for concentrating viruses from different matrices;
- When the use of genome detection or infectivity properties is more appropriate.

Regarding the persistence of SARS-CoV-2 in DW, WHO maintains that there is no evidence of their presence in surface or groundwater sources or of the possibility of virus transmission through DW [94]. However, the fact that SARS-CoV can replicate in the

enteric tract makes it a possible enteric pathogen causing concern regarding its potential environmental transmission [95]. The recent review of Langone et al. [96] about the presence and impacts of SARS-CoV-2 in water systems highlights the issues of efficient water management and surveillance through the monitoring of sewer systems, while water itself may represent a potential means of transmission.

3.2.2. Antibiotic-Resistant Bacteria and Antibiotic-Resistance Genes (ARG)

Antibiotic-resistant bacteria and antibiotic-resistance genes (ARGs) released into the environment are another emerging issue in the field of water safety [97]. The antibiotics consumed by humans and animals end up in sewage and eventually in urban waste water treatment plants (WWTPs) [98], which are among the main sources of ARBs and ARGs [97]. Naturally occurring substances in water can also promote the spread of ARGs, such as microcystins (MCs), which are produced and stored in living and healthy cells of *Microcystis*, a cyclic peptide toxin [99]. The recent EU DWD includes provisions for microcystin levels with the limit value of 1.0 µg/L, but only in the case of potential blooms in source water [6].

ARBs and ARGs reduce the therapeutic potential against human and animal pathogens [98], leading to approximately 33,000 deaths per year [100]. The burden of infections with ARBs on the European population is comparable to that of influenza, tuberculosis, and HIV/AIDS combined [100]. It is estimated that by 2050, antibiotic resistance (AR) will account for 10 million deaths and a financial burden of approximately USD 100 trillion [101]; however, ARGs have not been included in the testing indicators of DW quality [99].

There is evidence that the *conventional DW treatment processes cannot remove all the microorganisms*, which can lead to the regrowth of disinfection-resistant bacteria in water distribution systems (WDSs) [102]. Although the occurrence of ARGs in different parts of the DW system has been confirmed, the way ARGs change along the full-scale DW system is still unknown [102]. Furthermore, currently available information on AR appears inadequate for the enactment of DW regulation due to lack of standardization in methods of sampling the various phases and analysis of AR [101]. Additionally, although it has been proven that ARGs exhibit high persistence in DW [103], it seems that the abundance of ARGs in tap water is lower than that of source water [104].

3.3. Radiological Contaminants

In 2013, the European Council Directive 2013/51/EURATOM established requirements for radioactive substances in DW [105]. As already set forth in the 1998 DWD, no actual limit for radioactive substances in DW is set, but there are parametric values for some indicators, which, if not complied with, the Member State is required to decide whether remedial actions are needed [105]. Among the regulated parameters is the indicative dose (ID), i.e., "...the committed effective dose for 1 year of ingestion, resulting from all the radionuclides whose presence has been detected in a supply of water, of natural and artificial origin, but excluding tritium, potassium 40, radon and short-lived radon decay products" [105]. Potassium-40 is excluded because of the fact that it does not accumulate in the body but remains at a constant level independently of intake [106]. Uranium (U) has been also addressed in the chemical parameters established for DW quality [6] regarding its chemical toxicity that is dominant over its radiological effect.

The Euratom Directive permits water suppliers to set limit values for radon in the range of 100–1000 Bq/L despite the proposed limit of 100 Bq/L. This guideline could create potential safety gaps among EU populations or disparities, even in the same country, between areas of different aquifer characteristics. Hence, one wonders whether there is sufficient information available proving that individuals receiving DW of, e.g., 900 Bq/L daily, are not exposed to higher radioactivity levels than those who consume water of 100 Bq/L.

In 2016, the EU established maximum permitted levels of radioactive contamination of food and feed in the case of a nuclear accident or any other radiological emergency [107]. The above regulation does not contain DW in the inclusive term of "food", but the maxi-

imum permitted levels of radioactivity in liquid food “could be applied to DW supplies at the discretion of competent authorities in Member States”.

Similarly, in the NPDWR of USEPA, there are MCLs for some radionuclides, along with the monitoring, reporting, and public notification requirements [22]. In 2016, USEPA completed a review of these standards (initially established in 1976) to determine if they need to be revised, expanded, or otherwise modified, and the results of this study were reported in January 2017 [108]. The outcome regarding radionuclides was that

“... it is not appropriate at this time to revise any of the NPDWRs covered under the Phase Rules or Radionuclide Rules. These NPDWRs were determined not to be candidates for revision for one or more of the following reasons: There was no new information to suggest possible changes in MCLG/MCL; new information did not present a meaningful opportunity for health risk reduction or cost savings while maintaining/improving public health protection; or there was an ongoing or pending regulatory action” [108].

There has been expressed concern about the whole regulatory perspective of radionuclides in water that is geared towards cancer and adults, excluding children and infants [32]. In addition, natural radioactivity levels in water show seasonal variations and might change over long periods [109], rendering the established monitoring specifications [22,105] probably inadequate in the case of a significant change in the aquifer’s composition. The highest concentrations of radon in DW have been reported in Finland (77.5 kBq/L) and Sweden (55 kBq/L) with 46% of DW samples tested in Sweden containing levels of radon-derived radioactivity above 100 Bq/L and 3% higher than 1000 Bq/L [31]. High levels of natural uranium have been determined in tap water from Canada, Greece, India, and Morocco and elevated, ^{226}Ra and ^{228}Ra concentrations have also been found in DW from Scandinavia, Hungary, and Spain [110].

4. Assessment of Standards Implementation

4.1. Monitoring Mode of Surveillance/Sampling

In recent decades, it is preferable to apply a preventive rather than corrective approach regarding the water supply network from the source to the final point of consumption [2]. In the revised European DWD of 2020, it is recognized that preventive safety planning and risk-based elements were only considered to a limited extent in previous directives [6]. A systematic approach for managing risk to water safety, a water safety plan (WSP), is internationally recognized as an important and modern method for reducing health risk from DW [19], and proper WSP preparation and implementation are critical in providing protection for consumers [18]. The most important step in a WSP is operational monitoring and management since it is an integral component for water treatment process control to ensure reliable water quality [111].

According to the WSP, *the whole supply chain must be constantly monitored* to ensure that the selected control measures are effective and that health-based targets are being met, thus shifting attention from control at the tap to preventive management [19]. The monitoring plan must be capable of responding to emergency situations, e.g., treatment plant failure; deliberate contamination; and natural disasters, such as earthquakes and flooding [27]. The regulations concerning the monitoring procedures for DW quality are based on the premise that the DW supplier configures the monitoring program based on the outcomes of the risk assessment for the catchment area and the supply system [5,6,22]. The WSP of the WHO’s Guidelines for DW Quality together with the standard EN 15975-2 could be the bases for water suppliers to design DW management [6]. According to the latest EU DWD, such risk-assessment based approach should consist of the following [6]:

1. The identification of the hazards associated with the catchment areas for abstraction points;
2. A possibility for the water supplier to adapt monitoring to the main risks and to take the necessary measures to manage the risks identified in the supply chain from the abstraction, treatment, storage, and distribution of water;

3. An assessment of the potential risks stemming from domestic DS, such as Legionella or lead.

Water suppliers serving between 50 and 500 people (supplying 10 and 100 m³ per day as an average) are exempted from this obligation, provided that regular monitoring is carried out in accordance with the Directive 2020/2184.

Every system has specific number and type of control measures, depending on the already and/or potentially existing hazards and the magnitude of the related risks. Apart from the enforceable guidelines, the International Organization for Standardization (ISO) has set standards throughout the years for the management of DW utilities, such as ISO 24510:2007 and ISO 24512:2007 [112], providing suppliers with good practices regarding the routine operation of a DW plant, including potential crises [113]. The Hazard Assessment and Critical Control Points (HACCP) is another system applied in water utilities that identifies potential hazards in production processes resulting in an unsafe final product [2].

Surveillance—Parameters and Frequency

DW quality is monitored within a specified time period in order to achieve effective system management [5]. The EU and USEPA regulations provide limit values for identified hazards in treated DW, with no demands/provisions for the measurement of the whole list of contaminants if the outcome of the risk assessment (of a particular supply system) does not indicate it. The EU “core list” of parameters that should be monitored in any case comprises 12 indicators, including *E. coli*, intestinal enterococci, coliform bacteria, colony count at 22 °C, turbidity, and conductivity [6].

The provisions of the EU directive [6] regarding the above parameters are as follows:

“... If a parameter is not detected, water suppliers should be able to decrease the monitoring frequency or to stop monitoring that parameter altogether. Risk assessment and risk management of the supply system should be carried out for most parameters... This Directive mainly sets provisions on monitoring frequency for the purposes of compliance checks, with only limited provisions on monitoring for operational purposes... Such additional monitoring should be performed at the discretion of water suppliers. In that regard, water suppliers could refer to the WHO Guidelines and Water Safety Plan Manual.” [6].

For instance, the *chemical quality parameters* of the EU DWD 2020/2184 shall be controlled at the minimum frequency of 12 samples per year for the first 100 000 m³/day plus 1 sample for each additional 25 000 m³/day and part thereof of the total volume [6]. For the *microbiological indicators* *E. coli*, intestinal enterococci, coliform bacteria and colony count 22 °C, the proposed sampling frequency is set at 16 samples per year for a produced water volume of 4300 m³/day plus 3 samples for each additional 1000 m³/day and part thereof of the total volume (Table 1, Part B of Annex II of the DWD 2020/2184 [6]). For both chemical and microbiological parameters, if the supply risk assessment indicates different sampling frequency, then that frequency should be applied. Moreover, if the indicator of somatic coliphages is found in raw water (>50 PfU/100 mL), treated DW should be analyzed/tested after the treatment train in order to determine the log removal by the barriers in place and to assess whether the risk of breakthrough of pathogenic viruses is sufficiently controlled [6].

For monitoring of *radionuclides* in DW, the EURATOM Directive proposes the minimum sampling and analysis frequencies at the Table of Annex II [105]. In the same Directive, apart from the indicative sampling frequency, “... the frequency, in derogation from the minimum sampling requirements, is to be decided by the Member State, taking into consideration the risk to human health”. A Member State could use the number of inhabitants in a supply zone, instead of the volume of water, to determine the minimum frequency, assuming a water consumption of 200 L/day/capita. The sampling point for all monitored parameters has to be the consumer tap to ensure compliance with the directives.

The USEPA regulations stipulate monitoring of *chemical contaminants* as follows:

- Groundwater systems: a minimum of one sample at every entry point to the DS, which is representative of each well after treatment, beginning in the initial compliance period.
- Surface water systems: a minimum of one sample at every entry point to the DS after any application of treatment or in the DS at a point, which is representative of each source after treatment in the initial compliance period.
- If a system draws water from more than one source and the sources are combined before distribution, the system must sample at an entry point to the DS during periods of normal operating conditions (i.e., when water is representative of all sources used).

Furthermore, in USEPA regulations, systems that exceed the MCLs shall be monitored quarterly, beginning in the next quarter after the violation occurred. For community and non-transient water systems, the repeat monitoring frequency for groundwater systems shall be quarterly for at least one year, following any one sample in which the concentration is $\geq 50\%$ of the MCL. The state may allow a groundwater system to reduce the sampling frequency to annually after four consecutive quarterly samples are reliably and consistently less than the MCL [22].

In the § 141.21 of USEPA's NPDWR, the routine sampling requirements for *bacteria indicators* are presented [22] with the foreseen minimum number of samples per month being proportional to the population served by the PWS. Samples must be collected at regular time intervals throughout the month, except groundwater systems serving 4900 persons or fewer that could collect them on the same day. The Revised TCR (RTCR) of 2013 [114] stipulates that the PWSs develop a sample siting plan that defines the system's sample collection schedule and all sample sites, including sites for routine and repeat monitoring.

For the monitoring of *radionuclides*, the § 141.26 USEPA's NPDWR specify the collection of gross alpha, combined radium-226/228, uranium, beta particle, and photon radioactivity at each entry point to the DS along with the proposed monitoring frequency [22]. The suggested sampling frequency by USEPA for meeting the radionuclide MCLs is one sample every 3 to 9 years after the initial sampling requirements.

Sampling/monitoring sites

The surveillance of DW quality should be performed throughout the entire supply network, from abstraction to tap. Within DW distribution systems, a broad range of microbiological and chemical processes can take place, which can lead to the formation of undesirable contaminants, including particles in the water bulk and sediments (loose deposits) as well as biofilm (bio-fouling) on the inner pipe surfaces [115]. Figure 1 provides a schematic overview of some of those processes, which can proceed in parallel with generation of dissolved contaminants. Water quality in DW DS can also be compromised by accidental or intentional incidents, with serious impact on public health. Of course, such incidents (in addition to public health) can have other negative consequences (economic and social), including loss of public confidence in the water supply system [116]. In May 2016, an incident of accidental intrusion was reported in Beijing, China, where a large amount of reclaimed water entered into the DS due to the misconnection between reclaimed and DW supply pipes, resulting in a severe public health hazard [117].

Premise plumbing has features such as the absence, or low concentration, of disinfectant, a high surface-to-volume ratio (providing a large surface area for pathogen adherence to piped and component surfaces) and extended periods of time when water flow is slow and oxygen concentration falls; however, such conditions do not prevent pathogen growth as most can grow at low oxygen levels or even under anaerobic conditions [118]. Considering the fact that the age of pipes in some water supplies could exceed 100 years [19], there is justified concern about the influence of infrastructure conditions on tap water quality [51].

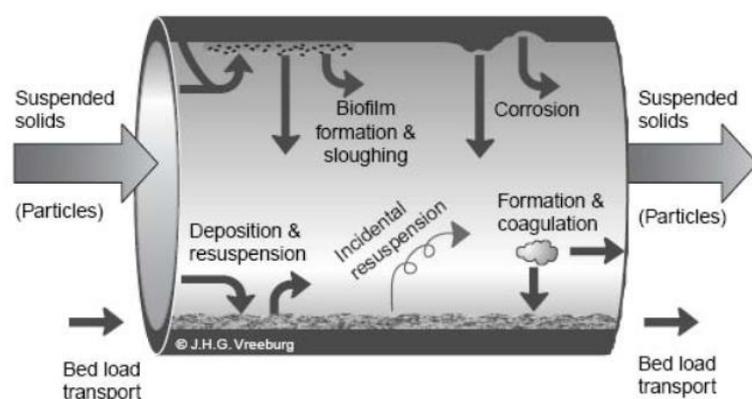


Figure 1. Overview of processes in the DW DS influencing water quality [115].

Even when water has been treated, bacteria can form *biofilms* on any surface that is in contact with the water as long as there is a source of dissolved organic matter (DOM) [27]. Practically, this means that all water distribution pipes could be normally coated with a thin biofilm comprising a broad spectrum of bacterial genera, all of which will rapidly multiply under near ideal conditions [27]. The presence of a biofilm allows the reproduction of potentially pathogenic bacteria due to its organized structure and increased resistance to disinfectants [93]. The health risk linked to the presence of such opportunistic pathogens in tap water systems is gaining an increasing amount of scientific attention [118].

From epidemiology studies of Legionnaires' disease, the commonly known pathways for exposure seem to be from DW within buildings and from cooling tower aerosols. For the period 2013–2017, the results from the Medical Record and Patient Interview Data in New York city reported 5% of cases associated with plumbing maintenance in residential buildings and another 5% from patients reporting a water service disruption [87].

Radionuclides, such as radium and sometimes strontium-90, can become attached to pipes in the system and be released as the composition of water changes. Such releases are downstream from where the utility is usually required to collect/test samples, so the "spikes" of radioactive contaminants are not captured in the data [32]. In general, the reaction mechanisms/processes for removing various species in the DW treatment plant, leading to DBP formation, may also increase the likelihood of radioactive contaminants accumulating in the DS [119].

The EU DWD of 2020 introduces the minimum hygiene requirements for *materials in contact with DW* to avoid contamination, stipulating that compliance samples for copper, lead, and nickel shall be taken at the consumer's tap without prior flushing [6]. Similarly, according to the Lead and Copper Rule (LCR) of USEPA, PWSs should monitor DW at customer's tap [120]. Legislation requires that samples are taken at several points of the DW supply chain in order to achieve effective monitoring, including sampling at the tap. Moreover, in the NPDWR, there is a requirement for sampling at the same points of the DS and at the same time as samples taken for total coliforms to determine the residual disinfectant concentration. Similarly, sampling at the tap is required for the control of lead and copper (corrosion control), apart from the measurement of parameters such as pH, alkalinity, conductivity, calcium, orthophosphate, silica, and water temperature [22].

Consequently, except for the measurement of water parameters in DW treatment plants, *the sensors' appropriate placement in the DS* is another important factor for obtaining the real picture of tap water quality. The main approach currently available to reduce the impacts of a contamination event in the DS is a *contamination warning system (CWS)*. This is a combination of monitors, institutional arrangements, analysis tools, emergency protocols, and response mechanisms designed to provide early warning of contaminants in order to minimize customer exposure [121]. Beyond the detection issue, an advanced CWS could also "intervene" and solve the problems of identification of a possible contaminant source location and its distribution through the DS [122]. However, due to high cost of purchase,

installation, and maintenance, the placement of sensors at every node in a WDS is not considered economically justified [116]. The best possible deployment of CWS has been the focus of several studies in which an optimization model is developed to determine the optimum layout of sensors with objective function, such as minimizing the affected population, time period to detection, volume of contaminated water, and maximizing probability of detection [116]. However, regarding water quality monitoring sensors, there are also other significant issues to be addressed, including internal structural failures, equipment/sensor malfunctioning, measurement errors, and communication failures [117].

Monitoring tools

There are several commercial tools (in the form of digital and related platforms) for DW systems [123] that provide online, continuous monitoring of water quality. The *Smart Pipe* [124] is an example of a promising monitoring tool, comprising compact and intelligent wireless nodes hosting miniaturized sensors for quantitative, continuous, and distributed monitoring of the water quality parameters, risks to health, and the efficacy of disinfection. Similar tools could be equipped with different sets of sensors and be installed both in the treatment plants (i.e., for optimization of the disinfection process) as well as across the whole distribution network [124].

The review of Storey et al. [125] regarding available and employed technologies for the online monitoring of DW quality summarizes progress made in this field in recent decades. For instance, several cities in Spain use a system [126] that comprises low-consumption digital nodes to monitor water quality, specifically designed for installation in water distribution networks and remote locations such as water tanks, without mains power [127]. However, the measured parameters of that monitoring system are restricted to the typical indicators of DW quality, such as pH, conductivity, turbidity, fluoride, hydrogen peroxide, and peracetic acid. [127]. The aforementioned digital platforms/systems are considered essential for the continuous monitoring of DW quality from treatment facilities to tap. However, the current lists of controlled substances and related hazards need further improvement to include emerging chemical and biological contaminants known for their harmful effects to human health.

An issue of great concern emerges from the current review: assuming that authorities and water suppliers need to enforce and implement a more comprehensive and stringent approach regarding the monitoring of various regulated parameters in DW, are the available tools (including the approved analytical methods for water contaminants) capable of providing reliable, robust, quick results for adequate and timely consumer protection? This issue is addressed in the following section.

4.2. Accepted Analytical Techniques

In conventional DW treatment processes, water quality monitoring is conducted using both *online sensors* and *offline analyses of periodically and/or manually collected samples* [111]. The approved analytical methods for the identification and determination of water contaminants are specified, either directly (USEPA) or indirectly (EU), with requirements such as the limit of quantification and/or compliance of the method with standards such as ISO. The EU DWD 2020/2184 specifies that the analytical methods for the *chemical* and *indicator parameters* should have a limit of quantification at $\leq 30\%$ of the parametric value, defined as the uncertainty of measurement (Table A1 of Part B Annex III [6]), and be validated and documented in accordance with EN ISO/IEC 17,025 or other equivalent international standards, as also stipulated for the microbiological parameters.

The analysis methods for some *microbiological parameters* have also been specified (i.e., as in EN ISO 9308-1 and EN ISO 9308-2 for *E. coli*), thus providing a uniform framework of protection for EU Member States. Standard methods for the detection and quantification of *pathogens* are based on culture media, with more advanced methods focusing on molecular biology tools [93]. Newer methods such as qPCR have great potential to quantitatively examine more samples at a lower cost and much more rapidly [87]. In particular, ISO 9308-1 describes a method based on membrane filtration, subsequent culture on a chromogenic

coliform agar medium, and calculation of the number of target organisms in the sample, and this is especially suitable for waters with low bacterial numbers, such as DW [128]. In general, data collection of waterborne pathogen occurrence requires the concentration of pathogens *from large volumes* of water due to the low number of microorganisms that are typically present in environmental water bodies and DW. For instance, the detection of human enteric viruses and protozoan parasites may require isolation from 10 L to more than 1600 L depending on the particular water matrix [129]. ISO 9308-2 specifies a method based on the growth of target organisms in a liquid medium and the calculation of the "most probable number" (MPN) of organisms in reference to MPN tables, and it can be applied to all types of water [130]. Overall, the majority of the specified analytical methods for the microbiological parameters of EU DWD are based on membrane filtration and colony counts in appropriate culture medium [6]. Notably, there is the exception of *Legionella* for which rapid culture methods, non-culture-based methods, and molecular-based methods (like qPCR) can be used [6].

Regarding *radionuclides*, EU specifies the limit of detection for such measurements without defining the methods; however, analytical quality control in the laboratories involved for such analyses is subject to validation by an external organization approved by a competent authority [105]. In the view of the Directive 2013/51/Euratom, a network was established for the monitoring of DW, where all data are collected and available via the Radioactivity Environmental Monitoring database (REMdb) [131]. In a study conducted by the EU Joint Research Centre [131], involving laboratories carrying out routine and emergency measurements of environmental and foodstuff parameters, the performance of the measurement methods was examined. It was reported that most laboratories apply gamma-ray spectrometry correctly, except when measuring the $^{226,228}\text{Ra}$ in water samples. The water matrix and pipe wall moderate alpha, beta, and gamma radiation to the extent that traditional sensors placed outside of a water pipe are not sufficiently sensitive to detect radionuclides. Because of this difficulty, few online sensors are commercially available for the detection of radiation in water, leading to rather uncommon use of these sensors in DW utilities [132].

Similarly, most studies reporting the occurrence of CECs in DW have been conducted using traditional sampling methods with grab or composite samples [133] of low inter-day frequency and often no intra-day repetition [134]. These methods often require a *large amount of water samples* to detect trace levels of an increasing number of CECs, providing only a single "snapshot" in time of what is present in the water [133]. The use of inappropriate sampling strategies is considered the greatest weakness of reported occurrence data regarding CECs [134].

The analysis of USEPA-regulated parameters in DW shall only be conducted by laboratories that have been certified by EPA or the state, with analytical methods that can be found in detail on the USEPA website [135]. One approved method (2013) for DW compliance monitoring of 1,4-dichlorobenzene and 1,2-dichloroethane, is the capillary column gas chromatography/mass spectrometry (GC/MS). The single approved method for the analysis of 2,3,7,8-TCDD (Dioxin) is the high-resolution GC/high-resolution MS (HRGC/HRMS), an analysis method that should be conducted only by experienced analysts or under the close supervision of such qualified persons. For the measurement of haloacetic acids (HAA5), one of the latest approved methods (2017) is the micro liquid-liquid extraction (LLE) GC method, which requires special laboratory equipment, and, despite its high sensitivity and low detection limits, remains *time consuming* [136,137]. Wider screening of organic chemicals needs a set of techniques for sample preparation, such as steady liquid-liquid extraction, solid-phase extraction, micro-extraction of solid phases, and collection of the upper space and flow injection [8]. Hence, collected grab samples need to be analyzed in the laboratory in most cases; for instance, special chemicals/contaminants, involved in potential accidental or intentional contamination, require such advanced analytical procedures [8]. However, water quality data from *online sen-*

sors are needed to promptly alert an operator on a water condition involving a regulated contaminant or parameter [132,138].

The standard methods employed for *coliform* detection by the analytical services of a PWS are also presented in the USEPA website [139]. The methods in their majority require 16–48 h for the detection of *E. coli* and/or total coliforms, with the exception of the Tecta EC/TC v.2.0 method, which is a self-contained benchtop device capable of receiving positive results in approximately 2 h (with final results obtained after 18 h of incubation) [140]. Despite the long list of available methods for coliform measurement, USEPA does not provide specific guidance regarding *Legionella*'s analytical method, allowing PWSs to employ techniques that are incapable of rapid results. Analytical kits for the detection of *Legionella pneumophila* may facilitate sampling at a lower cost, but the time to obtain results could be up to one week [141].

Inevitably, by the time routine microbial analysis reveals a possible bacterial pollution, the tested water could already be distributed and consumed [142]. For cell culture detection of viruses, the cytopathogenic effect may require 7–10 days to occur [143]. The limitations associated with current growth-based methods and the missing specificity of current on-line methods make it practically impossible to proactively react on contamination events of distributed DW. The existing contingency of not recognizing the conditions that could lead to a public-health threat due to inadequately trained personnel [18] is an additional factor of concern, intensifying the need for the development of appropriate sensors. Most online sensors currently used in water facilities can only measure common physicochemical parameters, such as total organic carbon (TOC), turbidity, pH, water temperature, free chlorine, fluoride, and conductivity [132,143]. Some novel sensors, such as those developed by Højris et al. (2016) (resolution time: 10 min), or by Simões and Dong (2018) (response time in milliseconds), are very promising in the field of rapid, online measurement of pathogens in water [142,144].

Online biosensors have great potential, enabling improved DW quality monitoring in DS, as they should be capable of identifying low-probability/high-impact contamination events in a sufficiently short time [127,145]. Biosensors are mostly based on toxicity tests that use bio-organisms instead of testing components and compounds to detect toxicity in water samples [8]. They are characterized by high sensitivity and selectivity, a fast response, ease of use, a low cost, and the potential for field testing [146]. Significant progress made in recent years on biosensor development is promising and indicates the possibility of equipping water suppliers with tools for rapid detection of various already known or emerging pollutants, such as heavy metals, aromatic compounds, pesticides, pharmaceuticals, ARGs, and biomolecules [146–149]. The extensive activity in the field is reflected in Table 3, as reported in a recent review [146].

Table 3. Summary of online biosensors for detection of *E. coli* [146,147].

Category	Description
Optics (non-imaging)	Measuring bacterial growth by detecting changes in optical signals using photometers
Optics (imaging individual cell)	Measuring physiological, morphological, metabolic, or structural features of bacteria with cameras integrated with microscopy
Optics (imaging population)	Measuring population of bacteria in liquid with imaging
Electrochemistry (sensor)	Measuring bacterial growth by detecting changes in electro-chemical features of the electrodes and analytes
Electrochemistry (biosensor)	Measuring bacterial growth by monitoring changes in electrochemical features of cells or metabolites using bio-elements immobilized on electrodes

Table 3. Cont.

Category	Description
Electrochemistry (contactless sensor)	Measuring <i>E. coli</i> growth by detecting changes in conductivity with C ⁴ D or other contactless sensors
Microcalorimetry	Monitoring heat generation by growing bacterial cells
Resonant mass	Quantifying cell number by measuring changes in the mass of individual cells using a small channel of cantilever
Gene analysis	Measuring <i>E. coli</i> growth by detecting genes via augmentation with PCR

5. Discussion

The current review reveals a variety of significant issues related to the regulation and monitoring of treated and distributed DW, which aim to ensure its good quality and to protect human health. These issues essentially result from the multitude of known, suspected, and emerging contaminants due to human activities and needs under conditions of a globally increasing population and diminishing clean water resources [42]. To summarize the findings of this review and provide useful conclusions, Table A1 provides an overview of the assessment for each category (and main sub-categories) of contaminants, i.e., chemical, biological, and radiological contaminants. In the ensuing discussion, based on these itemized comments, a generalized assessment is presented using three criteria: *completeness of standards* (i.e., are all known and potential contaminants satisfactorily included/considered?), *adequacy of standards/regulations* (i.e., are the stipulated/enforced limit values and/or indices of regulated contaminants adequate and/or representative?), *implementation/monitoring* (i.e., adequacy of approved/foreseen tools and methods for indispensable effective monitoring).

Completeness of standards for DW quality

In recent decades, the WHO guidelines for DW quality have been the basis for the regulations set by authorities worldwide [5,17]. The legislative framework provided by the EU and the USEPA regulations are generally considered advanced, as they provide enforceable standards regarding DW characteristics from the abstraction point to the consumer tap, and they are periodically revised [23,108]. The recently approved EU DWD 2020/2184 is the result of updates and revision of much older, former directives [6]. However, weaknesses are identified even in these advanced standards regarding *unregulated contaminants* [1,52,89,120]. For instance, based on results of a detailed review made by the WHO Regional Office for Europe regarding the new directive [6], enteric pathogens and *Legionella* should be controlled, six chemical parameters or groups should be added, and three representative EDCs may be considered as benchmarks where necessary. However, the 2015 opinion of the European Food Safety Authority (EFSA) was that only one (Bisphenol A) out of the three EDCs should be added to this directive with a parametric value of 2.5 µg/L, whereas the substances of nonylphenol and beta-estradiol should be added to the *watch list* of the EU Commission pursuant to this directive [6].

The present review reveals that although there is intensive research activity in the various emerging contaminant classes (i.e., CECs, ARB/ARGs, PFAS, DBPs, and microorganisms related to infectious diseases such as enveloped viruses) [24,35,46,52–55,57,61,62,64,89,96–101], *only a limited number or none* of the aforementioned are included in the current regulations, including the EU 2020/2184 Directive. The proven impacts on human health related to acute effects from (or health hazards after chronic exposure to) those emerging contaminants generate serious concerns about the existing regulatory framework [16,47]. However, there is little doubt that it would be practically impossible to include each potential hazard in the monitoring procedure of a DW supply network. Evidently, for this reason, the recently approved EU DWD 2020/2184 introduces the implementation of a risk assessment approach in all regulated water supplies, along with the minimum hygiene requirements for materials in contact with DW, such as pipes and taps [6].

The literature confirms that there are *unregulated substances* detected in groundwater or surface water, in DW treatment facilities, and even in tap water, reflecting the impact of human activities associated with industry, agriculture, pharmaceuticals (including antibiotics), and synthetic chemicals on the environment [9,37,52,54,57,63,106,121]. Furthermore, the justified pressure regarding adequate wastewater treatment (enabling water recycling in view of foreseen water shortages) is leading to the development and implementation of novel technologies (advanced water treatment, e.g. [2,9,11–14]) that can eliminate these hazards from DW sources and effectively protect consumers. Thus, there is a need for more frequent revision of the DW standards (e.g., the former EU DWD was published in 1998) and for the inclusion of more parameters known for their toxicity. Setting appropriate limit values for a wider range of contaminants is a prerequisite in the following:

- Identifying the characteristics of source water and determining its required treatment.
- Evaluating the performance/efficacy of DW treatment plants.
- Monitoring the (mostly undesirable and/or unforeseen) processes taking place in the DW DS (including the detection of accidental or intentional release of harmful substances).

The main difficulties in setting limit values for emerging contaminants and/or pathogens are related to the following [30,37,47,52,73,88,92]:

- Insufficient or contradictory data regarding the contaminant's presence and persistence in DW.
- Drawbacks in the available analytical methods/procedures for the identification and quantification of contaminants, including sampling protocols and lack of standardization thereof (e.g., large volumes of water samples required for some contaminant classes).
- The significant cost of monitoring (e.g., for specialized analytical equipment and personnel and extensive water supply risk assessment associated with the WSP approach).

Adequacy of current DW standards

There is considerable concern and debate in the literature regarding the existing parameters that serve as *indicators* for DW quality, with emphasis on the selected/stipulated reference organisms that represent the biological composition of water sources [1,30,102]. The typical indicators of *E. coli*, Enterococci, and coliform bacteria are not considered as credible surrogates to more resistant species, such as those of human enteric viruses, *Pseudomonas aeruginosa*, *Giardia lamblia*, or *Cryptosporidium* [5,80,82,85]. In respect of chemical contaminants, the regulated upper limits of some species such as cadmium and vinyl chloride, which exceed the WHO guidelines [5,6], are also a matter of concern for the new DWD 2020/2184. Regarding radioactive substances, questions are raised regarding the range of the accepted levels of radon (100–1000 Bq/L) in contrast to the proposed limit value of 100 Bq/L (Directive 2013/51/EURATOM) [105]. The established limit values of radionuclides that address only health risk of adults, but not of children or infants, is another expressed concern in the literature [32].

Implementation of standards and monitoring

The good quality of DW is assured by the implementation of monitoring plans such as the WSP, which are made after the risk assessment of a particular catchment area and supply system (e.g., [2,3,17,19,127]). Extreme events, such as operational failure, accidental/deliberate contamination, and natural disasters, should be considered in this approach [17,117,144]. The regulatory authorities set enforceable standards for the management of DW utilities that include the following:

- The measured quality parameters;
- The frequency of sampling;
- The points of compliance;
- The specifications of the employed/approved analytical methods.

In addition to the aforementioned completeness and adequacy of the regulated parameters, the compliance to the above monitoring standards is of crucial importance for the assurance of good DW quality. The importance and necessity of adequate (spatial and

temporal) control of water characteristics from the feed to the exit of treatment plant [127] in the WDS network [115] and finally at the consumer's tap are dictated by the numerous (planned and undesirable) processes that occur in this system, and this control can affect DW quality and have an impact on human health [123]. Common failures in DW source-protection and treatment (e.g., not preventing livestock access to, or human sewage discharges in, source waters) are well-known threats that have led to serious disease outbreaks in recent decades, despite the large experience in the field [18]. The WDS condition and inherent features (e.g., infrastructure age/materials, anaerobic conditions, low disinfectant concentration, and large surface area for interaction with pathogens.) have been issues of great concern [62,88,121,124], highlighting the need for a *contaminants warning system (CWS)* [123,124,150].

The progress made in the field of artificial intelligence (AI), both in general [150] and in particular on digital platforms [125,128] that facilitate/enable the remote and continuous monitoring of water quality, provides suppliers with very useful surveillance tools, though costly depending on the implemented sensor network. Indeed, the use of optimally placed online sensors (e.g., [117]), capable of providing adequate data for effective system monitoring, is a novel feature with great potential for implementing an advanced CWS as well as for the general management of DW systems. However, the *inherent drawbacks* of some important practices/protocols [61], and of analytical procedures [101], including the required grab-sampling (of relatively large quantities) [10,52,89], sample pretreatment [8], and time-consuming laboratory analysis [128,131], with a *long response time* [129,138], pose serious challenges, effectively inhibiting the application of the aforementioned AI-based tools.

It is noted that the provisions of the EU Directive 2020/2184 regarding the acceptable analytical methods for the monitoring of DW quality include methods that are in accordance with ISO or equivalent standards in respect of the limit of quantification and the accepted uncertainty of measurement [6]. However, these approved methods exhibit the above-mentioned inherent drawbacks. For instance, focusing on microbiological hazards that can affect public health with acute effects after *short exposure*, the delay and limitations associated with currently approved methods (e.g., analysis time > 16 h in most cases [6]) and the missing specificity of the available online methods [133] make it practically impossible to effectively react to unforeseen DW contamination events [143,144]. Recent developments of some fast-response and robust biosensors (e.g., [144,149,151]) are promising and could contribute in the direction of developing efficient and reliable early warning systems in DW DS. Such systems would cater to the needs of the stakeholders (water suppliers and regulatory authorities) to implement rapid-response-time tools as part of the standard monitoring procedures for DW quality monitoring.

6. Conclusions

This review reveals serious issues regarding standards and regulations for DW quality and their implementation at three levels, i.e., completeness/comprehensiveness, adequacy, and monitoring.

- **Completeness.** There are serious deficiencies regarding inclusion in the standards mainly of chemical (CECs, DBPs, PFAS, perchlorate, and Cr (VI)) and microbiological contaminants (enteric viruses, *Pseudomonas*, *Cryptosporidium*, *Giardia*, *Legionella*, ARB/ARGs, and enveloped viruses).
- **Adequacy.** The most serious issues are related to the microbiological contaminants regarding the representativeness of indices, currently employed not for individual contaminants but for entire classes (e.g., bacteriophages as indicators of enteric viruses). Significant uncertainties are also identified regarding the stipulated limit values for several chemical contaminants.
- **Implementation/monitoring.** The importance of this aspect regarding drinking water quality is obvious, considering the variety of contamination sources in the distribution network, i.e., between the DW treatment plant and consumers taps. It is,

therefore, understandable and appropriate that emphasis is placed on the regulations to adequately monitor DW quality. However, regarding effective monitoring, there are major issues and concerns due to the inherent deficiencies of the presently available/approved analytical techniques for determining chemical and, in particular, microbiological contaminants. Such deficiencies are related to the required sampling protocols (necessitating large sample volumes, adequacy of sensor networks, and sampling location/frequency) and in particular to the considerably long analysis time (of several hours) that essentially determines the response time of the entire monitoring system. Therefore, the time to implement such protocols is at present too long, rendering the system inefficient and incapable to cope with problems requiring relatively fast system response (e.g., unforeseen events, such as accidents and natural disasters). Moreover, the long analysis time (and delayed response) essentially neutralizes the benefits resulting from the recent progress made in fast signal acquisition/transmission and data collection and management systems.

Regarding R&D priorities to address the aforementioned deficiencies, it is clear that at the top of the list is the development of sensors and of related fast-response analysis techniques. In parallel, a great deal of work is required in the direction of completing and enriching the standards by including many contaminants of chemical and biological origin (not included in the current standards/regulations) that are known or suspected to be harmful to human health.

From the viewpoint of monitoring and management the DW systems, it is clear that the good condition, integrity, and maintenance of the DS are of utmost importance. Indeed, it seems that most disease outbreaks and related issues (at least in developed countries) in recent years originate from problems in the DS.

Regarding advanced techniques for water purification, the quite extensive ongoing activity (e.g., on advanced oxidation processes (AOPs) and on other AOP–membrane hybrid processes) has led to novel methods that should be further developed and employed against the assorted emerging contaminants. In parallel, considering all of the aforementioned weaknesses of the standards and regulations, the current approach of required risk assessment studies, adopted in the recently enacted EU DW Directive, is well justified. It is noted, however, that the responsibility for such adequate risk assessment studies (as well as for the entire monitoring system) rests with the DW provider/distributor. Therefore, some uncertainty and concern regarding the adequate execution and implementation of such tasks, particularly by the DW providers operating small DW systems, are generated. Finally, although not directly related to DW standards and regulations, an overarching issue impacting on DW quality is the status and preservation of a good condition of water bodies from which the respective treatment plants draw feed water.

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Appendix A

Table A1. Overview of assessment regarding the standards/regulations for chemical, microbiological, radiological contaminants in DW, focusing on the *EU Directive 2020/2184*, *USEPA's NPDWR*, and *WHO (2017) regulations/guidelines* [5,6,22].

Contaminant	Inclusion in EU, USEPA, WHO Standards	Standards	Measurement Technique	Comments-Assessment	
Chemical <i>Limit values or MCLs of chemical parameters</i>	EU Directive 2020/2184	Yes	Annex I, Part B	<ul style="list-style-type: none"> Capable of measuring concentrations equal to the parametric value with a LOQ of $\leq 30\%$ of the parametric value and an uncertainty of measurement as specified in Table A1 of Part B Annex III The analytical methods should be validated and documented in accordance with EN ISO/IEC 17025 or other equivalent standards accepted at international level 	<p><u>General comments:</u></p> <ul style="list-style-type: none"> Chemical hazards do not change water color, odor or taste; thus, exposed populations may continue to use contaminated water if there is no warning [5] There are regulated substances with higher limit values or MCLs than those suggested by WHO (Table 2). Standards incomplete, e.g., Cr(VI) and perchlorate not included [35,37] The accepted analytical techniques require specialized personnel and long response time Wider screening on organic chemicals needs a set of techniques for sample preparation [8]
	USEPA NPDWR	Yes	§ 141.11 and § 141.50-51	<ul style="list-style-type: none"> § 141.23 (inorganic chemicals) and https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WD2D.txt (accessed on 11 October 2020) § 141.24 (organic chemicals) and https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WD47.txt (accessed on 11 October 2020) 	
	WHO Guidelines	Yes	Table 8.10, 8.13, 8.16 & Table A3.3/Annex 3	Table A4.1-4 of Annex 4 ^a	
CECs		Pesticides ^b	0.1 µg/L ^b	<p>Pesticides: The performance characteristics for individual pesticides are given as an indication (Table A1 of Part B Annex III). Values for the uncertainty of measurement as low as 30% can be achieved for several pesticides, while higher values up to 80% may be allowed for a number of pesticides.</p> <p>PAHs: the performance characteristics displayed in Table A1 of Part B, Annex III, apply to individual substances, specified at 25% of the parametric value.</p>	<ul style="list-style-type: none"> They are generally put on "priority pollutant" lists Human and veterinary medicinal products remain unregulated [49,51] Inappropriate sampling strategies [135] CECs identification in DW is a matter of concern for the managers of DW treatment facilities [54]
	EU Directive 2020/2184	Pesticides Total ^c	0.5 µg/L ^c		
		PAHs ^d	0.1 µg/L ^d		
	USEPA NPDWR	A few EDCs and PPCPs in the CCL 4, not in enforceable standards		<ul style="list-style-type: none"> Some are listed in the CCL They are a recognized potential risk in DPR projects but most of them have no regulatory limits in DW. Some states such as California have started to fill this gap with specific regulations [47] 	
	WHO Guidelines	Focus on pharmac/cals; no values	Pesticides: Table A4.5 of Annex 4		
PFAS	EU Directive 2020/2184	Total ^e	0.50 µg/L ^e	<p>By 12 January 2024, the EU Commission shall establish technical guidelines regarding methods of analysis including detection limits, parametric values, and frequency of sampling.</p>	<ul style="list-style-type: none"> Monitored when the risk assessment and risk management of the catchment areas for abstraction points conclude that those substances are likely to be present in a water supply The current limit value is far above recommended values such as that of the EWG [59]
		Sum of PFAS ^f	0.10 µg/L ^f		
	USEPA NPDWR	No federal enforceable standards		Although they have been systematically detected in more than 25 states, there are no federal enforceable standards [57]	
	WHO Guidelines	No values			

Table A1. Cont.

Contaminant	Inclusion in EU, USEPA, WHO Standards	Standards	Measurement Technique	Comments-Assessment		
Perchlorate	EU Regulation 2020/749 for chlorate residues in food and DW	Maximum residual level (MRL)	0.01 mg/kg	[34]		
	USEPA NPDWR	Unregulated		[38]		
	WHO Guidelines	Yes	0.07 mg/L			
DBP		HAA5 ^g	60 µg/L ^g			
	EU Directive 2020/2184	THM (Total) ^h	100 µg/L ^h	THM: the performance characteristics displayed in Table A1 of Part B, Annex III, apply to individual substances, specified at 25% of the parametric value.		
	USEPA NPDWR	Bromodichloromethane, bromoform, bromate	0 mg/L	§ 141.131 and https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WD1L.txt (accessed on 8 September 2020)	<ul style="list-style-type: none"> • Incomplete worldwide standards. More than 600 DBPs have been identified with less than 20 currently regulated [65]. • Once formed, DBPs can be readily delivered to consumers' taps [63] • Many unregulated DBPs are apparently more toxic than those currently regulated [37] • Potential difficulties in DBP identification in water [61] but through the detection of toxicity drivers [65], stakeholders could take appropriate measures 	
		chlorite,	0.8 mg/L			
		chloroform,	0.07 mg/L			
		dibromochloromethane,	0.06 mg/L			
		dichloroacetic acid	0 mg/L			
		Monochloroacetic acid	0.07 mg/L			
	Trichloroacetic acid	0.02 mg/L				
	WHO Guidelines	HAA5, THMs included in EU and USEPA regulations	Table 8.16 and Table A3.3 of Annex 3			
Microbiological <i>Limit values, MCLGs and treatment techniques (TT)ⁱ for indicator pathogens</i>	EU Directive 2020/2184	Yes	Annex I, Parts A and C	Annex III, Part A		<p>General comments:</p> <ul style="list-style-type: none"> • <i>Indicator pathogens</i>, or <i>reference organisms</i>, potentially unrepresentative of individual pathogens (common and/or emerging) [8,21,68,86] • Enveloped viruses such as SARS-CoV-2 are not included in the microbial risk assessments of DW treatment plants [94] • Long analysis/response time (>16 h in most of the cases) [143,144] • Large volumes of water needed for the collection of data [89]
	USEPA NPDWR	Yes	§ 141.52	§ 141.21		
	WHO Guidelines	Yes	Table 7.5 and 7.10	Table 7.11 with ISO standards for detection and quantification of fecal indicator organisms in water		
Enteric viruses	EU Directive 2020/2184	Not included			<ul style="list-style-type: none"> • Somatic coliphages are useful surrogates for enteric viruses, but environmental factors such as water temperature could affect the correlation among microbial parameters [32,74,75] • The absence of coliphages does not entail a negative sample for norovirus, a human enteric virus [76] • Adenoviruses could be reliable indicators for viral contamination in DW [70,74] 	
	USEPA NPDWR	No MCL but MCLG or treatment technique (TT) ⁱ	Zero and 99.99% removal/inactivation	Not specified		
	WHO Guidelines	No value				

Table A1. Cont.

Contaminant	Inclusion in EU, USEPA, WHO Standards		Standards	Measurement Technique	Comments-Assessment
<i>Pseudomonas</i>	EU Directive 2020/2184	Not included			Detected in treated water samples with free residual chlorine of 0.2–2.0 mg/L [79], confirming this species' resistance to conventional water treatment processes [80]
	USEPA NPDWR	No MCL but MCLG or TT ⁱ		Not specified	
	WHO Guidelines	No value			
<i>Cryptosporidium</i>	EU Directive 2020/2184	Not included			<ul style="list-style-type: none"> Both parasites can be transmitted through water in the case of poor sanitation systems, lack of hygiene, an inadequate water management system, and wastewater reuse practices [83,85] leading to disease outbreaks [84]
	USEPA NPDWR	No MCL but MCLG or TT ⁱ	Zero and 99% removal/ filtration ^j	§ 141.704 ¹	
	WHO Guidelines	No value			
<i>Giardia lamblia</i>	EU Directive 2020/2184	Not included			<ul style="list-style-type: none"> Both pathogens have been detected in treated water samples [18,28] and in DW [51,83] No correlation between indicator bacteria and Giardia cysts in treated water [83]
	USEPA NPDWR	No MCL but MCLG or TT ⁱ	Zero and 99.9% removal/ inactivation	Not specified	
	WHO Guidelines	No value			
<i>Legionella</i>	EU Directive 2020/2184	Limit value in the case of a risk assessment that indicates <i>Legionella</i> 's monitoring	<1000 CFU/L	In accordance with EN ISO 11731 For risk-based verification monitoring and to complement culture methods, methods such as ISO/TS 12869, rapid culture methods, non-culture-based methods, and molecular-based methods (in particular, qPCR), can be used.	<ul style="list-style-type: none"> The leading cause of reported waterborne disease outbreaks in USA caused by Legionella bacteria [87] Species have been detected in disinfected DW distrib. systems [88] No specified methods for the detection in DW; PWSs could employ techniques that do not provide rapid results (even up to one week [142])
	USEPA NPDWR	No MCL but MCLG or TT ⁱ	Zero ^k	Not specified	
	WHO Guidelines	No value			
ARB and ARGs	EU Directive 2020/2184	Not included			<ul style="list-style-type: none"> The conventional DW treatment processes cannot remove all the microorganisms, which can lead to the regrowth of disinfection-resistant bacteria in drinking WDSs [102] Lack of standardization in methods of sampling the various phases and analysis of AR [101]
	USEPA NPDWR	Not included			
	WHO Guidelines	Not included			

Table A1. Cont.

Contaminant	Inclusion in EU, USEPA, WHO Standards	Standards	Measurement Technique	Comments-Assessment	
Radiological Limit values or MCLs of radiological indicators	EU Directive 2013/51/EU- RATOM	Yes	Annex I	§3, Annex III	General comments: <ul style="list-style-type: none"> Concern about the whole regulatory perspective that is geared to cancer and adults excluding children and infants [32] Seasonal variations of natural radioactivity levels in water [109] The monitoring specifications [22,105] are probably inadequate in the case of a significant change in aquifer's composition Few online sensors are commercially available [133]
	USEPA NPDWR	Yes	§ 141.66	§ 141.25 and https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockkey=P100WD57.txt (accessed on 11 October 2020)	
	WHO Guidelines	Yes	Table 9.2, Box 9.4 and Table A6.1, Annex 5		

^a Analytical achievability for chemicals for which guideline values have been established. ^b The parametric value of 0.10 µg/L applies to each individual pesticide. In the case of aldrin, dieldrin, heptachlor, and heptachlor epoxide, the parametric value is 0.030 µg/L. Includes organic insecticides, organic herbicides, organic fungicides, organic nematocides, organic acaricides, organic algicides, organic rodenticides, organic slimicides, related products (inter alia, growth regulators), and their metabolites, considered relevant to drinking water, as defined in point (32) of Article 3 of Regulation (EC) No 1107/2009 of the European Parliament and of the Council. ^c The sum of all individual pesticides detected and quantified in the monitoring procedure. ^d Sum of concentrations of benzo(b)fluoranthene, benzo(k)fluoranthene, benzoperylene, and indeno(1,2,3-cd)pyrene. ^e The totality of per- and poly-fluoroalkyl substances. This parametric value is applied only once the technical guidelines for monitoring this parameter are developed in accordance with Article 13. Member States may then decide to use either one or both of the following parameters: "PFAS Total" or "Sum of PFAS". ^f This is a subset of "PFAS Total" substances that contain a perfluoroalkyl moiety with three or more carbons (i.e., -C_nF_{2n-}, n ≥ 3) or a perfluoro-alkylether moiety with two or more carbons (i.e., -C_nF_{2n}OC_mF_{2m-}, n and m ≥ 1). ^g The sum of monochloro-, dichloro-, and trichloro-acetic acid and mono- and dibromo-acetic acid. ^h The sum of concentrations of chloroform, bromoform, dibromochloromethane, and bromodichloromethane. ⁱ Treatment technique (TT)—a required process intended to reduce the level of a contaminant in DW. ^j Unfiltered systems are required to include *Cryptosporidium* in their existing watershed control provisions. ^k No limit, but USEPA supports that if Giardia and viruses are removed/inactivated according to the treatment techniques in the surface water treatment rule, *Legionella* will also be controlled. ^l Systems must analyze at least a 10 L sample or a packed pellet volume of at least 2 mL. Systems unable to process a 10 L sample must analyze as much sample volume as can be filtered by two filters approved by USEPA for the methods listed, up to a packed pellet volume of at least 2 mL.

Table A2. Definition of abbreviations.

Abbreviation	Definition
2,3,7,8-TCDD	2,3,7,8-Tetrachlorodibenzodioxin
AdVs	Adenoviruses
AI	Artificial intelligence
AR	Antibiotic resistance
ARB	Antibiotic-resistant bacteria
ARGs	Antibiotic-resistant genes
CCA	Chromogenic coliform agar
CCL	Contaminant Candidate List
CDC	Centers for Disease Control and Prevention
CECs	Contaminants of emerging concern
COVID-19	Coronavirus disease 2019
CUPs	Current-use pesticides
CWS	Contamination warning system
DBPs	Disinfection byproducts
DOM	Dissolved organic matter

Table A2. *Cont.*

Abbreviation	Definition
DPR	Direct potable reuse
DS	Distribution system
DW	Drinking water
DWD	Drinking Water Directive
<i>E. coli</i>	<i>Escherichia coli</i>
EBOV	Ebola virus
EC	Effective concentration
EDCs	Endocrine-disrupting compounds
EQS	Environmental quality standards
EWG	Environmental Working Group
GC/MS	Gas chromatography/mass spectrometry
HAAs	Haloacetic acids
HACCP	Hazard Assessment and Critical Control Points
HALs	Haloacetaldehydes
HRGC/HRMS	High-resolution (HR) gas chromatography/HR mass spectrometry
ICCs	Industrial and commercial compounds
ID	Indicative dose
ISO	International Organization for Standardization
LCR	Lead and Copper Rule
LLE	Liquid–liquid extraction
MCLs	Maximum contaminant levels
MCs	Microcystins
MERS-CoV	Middle East respiratory syndrome coronavirus
MPN	Most probable number
NOM	Natural organic matter
NPDWR	National Primary Drinking Water Regulations
NSFWQI	National Science Foundation Water Quality Index
ORP	Oxidation reduction potential
PAF	Population attributable fraction
PAHs	Polyaromatic hydrocarbons
PFAS	Per- and poly-fluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PhACs	Pharmaceuticals
PPCPs	Personal care products
PWS	Public water system
qPCR	Quantitative polymerase chain reaction
R&D	Research & development
REMdb	Radioactivity Environmental Monitoring database
RNA	Ribonucleic acid
RTCR	Revised Total Coliform Rule

Table A2. Cont.

Abbreviation	Definition
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
SDWA	Safe Drinking Water Act
SWTR	Surface Water Treatment Rule
TCR	Total Coliform Rule
THMs	Trihalomethanes
TOC	Total organic carbon
UCMR	Unregulated Contaminant Monitoring Regulation
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
WDS	Water distribution system
WHO	World Health Organization
WQI	Water quality index
WRD	Water-related disease
WSP	Water safety plan
WWTPs	Waste water treatment plants

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