Review

Microbial Indicators and Their Use for Monitoring Drinking Water Quality—A Review

Xiaotong Wen [1], Feiyu Chen [2], Yixiang Lin [1], Hui Zhu [3], Fang Yuan [4], Duyi Kuang [4], Zhihui Jia [1] and Zhaokang Yuan [1,*]

[1] School of Public Health, Jiangxi Province Key Laboratory of Preventive Medicine, Nanchang University, Nanchang 330006, China; 406530517824@email.ncu.edu.cn (X.W.); linyixiang338@163.com (Y.L.); jiazhihui443@126.com (Z.J.)

[2] Center for disease control and prevention in Dongxiang district, Fuzhou 331800, China; dxaids@163.com

[3] Jiangxi Province Center for disease control and prevention, Nanchang 330006, China; ncuzhuhui@126.com

[4] Office of Public Health Studies, University of Hawaii at Mānoa, Honolulu, HI 96822, USA; fangy@hawaii.edu (F.Y.); tina_kuang@berkeley.edu (D.K.)

* Correspondence: yuanzhaokang@ncu.edu.cn; Tel.: +86-135-7693-5811

check for updates

Abstract: An increase in the incidence of water-borne human diseases, such as diarrhea and emesis, has occurred due to drinking polluted water. These water-borne diseases can lead to death, if correct treatment is not provided. Assuring that drinking water quality is safe has been a crucial challenge for public health. Water contamination with pathogenic microorganisms represents a seriously increased threat to human health. Currently, different microorganisms are being used as the primary indicator to assess water quality total coliform and *Escherichia coli* (*E. coli*) being the most common. However, increasing the occurrence of water-borne illness from sources deemed safe by the microbial standard criteria has raised the question—are these microbial indicators reliable and sensitive enough to ensure water quality? Currently, other microorganisms including bacteria, enteric virus, and protozoa are being tested and used in different countries as alternative indicators to monitor water quality. It is necessary to study the diverse water quality indicator systems used throughout the world and their efficacy with the present water quality. Although water quality standards suggest adding pathogenic microorganisms such as enteric virus as an indicator, China only uses pathogenic *E. coli*, protozoa. Pin-pointing the shortage of the current water quality indicator system in China is crucial in order to propose changes in future water quality indicator systems.

Keywords: microbial indicators; monitoring; water quality

1. Introduction

Water is an indispensable resource that humans need to live by. Unfortunately, water is also an efficient medium in the transmission of diseases. Drinking water safety is a considerable public health concern. It is reported that 4.6% of global disability-adjusted life-years (DALYs) and 3.3% of global deaths is related to water quality [1]. Millions of people die from waterborne diseases every year all over the world [2,3]. With the growth of the economy, the water contamination problem is becoming progressively more serious, consequently, influencing the quality of drinking water. According to a research, 50% of global diseases are caused by contaminated drinking water [4]. This contamination can cause more than 50 serious illnesses including digestive disease, infectious disease, skin disease, cancer and so on. In the USA, 32 drinking water-related outbreaks were reported between 2011 and 2012, accounting for at least 431 cases of illness, 102 hospitalizations and 14 deaths [5]. Almost one third of the global population is living in developing South Asia where people are unaware of

water-borne diseases and cost of illness [6]. China is ranked sixth in the world for possessing abundant water sources, however, due to the large population, water availability per capita is relatively small. Typhoid, dysentery, cholera, gastrointestinal diseases and other waterborne diseases occur frequently in China [7–9]. A wide variety of enteric bacteria and viruses have been associated with waterborne gastroenteritis [10,11]. They can cause bodily harm through drinking, inhalation, consumption and direct skin contact with water [10–12]. About 300 of 600 cities country-wide belong to an area that is short of water. In addition, the increasingly serious water pollution problem is causing a scarcity of sources. Therefore, the need to implement an effective water quality monitoring system is vital to the health of those living in China.

Water-related illnesses can be acquired by disease-causing microbes or pathogens through drinking contaminated water and participating in recreational activities such as swimming, boating, and aquatic sports in contaminated water [13]. A number of the pathogens in water come from human feces and other animal sources. These pathogens are distributed throughout the public by oral means. The assessment of microbiological quality of drinking water should aim to protect human beings from illness due to the consumption of water that may contain pathogens contributing to water-borne disease such as bacteria, virus and protozoa. A microbiological water quality indicator is generally one specific species or group of microorganisms, which can enter into water via fecal matter, but are easier to measure than the full spectrum of microorganisms that pose a risk to human health [14]. A useful indicator is known to possess the following properties: it must be widely present in the feces of humans and other warm-blooded mammals, it must be easily detected by simple methods, it must not grow in natural water, the general environment, or in water distribution systems, it must be present in the body of water of interest and lastly, the degree to which it is removed by water treatment must be comparable to other pathogens of concern [15]. At present, fecal indicator bacteria (FIB) are used to detect the presence of fecal contamination in a body of water and are also likely to be present with other intestinal pathogenic bacteria. Total coliform, fecal coliform, *E. coli* and fecal *Streptococcus* are presently being used to assess contamination in water quality management due to their simple and cost-efficient detection compared to other pathogens [16]. However, none of the bacterial indicators used today can meet all of the ideal water quality indicator criteria [17]. On the other hand, enteric virus is excreted in feces and, therefore, can be detected in wastewater. The process of wastewater treatment does not fully eliminate viral concentration and infectivity, which in turn, can contaminate receiving water presenting a health risk [18]. Literature has shown that the presence of enteric virus does not always correlate with the detection of bacterial indicators such as *E. coli* and fecal coliform [19–21]. In addition, the survival of bacteriophages in water resembles that of human enteric virus closer than other bacterial indicators presently used. Other than the above-mentioned microbiological indicator, there are several indicators used in the standard, however, these indicators vary depending on the part of the world.

This paper describes the microbiological indicators used in the water quality indicator system, compares criteria from several selected countries, reviews current water quality indicator systems in place, and lists microbiological indicators commonly used and their effectiveness with respect to the local application. The main purpose of this paper is to produce a discussion about the indicators currently used for assessing microbiological water quality, which will subsequently help generate a more successful water quality monitoring system in the future.

2. Water Quality Indicator Systems and Criteria for Selection

Currently, there are a quite a few different types of drinking water quality standards being used in many individual countries. The three are most common suggested as global standards include a) USEPA National Drinking Water Criterion, b) EC Drinking Water Quality Directive and c) WHO Drinking Water Quality Criterion, which have served as a foundation for other national water quality standards.

In 2011, WHO issued a fourth Drinking Water Quality Standard, which includes the 28 microbiological indicators that are acknowledged waterborne pathogens. It contains 12 kinds of bacteria, 8 kinds of viruses, 6 kinds of protozoa and 2 kinds of parasites [22]. The presently used

USEPA National Drinking Water Quality Standard, which was issued in 2009, is divided into two parts: the National Primary Drinking Water Regulation (NPDWRs) and National Secondary Drinking Water Regulation (NSDWRs). The NPDWRs belong to the compulsory standard for the public water supply system, with a total of seven microbial indicators used. In contrast, The EU Drinking Water Directive 98/83/EC, passed in 1998, contains only two microbial indicators. It is necessary to urge the standard to raise the requirements regarding the frequency of the indicators. For instance, several easily detectable indicators, such as *E. coli*, need to be tested more frequently and the full-scale detection needs to be done once these indicators exceed the standard [23].

This paper also conducted an in-depth analysis and comparison of water quality indicator systems from selected parts of world, specifically those used in Asian countries, European countries, the USA and Africa.

3. Different Indicator Systems for Water Quality Currently Used in Different Parts of the World

3.1. Water Quality Indicator Systems in China

The relationship between national water environment quality standards and human health has always posed a serious concern in China. Drinking water quality standards are standards that ensure the safety of drinking water and provide a basis for the department of health to monitor drinking water. The principles behind the Drinking Water Quality Standard in China are pathogenic microorganisms are not allowed in water, chemical substances and radioactive substances in water cannot pose harm to human health and good sensory properties of water.

In China, Shanghai was one of the first cities to establish local drinking water management system and the government issued Drinking Water Standards in 1950. Following the establishment of Drinking Water Standards, the Ministry of Health drew up a drinking water provisional act in 1955 and put it into effect in twelve big cities. Then in 1959, the provisional act was renamed as The Drinking Water Quality Standard by the Ministry of Health, which contained two bacterial indicators: aerobic bacterial count and total coliform [24]. With increasing incidence of illness caused by protozoa, *Giardia* and *Cryptosporidium* were then added to the standard in 2006. The specific indicators and limit values are shown in Table 1. The indicator aerobic plate count and total coliform are used to indicate microbial contamination. The former presents an overall microorganism contamination in water, the latter present the overall pathogenic microorganism contamination. However, some pathogenic microorganisms such as enteric viruses are more stable during chlorination, which can be a potential risk to harm public health. Therefore, enteric viruses are detected as an alternative indicator to assess water quality by some studies in China. For instance, Allmann Erin et al. tested for the presence of enteric viruses in recreational water in Wuhan using methods established at the University of Hawaii [25]. The study confirmed the resistance of enteric viruses to chlorination by detecting its presence in a previously approved recreational water source [25]. In addition, Huiling Chen et al. used the real-time RT-PCR method to detect enteric viruses in Shenzhen and concluded that it is necessary to reinforce continuous monitoring of enteric virus [26]. However, due to a number of reasons, enteric viruses, still, have not been used as a water quality indicator in China.

Table 1. Comparison of microbial items of major quality standards for drinking water selected.

Country or Organization	Indicator	Limitation Requirement
China	Total coliform	Not detected (MPN/100 mL or CFU/100 mL)
	Thermotolerant coliform	Not detected
	Escherichia coli	Not detected
	Plate-count bacteria	100 (CFU/mL)
	Giardia cysts	< 1/10 L
	Cryptosporidium	< 1/10 L

Table 1. *Cont.*

Country or Organization	Indicator	Limitation Requirement
WHO	Total coliform	Not detected/100 mL
	Escherichia coli	Not detected
	Thermotolerant coliform	Not detected
	Intestinal enterococci	Not detected
	Coliphage	Not detected
	Enteric Virus	Not detected
EU	Total Plate count (22 °C)	100/mL
	Total Plate count (37 °C)	20/mL
	Escherichia coli	0/250 mL
	Enterococcus	0/250 mL
	Pseudomonas aeruginosa	0/250 mL
	Clostridium perfringens	0/250 mL
USEPA	Fecal coliform and *E. coli*	Public health goals: 0
	Total coliform	0
	Cryptosporidium	0
	Viruses	0
	Giardia lamblia	0
Japan	Common bacteria	< 100/mL
	Coliforms	Not detected
Singapore	The same as WHO	
The UK	*Enterococcus*	0/mL for faucet
	Escherichia coli	
	Coliforms	0/mL for reservoir or water plant
	Escherichia coli	
France	Total Plate count (22 °C)	< 100/mL (72 h)
	Total Plate count (37 °C)	< 10/mL (24 h)
	Total coliform	0/100 mL
	Thermotolerant coliform	0/100 mL
	Streptococcus faecalis	0/100 mL
	Salmonellas	0/5 L
	Fecal phages	0/50 mL
	Enteric virus	0/10 L
Germany	*Escherichia coli*	0/100 mL for pipeline water
		100/1 mL for treated water
Russia	Plate-count bacteria	100/mL
	Total coliform	3/1000 mL
	Pathogenic microorganism	Not detected/50 mL
	Escherichia coli	Not detected/100 mL
	Enterococcus	Not detected/100 mL
	Thermotolerant coliform	Not detected/100 mL
	Rod phage	Not detected/100 mL
	Clostridium spores	Not detected/20 mL
Australia	*Escherichia coli*	Not detected/100 mL
	Total coliform	Not detected/100 mL

3.2. Indicators in Other Asia Countries

3.2.1. Indicators in Japan

The first drinking water quality standard in Japan was established in July 1955 by the Japanese Ministry of Health. This drinking water standard referred to the WHO Drinking Water Directives and was amended twice after being established. In 1993, Japan adopted general bacteria and coliform bacteria as microbial indicators. General bacteria cannot exceed ≥ 100 per mL and coliform bacteria cannot be detected in drinking water [27]. The new revision of water quality criteria was carried out in April 1st, 2015. The new microbiological indicators added to the revised standard were similar to those used in China. The revised standard states that total coliform, thermotolerant coliform bacteria, and *Escherichia coli* cannot be detected in water, and general bacteria cannot exceed ≥ 100 per mL [28].

3.2.2. Indicators in Singapore

Singapore is a tropical island nation located on the southernmost point of the Malay Peninsula in Southeast Asia [29]. Singapore is a nation without groundwater and its sources of water mainly depend on the four factors: desalination of sea water, new water, reservoir water and water supply from other countries such as Malaysia. The role of reservoir water is quite important, it not only provides a source of drinking water, but it also serves a recreational purpose. Therefore, the local government has paid more attention to the management of reservoir water sources and monitoring water quality. Singapore has been using the water quality indicator standards issued by the WHO for drinking water. The guidelines were drafted in 1965 by the WHO, which then issued a fourth guideline in 1986. A fifth guideline was issued during International Water Week in Singapore in July of 2011 [30]. The first and second guidelines, contained only two microbial indicator systems. When issuing the third guideline; however, the WHO began to pay more attention to the large variety of microbiological indicators, and added 25 new waterborne pathogen indicators. Up until 2011, the WHO has clearly suggested the risk of waterborne illnesses caused by polluted water, and listed microorganism causing the illness in the first place. Therefore, the latest guideline issued in 2011 contained 28 waterborne pathogen indicators, including 12 bacteria and 8 enteric viruses.

3.2.3. Indicators in Malaysia

In Malaysia, the main water sources are rivers and streams, which largely depend on rainfall [31]. The establishment of the drinking water quality standard in Malaysia was dependent on the standards recommended by the WHO and by Australia. According to the standard issued in 1990, the microbial indicators in Malaysia contained seven types. Total coliform and enteric viruses were chosen from the WHO's Drinking Water Quality Standards issued in 1984. Two methods are currently used to detect the total coliform: most probable number (MPN) and the membrane filtration method. These two methods have different indicator limitation requirements. The advantage of this standard is the determination of test frequency according to different water sources (Table 2).

Table 2. Microbial indicator of drinking water in Malaysia.

| Indicator | Value | Test Frequency | | | | Reference Source |
		Treated Water	Reservoir	Pipeline Water	Well Water	
Total coliform	MPN: < 10 MPN/100 mL; Membrane filtration: 3/100 mL	W	W	M	2Y	WHO
Fecal *Escherichia coli*	0/mL	W	W	M	2Y	
Fecal streptococci	0	WN	WN	WN	WN	British
Clostridia	0	WN	WN	WN	WN	
Virus	0	WN	WN	WN	WN	WHO
Protozoa	0	WN	WN	WN	WN	
Parasite	0	WN	WN	WN	WN	

W: testing at least once a week; M: testing at least once a mouth; 2Y: testing at least two years; WN: required indicator.

3.3. Indicators in European Countries

European Community (presently called "European Union"), which consisted of a total of 28 countries such as France, Germany and other countries, issued standards concerning the quality of surface water with the intention for the abstraction of drinking water in the Member States (75/440/EEC) in June 1975. Currently, two important instructions for water protection are (1) The European Union Water Quality Directive (98/83/EC) [32] and (2) The Water Framework Directive (2006/60/EC) [33,34]. In the first instruction, microbiological indicators for drinking water include *E. coli* and Enterococci, according to the directive, water is considered safe for consumption if no microorganisms are detected in 1 mL [33,34]. The directive was suggested for every member country, and each member country can amend indicators based on their own situation. The majority of countries in Europe have adopted the

above instructions; but there are several countries, such as the United Kingdom, France and Germany who have established standards based on European Union Water Quality Instructions (EUWOI). Russia, however, has established their own standards different from EUWOI and WHO.

The UK possesses a developed economy and the most abundant water sources, predominantly rivers, among the EU. In 1996, The Surface Water (Abstraction for Drinking Water; Classification) Regulations of 1996 was issued in England and Wales. The regulations required bacterial indicators stipulated, like Enterococci and *E. coli*, to be 0 per 1 mL in faucet water and coliform and *E. coli* to be 0 per 1 mL in reservoir water and water from water treatment plants [35]. This standard was consistent with European Union Water Quality Directive. In 2000, Water Supply (Water Quality) Regulations 2000 required surface water sources for drinking water to be the same as the 1996 standard. Three organizations are in charge of the system for monitoring water quality: The Office of Water Services, Drinking Water Inspectorate and Consumer Council for Water.

Predominately used Drinking Water Quality Criterion (95-368) in France refers to EU 80/778/EC, with the addition of three new amendments made in 1990, 1991 and 1995. Most index values used were the European highest tolerant level, especially the comprehensive microbiological standards. The standard contained seven microbiological pathogens, five bacteria indicators and two viruses. For bacterial indicators, both *E. coli* and fecal enterococci was required to be 0 per 100 mL, sulfite-reducing Clostridia was required to be < 1/20 mL, *Salmonella* was required to be 0/5 L and *Staphylococcus* was 0/100 mL. For viral requirements, a phage was to be 0/50 mL and no detection of enteric viruses per 10 L [36].

The majority of rivers in Germany, a country located in central Europe, are transboundary waters. Even though water shortage is not a problem plaguing Germany, water pollution is a great concern. In the 1970s, Germany experienced rapid economic development. Along with economic development came serious environmental pollution. Therefore, rather than participating in the draft of policy and rules in the EU, Germany established several standards of its own for the international rivers. Germany began enforcing France's Drinking Water Law on May 22, 1986. What is more, Germany's standard in 2000 clearly required drinking water to meet the following requirements: (1) it must be without pathogens, (2) without risk to human bodies and (3) without the majority of microorganisms. The standard for *E. coli* was 0 per 100 mL for pipeline water and 100/1 mL for treated water [37].

Russia's capital city Moscow holds three quarters of the Russian population. Drinking water in Russia mainly comes from central water supply. Biological contamination reached 27% in Evenk Autonomous Okrug, an urban-type settlement in central Russia, while other areas' biological contamination were relatively lower (2.5%–12%). The pollution sources mainly result from general bacteria (17.5%) and *E. coli* (12.5%) [38]. Russia's drinking water standards were established by their ministry of health with special characteristics. Since their standard level is similar to the international level, the Russian government formulated a national water standard: The Drinking Water Standard 2874-82, and a health standard called Standard 2.1.4.599-96 for new water plants set up after 1998. The microbial indicators of the two standards are shown in Table 3.

Table 3. Microbial indicator of drinking water in Russia.

	Unit	Standard 2874-82	Standard 2.1.4.599-96
Total Plate Count	/mL	100	50 (95%)
Total Coliform	/1000 mL	3	0 (95%)
Pathogenic microorganism	/50 mL	-	0
Rod phage	/100 mL	-	0
Clostridium spores	/20 mL	-	0
Escherichia coli	/100 mL	-	0 (95%)
Enterococcus	/100 mL	-	-
Thermotolerant coliform	/100 mL	-	0

Standard 2874-82 is the national standard; Standard 2.1.4.599-96 is health standard after 1998.

3.4. Indicators in American Countries

3.4.1. Indicators in the United States of America (USA)

The United States established the Environmental Protection Agency (EPA) on December 2nd 1970 in order to protect humans from risks caused by environmental pollution. The EPA developed documents and criteria of water quality to make sure water is safe for human use. The first water quality criterion in the United States was proposed in 1968 by the National Technical Advisory Committee (NTAC) of the department of federal government. Several microbial indicators were used for measuring recreational waters including total coliform, fecal coliform, *E. coli*, and enterococci [39]. Total coliforms and fecal coliforms were proposed by the US Environmental Protection Agency (EPA) in 1976. At that time, the EPA recommended the standards for recreational water in the Water Quality Criteria, which states "Based on a minimum of five samples taken over a 30-day period, the fecal coliform bacteria level should not exceed a log mean of 200 per 100 mL, nor should be more than 10 percent of the total samples taken during any 30-day period exceed 400 per 100 mL". This criterion, which was first proposed by the National Technical Advisory Committee (NTAC) to the Federal Water Pollution Control Administration in 1968, was adopted by nearly 95% of the states and territories in the United States. Fecal coliform appearing in drinking water and/or swimming sites indicates that the water has been polluted by human or animal feces. The coliform bacteria (total coliform and fecal coliform) do not fully reflect the occurrence of pathogens in disinfected wastewater due to their relatively high susceptibility to chemical disinfection and failure to correlate with protozoan parasites and enteric viruses [40]. In addition, coliforms are usually considered as irresponsible indicators of fecal contamination because they are able to grow in the environment [41]. Therefore, alternative indicators have been advised for evaluation of drinking water and recreational water including enteric virus, *Enterococcus*, *Clostridium perfringens* and coliphage [40]. A study by Dufour that was conducted at three marine beaches and two freshwater beaches between 1972 and 1982 revealed a direct linear relationship between swimming-associated gastroenteritis and the concentration of two bacterial indicators, enterococci and/or *E. coli* in water, but no statistical relation with fecal coliform concentration. Due to the strong relationship between the concentration of *E. coli* and/or enterococci and the rate of gastrointestinal illness, the US EPA amended the use of *E. coli* and enterococci as indicators of fecal pollution in state recreational water-quality criteria in 1986. The 1986 Recreational Water Quality Criteria (RWQC) set the water quality criteria of enterococci at geometric means of 33 and 35 CFU/100 mL [42]. For about a century, the fecal indicator bacteria (FIB) had been used to assess water quality to protect human health through monitoring fecal indicators. However, Ostrolenk et al. proposed in the year of 1947 that the enterococci may be a more suitable FIB than *E. coli* [43]. This proposition was further confirmed by studies conducted in the 1970s [43,44]. Currently, the only FIB species recommended by the US EPA is enterococci for swimming-related water, since it shows a stronger correlation with human health effects than other FIBs, such as fecal coliform and *E. coli* [44,45]. Other pathogenic indicators, like *Clostridium perfringens*, have been considered as potential indicators of water pollution in an aquatic environment [46]. Currently, water quality is monitored using National Primary Drinking Water Regulations (NPDWR) established in 2001, which is the compulsory standard. The microbial indicators in the standard are shown in Table 4. The standard includes *Cryptosporidium*, *Giardia*, *Legionella* and enteric virus, which are not common in other national standard listed. The standard also includes turbidity as a microbial indicator because high turbidity levels are usually related to the high levels of other pathogenic microorganism such as virus and bacteria [47].

Table 4. Microbial indicator in NPDWRs.

Indicator	Limitation Requirement (mg/L)	Pollutant Sources for Drinking Water
Cryptosporidium	0	Human and animal feces
Giardia	0	Human and animal feces
Total heterotrophic bacteria count	Undefined	Natural existence
Legionella	0	Common in water
Total coliform (fecal coliform and *E. coli*)	0	TC: natural existence; FC and *E. coli*: Human and animal feces
Enteric virus	0	Human and animal feces
Turbidity	Undefined	Soil washing

The USEPA recommends several standards of *E. coli* and enterococci for fresh water [42]. In October 2000, US Congress required states to adopt the USEPA criteria and establish a monitoring program [48]. However, ecology and physiology, survivability of treatment and varying number of bacteria indicators relationships to pathogens, caused some states to add monitoring parameters specific to their local concerns rather than developing the site-specific criteria for themselves. Hawaii, Southern California, Great Lakes states and Southern Florida are four different regions containing popular beach destinations in the USA [44]. In 2012 the Recreational Water Quality Criteria (RWQC) compared these states with each other and discussed regional differences in climate, water condition, distribution of animals and plants, frequency of rain or dry and even difference between coastal water and inland water [42]. Since 1958, California used a single total coliform (TC) standard as the local recreational water quality standard, however, a change in July 1999 suggested a standard requiring measurement of three indicator organisms: total coliform, fecal coliform and *E. coli* [49]. Hawaiian streams are classified as recreational waters and therefore require < 200 fecal coliform /100 mL, these water quality criteria were established in 1982. Since FIB generally occurs in ambient environment and has high concentrations in soil and water, *C. perfringens* has been used as a second recreational water quality indicator to provide better water monitoring in Hawaii.

The concern now in the US focuses on the study of enteric virus and other indicators that can reflect fecal contamination. US indicators rely solely on bacterial indicators such as total coliforms, fecal coliforms and enterococci for inferring water microbiological quality, however, bacteria indicators do not always indicate the quality of water in a situation where the water meets the bacterial standards but contains a low number of viruses.

3.4.2. Indicators in the Canada

Canada is a country in North America. It is north of the United States. Canadian drinking water supplies are generally of excellent quality. However, water in nature is never "pure". It picks up bits and pieces of everything it comes into contact with, including minerals, silt, vegetation, fertilizers and agricultural run-off. While most of these substances are harmless, some may pose a health risk. To address this risk, Health Canada works with the provincial and territorial governments to develop guidelines that set out the maximum acceptable concentrations of these substances in drinking water. These drinking water guidelines are designed to protect the health of the most vulnerable members of society, such as children and the elderly. The guidelines set out the basic parameters that every water system should strive to achieve in order to provide the cleanest, safest and most reliable drinking water possible. The most significant risks to people's health from drinking water come from microscopic organisms such as disease-causing bacteria, protozoa and viruses [50]. The guidelines that relate to these microorganisms are stringent because the associated health effects can be quite severe. They can also affect health over the long-term. The microbial indicators are shown in Table 5.

Table 5. Microbial indicator in Canada.

Parameter (Published, Reaffirmed)	Guideline	Common Sources
Enteric protozoa: Giardia and Cryptosporidium (2019)	Treatment goal: Minimum 3 log removal and/or inactivation of cysts and oocysts	Human and animal feces
Enteric viruses (2019)	Treatment goal: Minimum 4 log reduction (removal and/or inactivation) of enteric viruses	Human and animal feces
Escherichia coli (E. coli) (2012)	MAC: None detectable per 100 mL	Natural existence

MAC: maximum acceptable concentration.

3.5. Indicators in Oceanian Countries

3.5.1. Indicators in Australia

Australia is a developed country belonging to Oceania with water shortage concerns making water sources very important to the public. Therefore, in terms of the safety of drinking water, Australia established comparatively perfect indicator standards based on the three authoritative standards spelt out by the WHO, EU and USEPA. The nation managed its water sources through cities and towns. The currently used drinking water standard was revised in 1996. It is worth pointing out that the standard not only contained microbiological indicators, but also listed irregular testing microbiological indicators. There were a total of 22 microbiological indicators including bacteria, virus, protozoa, toxic algae, *E. coli* and total coliform all in which cannot be detected per 100 mL of water, including two microbiological indicators (*Escherichia coli* and total coliform), and twenty irregular testing microbiological indicators, which contain several microbiological indicators that can not be tested in water, otherwise it is necessary to adopt corresponding measures for the government and several microbiological items that have not been used as indicators due to inadequate data. Furthermore, the regulation requires microbial test to be performed once a week for surface water and once for 2 weeks for groundwater. Enteric virus: adenovirus, enterovirus, hepatitis virus, norovirus and rotavirus, all can cause gastroenteritis through contaminated drinking water [51]. Although those indicators are not given limiting values, they are listed in the standard to protect public health. Meanwhile, there were several microbiological species, which were not used as indicator due to insufficient data such as *Legionella* and *Pseudomonas*. Drinking water standards in Australia have relatively wide coverage, concerning the most microbiological indicators that may pose risk of human health.

3.5.2. Indicators in New Zealand

New Zealand is a country of two large islands (called the North and South Islands) and many much smaller islands in the South-Western Pacific Ocean. The National Environmental Standard (NES) for Sources of Human Drinking Water came into force in June 2008. The Drinking-Water Standards for New Zealand (DWSNZ) are an important resource for monitoring whether water is safe to drink. The indicator organism *Escherichia coli* (*E. coli*) is used in the DWSNZ to assess the bacterial quality of water. The bacterial quality of treated water is satisfactory if the *E. coli* concentration is less than 1 organism per 100 mL. When *E. coli* is detected in water it shows that the water has been in contact with feces: this means that pathogens may also be present [52]. There is too little information available on which to base maximum acceptable values for a viral indicator or individual viruses. A virus suitable to act as a viral indicator (similar to *E. coli* for bacteria) has yet to be found.

3.6. Indicators in Africa

Currently, Africa projects demographic changes, which will lead to fast movement in population growth and urbanization. It is predicted that 57.7% of all Africans will be living in urban areas by 2050. The infrastructure in low-income countries does not follow the pace of demographic change and urbanization, which will increase the risk of water shortage and water contamination. Nearly half

of population in Africa cannot get clean drinking water and two thirds of the population lacked the infrastructure for the management of feces. Fecal coliform has been the only indicator in the water quality criteria (WQC) in South Africa since 1984: microbial levels cannot exceed 100 CFU per 100 mL for direct contact recreational water and must be < 15 per 100 mL for drinking water. Water quality on the African continent is a challenge because it is unknown for larger parts due to very little measured data. Due to the rapidly increased population in Africa, water sources supply and public health service is scarce, with economic depression and natural hazard, leading to unsafe drinking water. In addition, there is no water quality criteria established for the whole African countries. Therefore, future concerns should focus on the establishment of water quality indicator for public health and introduction of facilities for fecal treatment.

4. Present Challenges with the Current Indicator System

Currently, drinking water standards issued by the WHO, EC and USEPA are the most advanced water quality standards on an international level and are the basis of standards for most countries around the world. Among these three standards, microbiological indicators contain two, five and seven items, respectively. The WHO listed the microbiological indicators as the important tool to monitor the safety of water quality. Microbiological pathogens are harmful to public health because they make people sick when exposed to contaminated water. This requires one to set up effective protection measures in the process of water source choosing, cleaning water methods, disinfecting and water supply. Current water quality monitoring systems is largely dependent on bacterial indicators, although there are other feasible methods adopted by several countries for detecting microbial pathogens. Bacteria such as *E. coli*, which represents fecal contamination, is an appreciated indicator to monitoring water quality. However, other pathogenic microorganisms, such as enteric viruses, is currently used in France, but have not yet accepted as alternative indicators for water quality monitoring in the majority of countries. Different countries have their own standards in terms of microbiological indicators. In the USA, drinking water standards-National Drinking Water Criteria by US EPA are relatively perfect, the enteric virus has not yet been included as an indicator for a variety of reasons including low concentration, infective nature, difficult detection and more costly for detection. Furthermore, epidemiological studies related to enteric virus resulting in waterborne diseases are short of data, which is a big concern holding current systems back from adopting enteric virus as alternative indicator. In China, studies about the enteric virus in water and studies involving bacterial indicators reflecting fecal contamination are very limited. One of the main challenges in adding water quality indicators is the variety of bacteria that can be used. For example, *Clostridium perfringens* is used in Hawaii as an alternative indicator because of its relationship with a waterborne illness in tropical areas. It is necessary to seek alternatives for monitoring water quality in different areas in China. Meanwhile, the limit value for bacterial indicator in the current standard are relatively more relaxed than countries such as Russia, therefore, more studies need to be done to analyze if the standard level used in today is effective to indicate today's water quality and fecal contamination situation. It is reported that the number of cases of waterborne illness in China remains high and 123 students were infected hepatitis A caused by polluted drinking water in the Sichuan province in 2004.

5. The Need for a New Indicator System—Future Indicator Systems in China

Concern about the drinking water safety is increasing in China due to potential exposure to microorganisms. To increase water quality, it indicates that China needs to establish a strict and more complete indicator system and strongly enforce water quality standards. The drinking water quality in China remained stagnant for about 11 years until recently. The increasing economic growth has subsequently caused water quality to decrease. The global concern for water quality is focused on microbiological indicators, therefore, it is a better way for future indicator systems to do the same by considering all possible bacterial indicators, considering enteric virus and protozoa as water

quality indicators, and lastly, reevaluating the indicator limit value associated with the present water quality situation.

6. Summary

This article reviews the information about the drinking water quality indicator systems in different parts of the world. Water quality security has been a subject of great importance across the public health field. Governments and policymakers have been highly aware of the role water plays in the transmission of diseases. The established process in the WHO Drinking Water Quality Standard is strict, containing a number of parameters and the microbiological indicators total coliform and *E. coli*. The WHO Drinking Water Quality Standards serves as a foundation for several different quality standards around the world such as standards in the Philippines and Thailand. Further, the WHO's standards have been fully adopted by many large cities such as Hong Kong and Singapore. The EU Drinking Water Quality Directive contains a total of five bacterial indicators, however, some European countries, like France, listed enteric virus as an indicator for monitoring water quality. The USEPA Drinking Water Quality relies solely on microbiological indicators, listing a total of seven indicators, including the bacterial indicators fecal coliform and *E. coli*; and protozoa such as cryptozoite and virus. According to epidemiological data, some protozoa such as *Giardia* and cryptozoite are the pathogens most associated with waterborne illness. Due to this association the USA, the UK and Australia have added both pathogens to their standards. For China to maintain its water quality, it is necessary for the country to expand their microbiological indicators by considering adding other bacteria, enteric virus and protozoa as alternative indicators in their water quality standards.

References

1. Water, Sanitation, Hygiene and Health: A Primer for Health Professionals. Geneva: World Health Organization; 2019 (WHO/CED/PHE/WSH/19.149). Licence: CC BY-NC-SA 3.0 IGO. Available online: https://apps.who.int/iris/bitstream/handle/10665/330100/WHO-CED-PHE-WSH-19.149-eng.pdf (accessed on 6 December 2019).
2. Hunter, P.R.; Neal, K. Waterborne disease. *Public Health* **1998**, *112*. [CrossRef]
3. Nyagwencha, J.M.; Kaluli, J.W.; Home, P.G.; Hunja, M. Water and water-borne diseases in north Maasba district. *Kenya Jomo Kenyatta Univ. Agric. Technol.* **2012**, *14*, 115–127.
4. Scott, J.T. *Saving Water*; Taylor & Francis: London, UK, 2013; pp. 127–131.
5. Liang, J.L.; Dziuban, E.J.; Craun, G.F.; Hill, V.; Moore, M.R.; Gelting, R.J.; Calderon, R.L.; Beach, M.J.; Roy, S.L. Surveillance for waterborne disease and outbreaks associated with drinking water and water not intended for drinking–United States, 2003–2004. *Mmwr. Surveill. Summ.* **2006**, *55*, 31–65. [PubMed]
6. Malik, A.; Yasar, A.; Tabinda, A.B.; Abubakar, M. Water-Borne Diseases, Cost of Illness and Willingness to Pay for Diseases Interventions in Rural Communities of Developing Countries. *Iran J. Public Health* **2012**, *41*, 39–49. [PubMed]

7. Hu, X.; Ding, G.; Zhang, Y.; Liu, Q.; Jiang, B.; Ni, W. Assessment on the burden of bacillary dysentery associated with floods during 2005–2009 in Zhengzhou City, China, using a time-series analysis. *J. Infect. Public Health* **2018**, *11*, 500–506. [CrossRef] [PubMed]

8. Shen, H.; Zhang, J.; Li, Y.; Xie, S.; Jiang, Y.; Wu, Y.; Ye, Y.; Yang, H.; Mo, H.; Situ, C.; et al. The 12 Gastrointestinal Pathogens Spectrum of Acute Infectious Diarrhea in a Sentinel Hospital, Shenzhen, China. *Front. Microbiol.* **2016**, *7*, 1926. [CrossRef]

9. Xu, C.; Li, Y.; Wang, J.; Xiao, G. Spatial-temporal detection of risk factors for bacillary dysentery in Beijing, Tianjin and Hebei, China. *BMC Public Health* **2017**, *17*, 743. [CrossRef]

10. Hewitt, J.; Bell, D.; Simmons, G.C.; Rivera-Aban, M.; Wolf, S.; Greening, G.E. Gastroenteritis outbreak caused by waterborne norovirus at a New Zealand ski resort. *Appl. Environ. Microbiol.* **2007**, *73*, 7853–7857. [CrossRef]

11. Benedict, K.M.; Reses, H.; Vigar, M.; Roth, D.M.; Roberts, V.A.; Mattioli, M.; Cooley, L.A.; Hilborn, E.D.; Wade, T.J.; Fullerton, K.E.; et al. Surveillance for Waterborne Disease Outbreaks Associated with Drinking Water—United States, 2013–2014. *Morb. Mortal. Wkly. Rep.* **2017**, *66*, 1216–1221. [CrossRef]

12. Forstinus, N.; Ikechukwu, N.; Emenike, M.; Christiana, A. Water and Waterborne Diseases: A Review. *Int. J. Trop. Dis. Health* **2016**, *12*, 1–14. [CrossRef]

13. Sinclair, R.G.; Jones, E.L.; Gerba, C.P. Viruses in recreational water-borne disease outbreaks: A review. *J. Appl. Microbiol.* **2009**, *107*, 1769–1780. [CrossRef] [PubMed]

14. Bosch, A. Virologists. In *Human Viruses in Water*; Elsevier: Amsterdam, The Netherlands, 2007.

15. World Health Organization. Surveillance and control of community supplies. In *Guidelines for Drinking-Water Quality*; World Health Organization: Geneva, Switzerland, 1997.

16. Meays, C.L.; Broersma, K.; Nordin, R.; Mazumder, A. Source tracking fecal bacteria in water: A critical review of current methods. *J. Environ. Manag.* **2004**, *73*, 71–79. [CrossRef] [PubMed]

17. Bitton, G. *Wastewater Microbiology*, 3rd ed.; John Wiley & Sons: New Jersey, NJ, USA, 2005.

18. Lin, J.; Ganesh, A. Water quality indicators: Bacteria, coliphages, enteric viruses. *Int. J. Environ. Health Res.* **2013**, *23*, 484–506. [CrossRef] [PubMed]

19. Morens, D.M.; Folkers, G.K.; Fauci, A.S. The challenge of emerging and re-emerging infectious diseases. *Nature* **2004**, *430*, 242–249. [CrossRef]

20. Hauri, A.M.; Schimmelpfennig, M.; Walter-Domes, M.; Letz, A.; Diedrich, S.; Lopez-Pila, J.; Schreier, E. An outbreak of viral meningitis associated with a public swimming pond. *Epidemiol. Infect.* **2005**, *133*, 291–298. [CrossRef]

21. Jurzik, L.; Hamza, I.A.; Puchert, W.; Uberla, K.; Wilhelm, M. Chemical and microbiological parameters as possible indicators for human enteric viruses in surface water. *Int. J. Hyg. Environ. Health* **2010**, *213*, 210–216. [CrossRef]

22. World Health Organization. *Guidelines for Drinking-Water Quality*, 4th ed.; World Health Organization: Geneva, Switzerland, 2011.

23. Cui, Y.; Liu, Y.; Tian, Z. Comparative review of microbial indexes of Chinese and foreign water quality standards. *J. Food Saf. Qual.* **2015**, *7*, 105–116.

24. Bai, F.L.; Yin, Y.J. Comparative Study on Hygienic Microbiological Criteria of Drinking Water in China and Developed Countries. *Chin. J. Food Hyg.* **2007**, *6*, 26–32.

25. Allmann, E.; Pan, L.; Li, L.; Li, D.J.; Wang, S.Q.; Lu, Y.A. Presence of enteroviruses in recreational water in Wuhan, China. *J. Virol. Methods* **2013**, *193*, 327–331. [CrossRef]

26. Chen, H.L.; Yang, H.; Chen, Y.J.; Wang, D.L.; Shu, B.H.; He, Y.-Q. Environmental surveillance of human enterovirus in rivers and wastewater in Shenzhen. *Chin. J. Health Lab. Tec.* **2012**, *12*, 2948–2950.

27. Magara, Y. The significance of the revised drinking water quality standard. *Jpn. J. Public Health* **1993**, *40*, 350–352.

28. Gruber, J.S.; Ercumen, A.; Colford, J.M., Jr. Coliform Bacteria as Indicators of Diarrheal Risk in Household Drinking Water: Systematic Review and Meta-Analysis. *PLoS ONE* **2014**, *9*, e107429. [CrossRef] [PubMed]

29. Li, X.X.; Koh, T.-Y.; Panda, J.; Norford, L.K. Impact of urbanization patterns on the local climate of a tropical city, Singapore: An ensemble study. *J. Geophys. Res. Atmos.* **2016**, *121*, 4386–4403. [CrossRef]

30. Zhang, Z.W.; E, X.L.; Zhang, L. Advances in Researches on Detection of Odorous Compounds in Drinking Water. *J. Environ. Health* **2010**, *2*, 171–173. [CrossRef]

31. Azrina, A.; Khoo, H.E.; Idris, M.A.; Amin, I.; Razman, M.R. Major inorganic elements in tap water samples in Peninsular Malaysia. *Malays J. Nutr.* **2011**, *17*, 271–276.

32. European Communities. Council directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. *Off. J. Eur. Communities* **1998**, *2*, 32–54.

33. European Communities. Common implementation strategy for the water framework directive(2006/60/EC). *Off. J. Eur. Communities* **2006**, *1*. [CrossRef]

34. European Communities. Council directive 2014/101/EU of 30 October 2014 amending Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for Community action in the field of water policy. *Off. J. Eur. Communities* **2014**, *3*, 32–35.

35. Guidance on the Water Supply (Water Quality) Regulations 2000. In *Drinking Water Inspectorate*; Wales: Wales, UK, 2001. Available online: http://www.legislation.gov.uk/uksi/2000/3184/contents/made (accessed on 6 December 2019).

36. The European Commission. *The Quality of Drinking Water in the European Union*; 2008; Available online: https://circabc.europa.eu/sd/a/58220131-ecc4-49f9-9ad1-bbb6e9e79578/report1999-2001.pdf (accessed on 6 December 2019).

37. Seifert, K.; Lyons, T.C. Water quality law in Federal Republic of Germany. *J. Water Resour. Plan. Manag. Div. Am. Soc. Civ. Eng.* **1976**, *102*, 23–33.

38. Wang, F.; Chen, Y.H.; Huang, T.; Chen, P.H.; Rufina, M. Comparison of the current sanitation situation and quality standards of drinking water between China and Russia. *Pract. Prev. Med.* **2015**, *10*, 79–81.

39. Shibata, T.; Solo-Gabriele, H.M.; Fleming, L.E.; Elmir, S. Monitoring marine recreational water quality using multiple microbial indicators in an urban tropical environment. *Water Res.* **2004**, *38*, 3119–3131. [CrossRef] [PubMed]

40. Harwood, V.J.; Levine, A.D.; Scott, T.M.; Chivukula, V.; Lukasik, J.; Farrah, S.R.; Rose, J.B. Validity of the indicator organism paradigm for pathogen reduction in reclaimed water and public health protection. *Appl. Environ. Microbiol.* **2005**, *71*, 3163–3170. [CrossRef] [PubMed]

41. Savichtcheva, O.; Okabe, S. Alternative indicators of fecal pollution: Relations with pathogens and conventional indicators, current methodologies for direct pathogen monitoring and future application perspectives. *Water Res.* **2006**, *40*, 2463–2476. [CrossRef] [PubMed]

42. Fujioka, R.S.; Solo-Gabriele, H.M.; Byappanahalli, M.N.; Kirs, M.U.S. Recreational Water Quality Criteria: A Vision for the Future. *Int. J. Environ. Res. Public Health* **2015**, *12*, 7752–7776. [CrossRef]

43. Ostrolenk, M.; Kramer, N.; Cleverdon, R.C. Comparative Studies of Enterococci and Escherichia coli as Indices of Pollution. *J. Bacteriol.* **1947**, *53*, 197–203. [CrossRef]

44. Cabelli, V.J.; Dufour, A.P.; Levin, M.A.; Mccabe, L.J.; Haberman, P.W. Relationship of microbial indicators to health effects at marine bathing beaches. *Am. J. Public Health* **1979**, *69*, 690–696. [CrossRef]

45. Byappanahalli, M.N.; Nevers, M.B.; Korajkic, A.; Staley, Z.R.; Harwood, V.J. Enterococci in the environment. *Microbiol. Mol. Biol. Rev.* **2012**, *76*, 685–706. [CrossRef]

46. Wade, T.J.; Calderon, R.L.; Sams, E.; Beach, M.; Brenner, K.P.; Williams, A.H.; Dufour, A.P. Rapidly measured indicators of recreational water quality are predictive of swimming-associated gastrointestinal illness. *Environ. Health Perspect* **2006**, *114*, 24–28. [CrossRef]

47. Sobsey, M.D. Inactivation of Healthrelated Microorganisms in Water by Disinfection Processes. *J. Am. Water Work. Assoc.* **1972**, *64*, 596–602.

48. Fogarty, L.R.; Haack, S.K.; Wolcott, M.J.; Whitman, R.L. Abundance and characteristics of the recreational water quality indicator bacteria Escherichia coli and enterococci in gull faeces. *J. Appl. Microbiol.* **2003**, *94*, 865–878. [CrossRef]

49. Noble, R.T.; Moore, D.F.; Leecaster, M.K.; McGee, C.D.; Weisberg, S.B. Comparison of total coliform, fecal coliform, and enterococcus bacterial indicator response for ocean recreational water quality testing. *Water Res.* **2003**, *37*, 1637–1643. [CrossRef]

50. Canada, H. Guidelines for Canadian Drinking Water Quality—Summary Table. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario. Available online: https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table.html (accessed on 6 December 2019).

51. National Health and Medical Research Council. *Australian Drinking Water Guidelines 6 National Water Quality Management Strategy*; National Health and Medical Research Council: Canberra, Australia, 2017.

52. Environmental Science and Research Limited. *A Guide to the Ministry of Health Drinking-Water Standards for New Zealand*; Environmental Science and Research Limited: Wellington, New Zealand, 2008; p. 43.