Potable Water Quality Standards and Regulations: A Historical and World Overview

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Abstract Since ancient times humans have understood the importance of clean drinking water and have used various techniques to improve its quality. In modern times, municipal and public water treatment systems began providing water to consumers worldwide, and safe drinking water became first a public health issue and then a human rights issue. Many countries have drinking water regulations and have set standards for maximum allowable levels of contaminants in drinking water. In wealthier nations, people have been living for nearly a century in a "water paradise," with inexpensive and safe drinking water readily available in most places. In many developing countries, people lack access to safe water; waterborne disease is a major cause of death, especially among children under 5; and countries that have set drinking water standards often lack the resources to implement or enforce them. The World Health Organization (WHO) has developed a set of standards and guidelines for implementation to help countries lacking regulations and, along with the United Nations Children's Fund (UNICEF), has set goals aimed at providing all people with safe drinking water, especially focused on the poor and disadvantaged of the world. This chapter provides an overview of drinking water in ancient times, the development of water treatment systems, the evolution of water analysis and drinking water standards, examples of current standards and regulations around the world, emerging standards and regulatory challenges, and global drinking water goals.

Keywords Drinking water • Historical perspectives on drinking water • History of water treatment • Evolution of drinking water standards and regulations • Emerging challenges • Global drinking water goals

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1 Introduction

I begin this chapter with a personal experience. Blacksburg, Virginia, where I live, is located approximately 20 km from an industrial complex. In 2013, I attended a meeting hosted by the Agency for Toxic Substances and Disease Registry (ATSDR), a U.S. public health agency. The meeting was called for community members concerned about toxins that the complex had been discharging into the New River, the major source of drinking water for surrounding towns.

Of the more than 50 people in the elementary school gymnasium where the meeting was held, only half were simply local residents. Others attending included representatives from federal, state, and local agencies, such as the U.S. Environmental Protection Agency (EPA), the county school board, the U.S. congressional district representative's office, the Virginia Department of Environmental Quality, and the Virginia Department of Health. In addition to these government representatives, members of several local and national groups, including the Sierra Club, the National Committee for the New River, two local and regional newspapers, a local radio station, a nearby university, and a citizens' group called Environmental Patriots, were present. Finally, representatives from the industrial complex, including members of its environmental restoration program and its public relations department, also participated in the meeting.

I attended this meeting as a "concerned citizen" but also as a scientist and science writer interested in the communication of risks and regulations to the public. I was just beginning the research for this chapter, and I describe the scene here because the meeting illustrates a great deal about drinking water in the United States and in other developed countries. Citizens of the developed world want safe and clean drinking water, and for the most part they have it. Multiple local, state, and federal agencies, citizens' groups, and industries are involved in regulating and monitoring what goes into water sources and what is in drinking water when it is delivered to homes and other buildings.

In the developed world, the past century has been an "aquatic paradise," with drinking water becoming abundant, cheap, and safe [1]. Most of the people living in this water paradise take drinking water availability for granted, as it always flows out of the faucet when they need it. So abundant and inexpensive is the water in many areas of the United States, for example, that 97 % of treated water, safe for consumption and cooking, is used for other purposes—flushing the toilet, watering the lawn, doing the laundry, or washing the car [2].

In less wealthy and developing countries, the drinking water situation is very different. The disparity in water availability, reliability, and quality between the developed world and developing countries is enormous. Around the world, almost one billion people—more than a tenth of the world's population—lack access to safe drinking water [3]. Approximately 780 million people drink water from "unimproved" sources—an unprotected dug well or spring, for example, or a polluted river [4]. In addition, millions more people using water from so-called improved sources also are drinking contaminated water, as "improved" does not necessarily mean the water is contaminant free [4]. Half the world's population depends on small community water suppliers for drinking water, and many small systems lack the financial resources to properly treat and monitor water quality [5].

According to the World Health Organization (WHO), about 2 million deaths each year can be attributed to unsafe water [5]. More children under the age of five die from diarrheal diseases—most related to unsafe drinking water—than die from malaria and HIV/AIDS combined. In 2011, 58 countries around the world reported nearly 600,000 cases of waterborne diseases—cholera, dysentery, typhoid, guinea worm infection, and other diseases caused by lack of access to safe drinking water.

In the twenty-first century, we are moving into an era of water scarcity that will be likely to affect most countries, in both the developing and the developed world [1]. Some of the drinking water challenges facing humanity include drought, overwithdrawal from aquifers, high demand due to population growth, water pollution, and increased competition for water from industry and agriculture. In addition to the basic issue of disease organisms in water, millions of people worldwide are exposed to chemical pollutants, both natural and man-made. In Bangladesh, Argentina, Chile, China, India, Mexico, and the United States, inorganic arsenic occurring naturally in groundwater presents a public health threat [6]. Naturally occurring fluoride also causes human health problems in some areas. The rate at which we introduce new man-made chemicals into the environment is much greater than the rate at which we evaluate their toxicity, creating significant water problems around the world [7]. And projected climate changes are expected to change water availability patterns and increase outbreaks of waterborne diseases [8].

How do we know our drinking water is safe? Unfortunately, that question is very hard to answer, because "safe" is a relative term. But in an attempt to provide safe water, many countries have adopted drinking water standards and regulations based on the health effects of exposure to contaminants. Some countries have set standards but have not fully implemented them. Others lack the resources to provide citizens with drinking water, safe or otherwise.

To understand today's drinking water standards and regulations, it is useful to have some knowledge about the historical, technical, and social aspects of drinking water. This chapter provides an overview of drinking water in the ancient world, the development of water treatment systems and of methods of water analysis, the evolution of drinking water standards and regulations around the globe, emerging contaminants and regulatory challenges facing the world, and global drinking water goals.

2 Drinking Water in the Ancient World

In many areas of the world today, water is transported from source to home in jugs or buckets. In developed countries, where most people have access to piped water in their homes, water is still transported in bottles or canteens for road trips, sports events, hikes, and picnics. This use of containers for carrying water is not new; in fact, it is possible that humans have been using some form of water bottle for many thousands of years. Scientists know from archaeological evidence that 60,000 years ago people in southern Africa punctured ostrich eggs and decorated them [9]. Contemporary hunter-gatherers use similarly punctured ostrich shells as canteens to carry water into the Kalahari, and scientists speculate that the ancient shell fragments they have found are the remainders of canteens used 60,000 years ago.

While not much is known about the details of the use of water in prehistoric times, we do know that early humans lived near water sources, that their survival and emigration patterns were affected by access to water, and that they developed methods of carrying and storing water. Drinking water has played a role in the geography of human settlement, in politics, in economics, in epidemics, and in religions.

Nomadic peoples traveled from water source to water source and moved on when the cleanliness of the water supply was endangered by the encampment. When permanent settlements began to develop, they did so near sources of water, such as the City of Jericho's establishment near springs sometime between 8000 BCE and 7000 BCE [10]. Humans could not live in densely populated settlements without solving the problems of waste removal, drainage, and a reliable water supply, and settlement sites were selected for their springs, which were protected by the construction of "fountain houses" over them [11]. In Egypt, evidence of 5,000-year-old wells has been found, and in Mesopotamia stone channels directed the flow of rainwater some 4,000 years ago [10]. Additionally, the private houses in Ur in Mesopotamia had "water closets" and rainwater drainage systems [10]. In Pakistan, ancient wells and water pipes can still be found, and many houses there thousands of years ago had individual indoor wells [10].

According to water historian and engineer M. N. Baker (1948), Egyptian inscriptions and Sanskrit medical lore give us our earliest recorded information about water use and treatment in ancient times [12]. From as long ago as 2000 BCE, written documents provide evidence that humans had opinions about how water should be treated, including methods such as storing water in copper containers; exposing it to sunlight; filtering it through charcoal; boiling it if "foul"; dipping pieces of copper into it; and filtering it through sand and coarse gravel. In Egypt, drawings on the walls of tombs from as long ago as 1500 BCE show various sophisticated apparatuses for clarifying liquids, some using siphons and others using settling tanks and wicks.

Many examples indicate that humans have long been sensitive to the taste, odor, and appearance of water; aware that water was connected to human health; and sophisticated in their approach to collecting, treating, and storing water. A sampling of such evidence follows:

- 3000 BCE: The Indus civilization had bathrooms in houses and sewers in streets [11], evidence that those who lived there understood that wastewater needed to be kept separate from drinking water.

- 2000 BCE: In India, water purification techniques included boiling, keeping in direct sunlight, and filtering through sand [10]. The Minoans of Crete had flush lavatories and running water in their homes [11].
- 1500 BCE: A well in Cairo was 90 m deep, an indication that people understood that having access to clean water was worth a lot of work [10].
- Ninth century BCE: In Sparta, a special cup was used that both hid the color of the water and caused mud to stick to its sides, improving the quality of the water right in the cup [12].
- Seventh century BCE: Greeks were building long-distance water supply lines and wastewater drainage channels [11].
- Sixth century BCE: In Persia, King Cyrus the Great hauled water in silver flagons in mule-drawn carts when he went to war. The water was boiled ahead of time to "make it keep," according to a Greek writer in the third and second centuries [12]. In Athens, wells of 45–60 feet were common.
- 460–354 BCE: Hippocrates, the "father of medicine," recognized the importance of water to health and that various kinds of water differed in their health effects. He described water in terms we understand today: "marshy and soft," "hard and running from. . .rocky situations," and "saltish and unfit for cooking" [12].
- 384–322 BCE: Aristotle described a method for filtering water through clay [10].
- 312 BCE: The first aqueduct for bringing water to Rome was built, followed by a second in 272 BCE that also had a settling tank [13].
- 168 BCE: An account of a trip on the Nile described how the travelers made river water into drinking water by exposing it to sun and air, straining it, allowing it to settle overnight, and cooling it with evaporation by storing it in jars that slaves kept wet [12].
- 116–27 BCE: Varro listed water types by quality, spring water topping the list. It was followed by running water from a stream, water from a covered rainwater cistern, and finally water from an open-air pond [13].
- First century BCE: Vitruvius wrote about where to find water and described various kinds, including "muddy and not sweet," "the best taste," "a good taste," "colder and more wholesome," "salt, heavy-bodied, tepid, and ill-flavored" [11].
- 47 BCE: Underground aqueducts that brought water from the Nile to cisterns in which water was allowed to settle before use were discovered by Caesar to be the water supply for the city of Alexandria [12].
- 15 BCE: A three-part cistern was in use, allowing water to move from one tank to another, with the purification associated with settling taking place in each compartment [12].
- 23–79 CE: Pliny the Elder wrote his *Natural History* and had much to say about water, including that medical men condemned all "stagnant, sluggish waters" and agreed that running water was better for one's health; cistern water was thought to be "bad for the bowels and throat" and held the record for most slime and "numerous insects of a disgusting nature" [14].
- 50 CE: In a document titled *Purification of Water*, Athenaeus of Attilia described channels that brought clean water from lakes or the sea, jars called "stacta" that

were used for purifying water, and single, double, and triple filtration systems [12].

- 97 CE: Frontinus became the water commissioner of Rome and wrote *Two Books on the Water Supply of Rome*, which Baker calls "the first known detailed description of a water works system" [12].
- First century CE: Macerated laurel, pounded barley, and bruised coral were all in use to improve bad-tasting water or to turn rainwater into drinking water. Pliny recommended the use of lime and "aluminous earth" as precipitants, a technique used in municipal water treatment plants many centuries later [12]. In Sri Lanka, reservoirs stored water for later use, as did "village tanks," "large tanks," and "feeder tanks" [15].
- 421 CE: Venice was founded and for the next 13 centuries used rainwater that was collected and stored in cisterns as drinking water; most of these cisterns were surrounded by sand filters. Drinking water was also brought from the mainland by boat, which gave the water a "pitch and tar" taste that Venetians learned could be removed by sand filtration [12].
- Fifth century CE: Greek cities recognized three kinds of water: drinking water, which was carried from flowing fountains or from springs; bathing and cleaning water, which was stored in cisterns in houses and was used for crafts and for livestock as well; and "gray water," which was wastewater that had not been contaminated by fecal material and so could be used in other ways [11].
- Seventh century CE: The Greek physician Aegineta prescribed straining or boiling for impure or bad-smelling water [12].
- Eighth century CE: The Arabian alchemist Geber described distillation [12].
- Eleventh century CE: The Persian physician Avicenna advised travelers to boil water or to strain it through cloth before drinking it [12].

This list shows that in many ways, little has changed over the centuries with regard to the desire for clean drinking water and the need for treatment: people depended on taste, odor, and turbidity to determine whether to drink water several thousand years ago, and people today do not like to drink smelly, bad-tasting, cloudy water [7]. Cleaning up water through settling, filtering, and disinfecting also has been taking place for millennia.

3 The Impact of Human Activities on Drinking Water Sources

Historical and archaeological evidence suggests that for as long as people have been living in settlements, they have been aware that this way of living requires a convenient source of clean drinking water and a system for disposing of wastes. Despite this understanding, waste disposal often has led to the fouling of drinking water sources, and human population growth has exacerbated the problem.

Human waste in drinking water sources continues to be a problem in many parts of the world today. For large segments of the human population, toilets are not available, and "open defecation" creates major sanitation problems in some areas of the globe, affecting drinking water sources. The leader of India's Ministry of Rural Development, Jairam Ramesh, recognizes the Bill and Melinda Gates Foundation's "reinvent the toilet" challenge as a step toward solving the problem [16]. Ending open defecation is a major goal of WHO and of the United Nations Children's Fund (UNICEF) [17].

Animal waste intrusion in bodies of water used as drinking water sources became an increasingly significant problem when humans began domesticating animals. Domestic animal waste continues to be a problem today, contributing 85 % of the world's fecal material [18]. The intensive use of chemical fertilizers and pesticides for crop production has significantly impacted the quality of surface and ground waters in many regions of the world.

Urbanization has had and continues to have a major impact on drinking water sources. By the beginning of the nineteenth century, the rivers and wells of many countries had been polluted by both domestic sewage outflows and industrial activities [19], and stormwater runoff carrying lawn chemicals, oil, sediments, and other pollutants from settled areas is the major source of water contamination in many places today [2]. Historian Christopher Hamlin notes that early in the nineteenth century, British people were drinking what was "little better than dilute sewage" [20]. Open defecation is a public health problem today, but discharging untreated sewage into rivers immediately upstream from the intakes for drinking water, as often happened in England and elsewhere [20, 21], guarantees the addition of contaminants to drinking water sources. Before the demonstration by Dr. John Snow in 1855 that cholera is a waterborne disease and the discovery by Louis Pasteur in the late 1880s that microscopic organisms are able to cause disease and can live in water [22], people did not understand the dangers of sewage discharge into water bodies.

In the United States, during the 1700s, industrial and urban wastewater discharge and agricultural runoff caused enough degradation of surface waters that in the 1800s people began voicing concerns about the effects of these human activities on water quality [5]. In 1907, it was demonstrated that some of these wastes had toxic effects on aquatic organisms; and as we know now, such wastes also can be harmful to humans. At present, pesticides, chemical fertilizers, and animal wastes from agriculture; drugs, bacteria, and other contaminants from human wastes; and chemical effluents from industries affect drinking water sources all over the world. Some 2,000 new chemicals are introduced into the environment every year, and many of them end up in natural water systems [5].

4 The Evolution of Municipal Drinking Water Treatment Systems

The earliest methods for improving drinking water quality suggest that humans connected drinking water with health long before there was a scientific understanding of what might be in water and of the problems associated with contaminated water. This connection, and a desire for water that at least looked, smelled, and tasted good, motivated people to engineer ways of treating drinking water, and water treatment as an organized municipal-level phenomenon was the eventual result. Water historian M. N. Baker [12] used an impressive array of primary sources to produce his book *The quest for pure water: The history of water purification from the earliest records to the twentieth century*, and this section provides a brief overview of that information as it applies to municipal water treatment.

4.1 Early Water Treatment Methods

Many of the modern water treatment methods for improving the taste, smell, look, and safety of water are essentially the same as they have been throughout history. That is not to say that no improvements have been made; it's just that most methods of water treatment in use today are based on principles developed centuries or even longer ago. A few examples of ancient water treatment methods are illustrated below.

According to Baker [12], coagulation has been practiced since ancient times [12]. Coagulants that are have been used include alum (aluminum sulfate), lime and iron used together, lime alone, almonds, beans and nuts, toasted biscuits, and Indian meal. A manuscript from 400 CE, summarizing ancient Aryan and Indic lore, tells about a nut that travelers used to clarify marsh waters, and alum was used for small-scale water clarification in ancient China [12]. At large industrial plants, coagulation has been in use since the early 1800s. Municipal water suppliers began incorporating coagulation into water treatment systems toward the end of the 1800s.

Sedimentation, the use of settling reservoirs to clarify turbid water, was used centuries ago. The earliest known city to use sedimentation was Laodicea, in what is now Turkey, about 260 BCE [12]. Vitruvius wrote about cisterns in 15 BCE: "If such constructions are in two compartments or in three so as to insure clearing by changing from one to another, they will make the water much more wholesome and sweeter to use" [12].

Disinfection has been around since civilization began, with the earliest written mention of disinfection via boiling in Herodotus (484–425 BCE) [12]. Other disinfection methods used through the centuries include heat, copper, silver, chlorine, ozone, and ultraviolet rays. A Sanskrit document from 2000 BCE advises exposing water to sunlight and filtering it through charcoal [12]. Chlorination was put into practice at the beginning of the 1900s both in Belgium and in the United States [2, 23] and is used all over the world today. The Arabian chemist Geber (or Jabir), born in 721 or 722 CE, is thought to have written the first known treatise on distillation [12]. Aristotle explained that pure water could be obtained from sea water through evaporation, and many other ancient writers told readers that the vapor rising from water is more pure than the water itself.

Well before municipal treatment plants were common, smaller scale filtration units and other methods were being invented and used. Baker (1948) describes historic advances in the recognition of contaminants, including mineral salts and algae, and what to do about them. Sir Francis Bacon described boiling, distillation, coagulation, and filtration in a 1627 work on drinking water, and multi-section sand and pebble filters were both used and described in the late 1600s in Europe. Records from the 1700s show the use of techniques for sedimentation, softening, filtering, and distilling, along with the use of alum as a coagulant. In 1703 a French scientist proposed a plan for a rainwater cistern with a sand filter and a light-excluding cover to prevent the growth of what he referred to as “a greenish kind of moss.” This, he said, would ensure an excellent source of drinking water, equivalent to spring water.

Prior to 1711, it was thought by many that drinking water could be made from seawater by filtration. However, an experiment in which seawater was filtered 15 times through clay and sand demonstrated that it could not. From a 1732 publication, Baker found evidence of using sedimentation, exposure to the sun, and sand filtration to purify water, including specific directions for washing the sand periodically. Baker found multiple references to using various types of filters in published works throughout the 1700s: filters made of layers of sand between perforated copper plates; layers of stone; sand and pulverized glass; filtering paper; wicks of cotton; and bags of woolen, linen, or flannel cloth.

Baker also recounts the use of various additives to make potable water in the 1700s, such as burned biscuits, powdered ginger, vinegar, cream of tartar, ashes, alum, “oil of sulfur,” and lime. Although Baker found no evidence that the water supply for any city had been filtered before 1769, he noted a statement in a book published that year suggesting that water supplies for “great towns” should be purified and that common methods of filtering and softening should be used to prevent the diseases bad water could cause. Evidence of a man-made filtration system in use in Senegal was reported in 1776; pits dug into sand allowed filtered river water to collect and be stored. The efficacy of charcoal use to purify and deodorize water was established by a paper published in 1790.

4.2 The European Experience

Baker’s history describes early attempts to use filtration techniques in European towns and cities. In France, filters were patented, manufactured, and sold for individual household use in 1750. In the decades to follow, a filter plant for the provision of larger quantities of drinking water was built, and filtered water in sealed containers was delivered to city residents. French inventor Joseph Amy was the first person to be issued a patent for a filter from any country, Baker reports, and Amy also published the first book on filters in the world, both in the mid-1700s. Amy wrote that layers of sand in copper containers had been used as household water filters since the 1550s. Later filters used in France contained sponge, charcoal, wool, sand, crushed sandstone, and gravel. People also were filtering water in their homes in England; a British patent was granted in 1790 to Mrs. Johanna Hempel, a Chelsea potter, for “a composition of materials and a means of manufacturing it into vessels” that would allow for the filtration of water and other liquids [12].

Baker’s historical overview tells us that Paisley, Scotland, in 1804 completed the first filter to supply water for a whole town—not through pipes, but delivered to customers by horse and wagon. A few years later, Glasgow began using pipes to deliver filtered water to customers. River water posed special problems, with flood waters clogging treatment systems, and in the early 1800s Glasgow held a filter design competition that attracted 22 plans. In 1810 a submerged pipeline and a filter gallery, each the first of its kind, were installed, the pipeline bringing water from a sand and gravel peninsula and a set of springs across the river from the city.

Throughout the 1800s, new and remodeled designs were built and tried out. A “self-cleaning” design solved a number of problems that had plagued city filter systems. Despite this, the use of municipal water treatment systems grew slowly. Between 1842 and 1870, a few cities in France built filters that were washed by upward reverse-flow water; Marseilles, Tours, and Dunkirk all installed such filters, joining Nantes in the distinction of being the only cities in France that filtered their entire municipal water supply before 1890.

Although filtration systems of a variety of designs were being built and used, Baker notes that at the beginning of the 1800s the understanding of how filtration worked was “vague and sometimes contradictory” [12]. For example, although most filters eventually came to be made up of sand and gravel arranged by size, with the finest sand at the top of the filter and the coarsest gravel or rock at the bottom, some were used by passing the water up from the bottom and others were used by passing the water down through the filter from the top. During the 1800s the goals of filtration also expanded from the removal of suspended material to a focus on organic matter. Before bacteria were known to exist, sand and gravel filters were removing microorganisms from drinking water. This benefit was proven toward the end of the century, by which time the function of filtration was well understood.

4.3 The North American Experience

Similar experiments in filtration were under way in North America, with the first—and unsuccessful—city filtration system in the United States in use in Richmond, Virginia, in 1832, and a charcoal, sand, and gravel filter at Elizabeth, New Jersey, in

1855, according to Baker. Kingston, Ontario, built a lake-intake filter in 1849, and Hamilton, Ontario, added one in 1859, but Baker reports that neither was successful [12]. In 1860, the United States had only 136 waterworks and Canada only 10. Not until 40 years after the first slow sand filters had been constructed in England and Continental Europe were they built in North America. Poughkeepsie, New York, built the country's first slow sand filter and began operating it in 1872 [12]. The city's 20,000 residents benefited greatly because the drinking water supply came from the Hudson River, which was often turbid, brackish, and full of raw sewage. In 1893 a water filtration plant for the city of Lawrence, Massachusetts, was opened, and the incidence of typhoid in the town was markedly reduced, a result that Baker says greatly increased confidence in water filtration in America.

The United States made three major contributions to municipal water treatment, according to Baker: (1) developing the rapid filter; (2) improving slow sand filter techniques; and (3) using chlorination to disinfect drinking water. By the end of 1900 there were 20 slow sand filters in the United States and 5 in Canada. Rapid filters were much more popular—by 1940 the United States had 2,275 rapid filter plants compared to 100 slow sand filtration plants. Canada at that time had 120 rapid filters and 12 slow sand filters.

Early attempts at filtration, before the advent of chlorine disinfection, did not always function as well as intended. In America, for example, throughout the nineteenth century, city residents relied on bottled water whenever they feared contamination of city water supplies [23]. During the first decades of the 1900s, Middlekerke in Belgium and Jersey City and Philadelphia in the United States began using chlorine to kill waterborne bacteria [2, 23]. By the early 1940s nearly all U.S. water treatment plants were chlorinating their water, effectively eliminating cholera and typhoid and the bottled water industry as well [2, 23].

4.4 Modern Water Treatment Methods

Today's modern treatment systems typically include a pretreatment step, flocculation, filtration, chemical treatment, and disinfection [7]. The use of organic flocculants and chlorine, bromine, or chloramines for disinfection removes contaminants but can add carcinogens to water. Other advanced treatment methods include the use of activated carbon for organic chemical removal, ion exchange for inorganic metals, ozonation for disinfection and to oxidize organic constituents, ultraviolet light for bacterial and viral control, reverse osmosis to remove organic and inorganic compounds, and enhanced coagulation [7]. The science and technology of water treatment is continuously evolving. For details, the reader is referred to current textbooks and the scientific literature.

5 The Evolution of Methods for Water Analysis

Water is a universal solvent. In addition, many different materials can be suspended in water, and many organisms live in water. For most of human history and prehistory, however, we have not known what is dissolved, suspended, or living in water; when early methods of treating and filtering water were developed, humans did not know what was being removed. When Leeuwenhoek first observed living creatures through a microscope lens, it must have stunned him and everyone he told: "In the year 1675, I discovered living creatures in Rain water, which had stood but a few days in a new earthen pot. . .[some] put forth two little horns, continually moving themselves." [12] These microscopic organisms were called "living Atoms," or "Animalcula."

5.1 Chemical Analyses

Historian Christopher Hamlin has noted that the analysis of water for its non-water components was used by the proprietors of "healing springs" to advertise the water's medicinal properties long before such analysis was used by governments or water treatment plant operators to assure citizens that water was safe to drink [20]. Mineral springs and "baths" in Europe were very competitive, and the proprietors of such healing waters used mineral analyses printed on advertising cards to draw in customers. Historical evidence traces this as far back as the fifteenth century, when early spas were promoted by the odor, taste, color, and temperature of their waters.

A history of bottled spring waters explains that "taking the waters" at these healing springs was guaranteed to make you feel better if what you were suffering from was related to your normal source of drinking water, as ". . .filthy drinking water was the norm in most of Europe from the middle ages right up to the twentieth century" [23]. If you planned a 3-month stay, you might indeed find that your dysentery or chronic intestinal upsets would clear up, simply because you were no longer drinking contaminated water. But the beneficial health effects were attributed to healing qualities in the spring waters, not to the absence of health-endangering contaminants.

Those first four "healing" characteristics of water—odor, taste, color, and temperature—were augmented using tests with reagents, some of which dated back to Pliny, who used oak galls to test for iron in water [20]. Other tests, similarly based on a change of color, were developed in the 1500s, and as far back as the thirteenth century Italian physicians were testing the residues left from the evaporation of water. Hamlin also points out that the dyeing of cloth was a well-developed technology many centuries ago, and chemical knowledge gained from dyeing contributed to the development of water analysis [20].

5.2 Early Attempts at Measuring Contaminants

In 1784, Torbern Bergman published *Physical and Chemical Essays*, a work that prescribed three methods of testing water:

- Examine its physical properties (taste, texture, odor, rate of heating and cooling, and sound).
- Use reagents to do a qualitative assessment.
- Evaporate a large quantity of water and then measure the evaporative residue [20].

Before about 1860, Hamlin tells us, there was nothing comparable to the *Standard Methods* available now for the analysis of drinking water [20]. The mineral analyses that were used to promote the healing properties of the baths and spas were applied to drinking water analysis beginning in the middle of the nineteenth century in England.

Compared to today's science, chemistry a century or two ago was fairly primitive. But the development of chemistry as a discipline during the 1800s was a critical part of the development of our contemporary approach to producing safe water. Hamlin explains [20]: "We might be tempted to see [early chemists] as charlatans, for prior to the 1890s they were claiming to be analyzing water without (as we know now) any correct (or even very definite) idea of what components or contaminants of waters had active effects. . .[but] we need to recognize that the authority sold by these chemists was a real and a valued commodity."

5.3 Linking Human Disease to Bacteria

Limitations in the understanding of what caused disease limited the usefulness of early water analyses. In 1866, for example, when a cholera epidemic swept London, chemical analysis showed that the city's water was safe to drink because chemical assays could not detect bacteria. Without accurate information about what can be dissolved in, or living in, water, all sorts of ideas were proposed in the 1800s. According to Hamlin, the smelly products of anaerobic decay got the most attention from scientists for a while, and it was thought that poisons were produced by matter decomposing in water [20]. These poisons, scientists thought, either weakened a person's resistance to disease or acted to cause disease. When microscopes allowed researchers to see some of water's living inhabitants, the images went viral in a nineteenth-century way: pub owners posted drawings of the "wriggling monsters" in shop windows to encourage consumers to drink ales and beers at the pub instead of drinking London's water, which was swarming "with living animalcules" [20].

Although in the mid-1800s people were beginning to suspect that water could be harmful and in some cases demonstrating *how* it could be harmful, chemists also were beginning to admit that whatever caused drinking water to be unsafe was not something they knew how to detect or measure [20]. In 1865, when Edward Frankland was appointed to serve as the official analyst of the London water supply, the city was using permanganate disinfection and filtration through animal charcoal, but Frankland began to lose confidence in these methods. After presenting evidence that "the cholera poison" might be something that scientists would be unable to detect by chemical means, Frankland began using inorganic nitrogen compounds to calculate what he called the "previous sewage contamination" (PSC) of water [20].

Similarly, although just what caused cholera was still unclear, after Snow demonstrated in the 1850s that it was linked to water supplies [23], people were beginning to accept that various diseases might each be caused "by a unique morbid poison" [20]. The concept of the "germ" arose at this time. The word "germ" was already in use to mean an egg or a seed, an extremely tiny particle that grew into something larger, and this was the first application of the word to disease. Scientists began to understand that just one of the tiny things—a germ—could become many, contaminate an entire water supply, and cause disease [20]. Hamlin describes the German bacteriologist Robert Koch's development of methods for culturing water-dwelling bacteria in a solid medium in the1880s as a major breakthrough—it provided a reasonably reliable technique to detect potentially dangerous bacteria in a water supply [20]. Koch's new culturing techniques also allowed the efficacy of filtration systems to be demonstrated, with tests showing many bacteria before filtration and hardly any after filtration. After many years of work on water-dwelling bacteria, Percy Frankland and his wife Grace Toynbee Frankland published "Micro-organisms in water: Their significance, identification, and removal," which combined their research with a review of hundreds of experiments from around the world, including the survival periods of various microbes in various kinds of waters [20].

Over the course of the nineteenth century in England, water contaminated by fecal material came to be seen as a principal source of human disease [20]. Analysts became confident in the use of coliform counts as an indicator of unsafe water, new purification technologies were developed, sewage treatment processes were improved, and the potential of chlorination to solve bacterial contamination problems was recognized [20].

5.4 Standardization of Analyses

Scientists were working on similar problems in the United States. In the 1880s, the need for adopting water analysis methods that were more "uniform and efficient" resulted in the convening of a special committee by the American Association for the Advancement of Science's chemical section [24]. The committee's work was published in the *Journal of Analytical Chemistry* in 1889 in a report titled "A Method, in Part, for the Sanitary Examination of Water, and for the Statement of Results, Offered for General Adoption" [25]. The report covered methods for measuring ammonia, oxygen-consuming capacity, nitrogen as nitrites, and total nitrogen as both nitrates and nitrites.

In 1895, the American Public Health Association (APHA) responded to concerns about how bacteria should be detected and quantified in water by sponsoring a convention of bacteriologists [24]. The results of the work that started then were submitted in 1897 and widely accepted as a standard method. In 1899, the same organization convened a committee to generate standard methods of water analysis so that other tests would be standardized as bacteriological tests had been. The result was the publication in 1905 of the first edition of *Standard Methods of Water Analysis*.

The American Public Health Association was joined in 1925 by the American Water Works Association (AWWA) and in 1935 by the Federation of Sewage Works Association (now called the Water Environment Federation) [24]. Since 1947, these three groups have worked together to review, revise, reorganize, and publish many editions of what is now called *Standard Methods for the Examination of Water and Wastewater*, a handbook that is still in use and is regularly updated. The 22nd edition, published in 2012, provides standard methods for the analysis of more than 150 contaminants or indicators of water quality. It also details water sampling methods, quality control issues, and precision and bias. Although color, smell, taste, and turbidity still indicate much about the quality of water, a wide variety of detection methods and instruments are now used. These include liquid and gas chromatography, radiation detection, mass spectrometry, ultraviolet absorption methods, electrophoresis, flow analysis, quantitative polymerase chain reaction, plasma emission spectroscopy, and many others.

6 The Evolution of Drinking Water Standards and Regulations

The transition from judging water quality on clarity, taste, and smell in the ancient world to using sophisticated laboratory techniques today was a gradual one. Baker [12] cites the testimony of an engineer at a hearing about a proposed water filter for London in the early 1800s, in which the engineer states that none of the men working on the project had any health complaints related to drinking the filtered water and that fish placed in the water did not die. How did we get from color, odor, taste, the presence of mud, and the death of fish to our contemporary sets of drinking water standards?

6.1 Potable Water as a Government Responsibility

Before standards can be set, we have to be able to detect and measure the contaminant in water; the development of methods of analysis was a critical element in setting standards. But the ability to find contaminants in water is only a small part of the development of drinking water standards. Hamlin's account of the evolution of drinking water standards and regulations in England in the nineteenth century [20] is relevant to drinking water problems around the world today.

During the late 1830s, providing safe water to its citizens was included with other public health issues as the British government fashioned its modern system of public health administration. Science was expanding rapidly at about the same time, and the idea that science could be used in public decision-making played a major part in developing standards. The Metropolis Water Act of 1871 established the government position of "water examiner," an official who would ensure that water filtration was carried out, and chemical analyses were soon included in the water examiner's reports [20].

Hamlin points out that compared to social, political, and economic factors, science was perhaps the simple part of working toward creating a safe water supply [20]. Drinking water standards are not only or even primarily the result of scientific discovery, he says. Rather, drinking water standards were hammered out by a number of interested parties—government, courts, consumers, various industries, water suppliers, farmers, and others. Each of these groups used "scientific arguments" to defend their positions at a time when it was not easy, or perhaps possible at all, to determine the reliability of these arguments [20]. Hamlin shows that although London's need for a safe drinking water supply was critical, factors that slowed the achievement of that goal included conflict over the political and financial control of the water supply and consumer objections to paying for water that was not always available or clean [20]. And what was the definition of pure water? Did it have to be entirely free of microscopic life? Was "soft water" pure water? If water had no microbial contamination, was it pure even if it had other contaminants? In the mid-1800s, Hamlin says, there was "a lack of consensus as to what standards of quality a public water supply ought to meet" [20].

"Safe water" is a relative concept and can be defined differently in different contexts or by different stakeholders in different countries. Because we depend upon the judgment of experts and because providing drinking water requires funding [2], the safety of drinking water today, as in the past, is tied to politics, economic factors, consumer satisfaction, and advances in science. The challenges of determining pricing, institutional control, testing, treatment, reporting, which parameters are important, and how parameter limits should be set are still being faced in many countries. But the importance of working to provide safer water is seen in the results of such work: between 1990 and 2010, for example, some two billion people worldwide gained access to improved water sources [26, 27].

6.2 Guidelines, Standards, and Regulations: An Introduction

Reading about drinking water can be confusing. Terms that mean one thing in one country may mean something else in another. The usual meaning of the word "standard," as it applies to drinking water, is a numerical limit, a concentration above which the contaminant should not occur in drinking water. In the United States, where such standards are legally enforceable, the standards are referred to as "regulations" and include not just the numerical limit but also the requirements for water testing, sample collecting, reporting of results, and techniques for treating contaminated water. In countries without a regulatory framework in place for the enforcement of standards, drinking water standards may exist as "guidelines," numerical values that water providers are expected to use as goals for providing safe water. The language used varies: In India, a list of drinking water parameters is titled "Standard Specifications" and includes comments about whether the limit can safely be extended if necessary or falls in the category of "no relaxation" of the limit. In Kenya, the list of parameters is called "Quality Standards." In the United States, "National Primary Drinking Water Regulations" spell out the details of allowable contaminant levels.

These systems have one thing in common: Drinking water standards around the world are health based. Each standard is set to minimize the threat to human health. For some contaminants, the threat is immediate (acute), but many regulated contaminants pose a threat only if consumed over a long period of time (chronic). The development of standards takes into account how much water an individual drinks per day (for example, in the United States the assumption is 2 L for adults and one for children) and is based on the idea that the average person will drink water for about 70 years. Standards are set based on the effects of the contaminant on laboratory animals, human exposure health data, and the contaminant's occurrence in water, food, and air.

A useful document for countries developing national drinking water quality standards and for those interested in the details of developing standards is *Guidelines for Drinking Water Quality Standards in Developing Countries* [28]. This WHO publication provides step-by-step directions for the entire process of standard development, from identifying the institution responsible for developing standards to surveillance and monitoring. Setting standards to ensure safe drinking water can include setting requirements for water sampling locations, frequency, and methods; laboratory accreditation; provision for the revision of standards; and many other aspects beyond just a contaminant level.

Selecting which drinking water contaminants need to be regulated is based on the threat posed by the contaminant, the prevalence of the contaminant in water sources, and various other factors. Back in 1850s Britain, Hamlin tells us, there was no understanding of the link between disease and human fecal contamination. But significantly for the development of drinking water standards, there was "a slow shifting of sensibility to the view that among types of filth, some types were significantly more dangerous than others" [20]. This recognition that some types of “filth” are more dangerous allows government agencies to focus their regulatory efforts on the contaminants that are most likely to cause human health problems. Reviewing lists of contaminants and adding new contaminants are continual processes.

6.3 Regulatory Framework: The United States

Government regulation of the quality of drinking water is about 100 years old in the United States. In 1914, the U.S. Public Health Service set the country’s first drinking water quality standards; these standards regulated bacterial contaminants that could cause contagious diseases [29]. The standards applied only to drinking water that moved between states, such as water supplies moved by train or ship from a source water system in one state to an end use in another state. These drinking water standards were revised and expanded in 1925, 1946, and 1962, at which time 28 substances were regulated. Individual states adopted the federal standards either as unenforceable guidelines or as legally enforceable regulations.

The federal government conducted a number of drinking water quality studies after the 1962 revision and found that many water suppliers were not meeting the Public Health Service standards [30]. These and other studies led to the passage of the Safe Drinking Water Act (SDWA) in 1974. The SDWA was updated in 1986 and 1996; when the 1986 amendments passed, federal standards for only 22 contaminants had been set, and the amendments required developing standards for a total of 83 specific contaminants.

Under the SDWA, the EPA sets national health-based drinking water standards [30]. The amount of a contaminant in drinking water that the EPA determines will not endanger human health over a lifetime of exposure is listed as its Maximum Contaminant Level Goal, or MCLG. MCLGs are not legally enforceable, but they are critical to the setting of standards because they are used to determine the enforceable Maximum Contaminant Levels (MCLs). MCLs differ from MCLGs when the contaminant cannot be detected at levels as low as the MCLG or when it is not possible to remove contaminants from water to a level as low as the MCLG. The EPA also publishes a document called a Health Advisory for each contaminant, providing information on health effects based on 1-day, 10-day, and lifetime exposures. Tables of these Health Advisories and more information about various drinking water contaminants can be found at the EPA website [31].

The EPA oversees the implementation of these standards by states, localities, and the nation’s more than 160,000 public water systems [30]. Most states and territories provide oversight of their own drinking water systems, which EPA allows as long as systems meet standards that are at least as stringent as the national standards. When contaminant levels are exceeded, treatment plants are required to notify consumers and the state or EPA. Violations typically result in a state regulatory agency providing technical assistance to solve the problem; repeated violations can result in penalties.

7 Current Drinking Water Standards and Guidelines: A Global Overview

A set of drinking water standards accepted and enforced worldwide does not exist, and not all countries have adopted standards. Some countries have a set of standards or guidelines but lack the resources to enforce them. Some have a set of standards, but such a large proportion of their population gets water from sources other than water treatment systems that the standards do not affect many people. Other countries have both standards and a regulatory framework to enforce them. While many of the numerical values of the parameter limits are similar from country to country, others may differ significantly.

A majority of the world's population today lives in countries with drinking water standards. China's Ministry of Environmental Protection set drinking water standards in 2002. The European Commission enforces the European Drinking Water Directive of 1998, with member states required to enact appropriate legislation to implement and enforce the directive in their own countries. In the United States, the EPA is responsible for drinking water standards, as required by the SDWA of 1974. A number of countries have guidelines rather than standards, with states or provinces taking responsibility for creating a regulatory framework, including Canada, New Zealand, India, Argentina, and Australia. Many countries have adopted standards using the European Union, United States, and WHO lists as guides and making changes as needed for their circumstances.

The standards set by and enforced in different countries reflect the politics, economy, and concerns about public health of each country. For example, in developing nations, pesticides are usually of far less concern than acute water-related diseases, and the "best available technologies" to reduce waterborne diseases may be public education, hand pumps, communal taps, and latrines rather than water treatment plants or drinking water standards [7]. In countries lacking resources to deal with the list of contaminants regulated in wealthier nations, drinking water standards are more likely to be set for contaminants that occur frequently and have the greatest health impact [28].

This section presents information about the drinking water standards of selected countries around the world. These descriptions are not meant to provide comprehensive views of each country but rather to illustrate various aspects of drinking water standards used around the world. We will begin with the WHO guidelines, as this organization's work is central to the provision of safe water in many countries [32, 33].

7.1 World Health Organization

In 2011 the fourth edition of the WHO standards, *Guidelines for drinking-water quality* [32], was published. The document includes health-based targets, water safety plans, information about microbial, chemical, and radiological parameters, a chapter on acceptability of water with regard to taste, odor, and appearance, and information about applying the guidelines in specific circumstances.

One of WHO's most downloaded documents, the *Guidelines* are used by many developed and developing countries to set national drinking water standards and to develop a regulatory framework for the enforcement of standards [2]. The European Union and Japan both have used this document to determine their approach to drinking water, and it forms the basis of Australia's drinking water guidelines. In addition to setting forth the standards for a variety of parameters, the *Guidelines* encourage the use of water safety plans, which require assessing risks at every step of the water supply process, from original source to consumer [33]. This approach, introduced in 2004, has spread to many areas of the world, including 60 of 74 developing countries that were assessed as part of the Millennium Development Goal (MDG) program [34].

WHO's *Water Quality and Health Strategy: 2013–2020* [2] details the organization's five strategic objectives for the next several years, which include obtaining evidence regarding water quality and health; providing water quality management guidelines and supporting resources; strengthening the capacity of member states to manage water quality; facilitating implementation of water quality activities; and monitoring the effect of these activities. The *Strategy*'s vision is "to attain the highest possible reduction in waterborne and water-related diseases by providing up-to-date, evidence-based guidance and coordination, and support for water, sanitation and hygiene interventions" [2]. Its mission is "for WHO to be the authoritative source on health-based water quality information, for use by water and health regulators, policy-makers, their advisors and other stakeholders" [2].

Although WHO generated its first set of drinking water standards in 1958, and many of these standards have been adopted by many countries around the world, the organization also recognizes that in many areas of the world such standards still represent a distant goal. Many countries lack the regulatory framework to enforce the standards, the financial resources to implement the standards, the political stability to move forward on providing safe water, or the physical infrastructure to deliver treated water to residents. One of the goals of the *Strategy*, thus, is to support 20 additional countries in establishing a drinking water quality regulatory framework and implementation strategies by 2020 [2]. A second goal is to complete an assessment of 50 countries by 2015 to determine whether their regulatory frameworks are operating to guarantee safe drinking water to citizens.

A third goal of the WHO *Strategy* is to help countries establish policies on household water treatment and safe storage interventions, with a specific target of 50 additional countries having such policies by 2020 [2]. For people who depend on water from rivers, lakes, and other sources of untreated or unsafe water—the 780 million people who drink water that comes from unimproved sources and the millions of others who drink water that is unreliably "improved"—such interventions can dramatically improve water quality and decrease diarrheal diseases [6, 35].

7.2 United States

The United States currently has 87 National Primary Drinking Water Regulations (NPDWRs) and 15 National Secondary Drinking Water Regulations (NSDWRs). The NSDWRs are non-mandatory standards for 15 parameters affecting taste, odor, and color. They provide guidance for public water systems. The contaminants do not provide a health risk, but problems with taste, odor, and color can cause consumers to stop drinking water. These secondary regulations can be found at the EPA website [36]. They include aluminum, chloride, color, copper, corrosivity, fluoride, foaming agents, iron, manganese, odor, pH, silver, sulfate, total dissolved solids, and zinc.

Because sets of drinking water standards are fairly similar from country to country in wealthier nations, it may be instructive to provide here an entire list of contaminants. Regulated contaminants in the United States include:

- Microorganisms: *Cryptosporidium*, *Giardia*, *Legionella*, viruses, turbidity, a count of the variety of bacteria found in the water (heterotrophic plate count, or HPC), and total coliforms, a measurement that indicates whether harmful bacteria may be present;
- Disinfectants: chloramines, chlorine, chlorine dioxide;
- Disinfection by-products: bromate, chlorite, haloacetic acids, and total trihalomethanes;
- Inorganic chemicals: antimony, arsenic, asbestos, barium, beryllium, cadmium, chromium, copper, cyanide, fluoride, lead, mercury, nitrate, nitrite, selenium, thallium;
- Organic chemicals: acrylamide, alachlor, atrazine, benzene, benzo(a)pyrene, carbofuran, carbon tetrachloride, chlordane, chlorobenzene, 2,4-D, dalapon, 1,2-dibromo-3-chloropropane, o-dichlorobenzene, 1,2-dicholoroethane, 1,1-dichloroethylene, cis-1,2-dichloroethylene, trans-1,2-dichloroethylene, dichloromethane, 1,2-dichloropropane, di(2-ethylhexyl) adipate, di(2-ethylhexyl) phthalate, dinoseb, dioxin, diquat, endothall, endrin, epichlorohydrin, ethylbenzene, ethylene dibromide, glyphosate, heptachlor, heptachlor epoxide, hexachlorobenzene, hexachlorocyclopentadiene, lindane, methoxychlor, oxamyl, PCBs, pentachlorophenol, picloram, simazine, styrene, tetrachloroethylene, toluene, toxaphene, 2,4,5-TP, 1,2,4-trichlorobenzene, 1,1,1-trichloroethane, 1,1,2-trichloroethane, trichloroethylene, vinyl chloride, xylenes; and
- Radionuclides: alpha particles, beta particles and photon emitters, radium 226 and radium 228, uranium.

A list of all primary drinking water contaminants and their maximum contaminant levels (MCLs), maximum contaminant level goals (MCLGs), common sources, and potential health effects can be found at the EPA website [37]. A table listing all the contaminants for which MCLs have been set also is available at this site [38].

MCLs are set as close to MCLGs as possible, taking both treatment and detection technology and cost into consideration, and represent the highest level at which a contaminant is allowed in drinking water. Because disinfectants that control microbial contaminants themselves have health effects, another set of standards has been set, Maximum Residual Disinfectant Level Goals and Maximum Residual Disinfectant Levels.

The 1996 amendments to the SDWA require the EPA to maintain a database of information about the occurrence of both regulated and unregulated contaminants found in public water systems. This information is found in the National Drinking Water Contaminant Occurrence Database at the EPA website [39].

Also found at this website is the "Six-Year Review of National Drinking Water Regulations," a report generated by the SDWA's requirement that EPA review each NPDWR at least once every 6 years. If new technology or a new health effects assessment makes it possible to protect public health better than the current NPDWR does, then EPA can revise the standard.

The second such 6-year review, of 71 NPDWRs that had been set before 2005, identified four NPDWRs to revise: acrylamide, epichlorohydrin, tetrachloroethylene, and trichloroethylene [40]. The review was conducted between 2003 and 2009. Fourteen NPDWRs were included in the review for which regulatory action had recently been taken or was under way: bromates, chloramines, chlorine, chlorine dioxide, chlorite (disinfectants); copper and lead; coliform bacteria, *Cryptosporidium*, *Giardia lamblia*, *Legionella*, viruses; HAA5 (haloacetic acid species); and TTHMs (total trihalomethanes).

The review found new information available for 24 NPDWRs but did not recommend revision to the standards because they were considered to be "low priority." Another set of three NPDWRs, all pesticides (atrazine, carbofuran, and simazine), was not recommended for revision because of data gaps or information that was just emerging [40].

The contaminants currently regulated in the United States, along with information about contaminants under consideration for regulation, can be found at the EPA website [41]. The report on the second 6-year review, "Six-Year Review 2 Health Effects Assessment: Summary Report," also is available online [42], as is general information on the 6-year review process [43].

7.3 The European Union

The European Union's Drinking Water Directive of 1998 states as its objective [44]: "to protect human health from adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean." The Directive applies to drinking water in bottles and containers, from tankers, and supplied by distribution systems serving more than 50 people or producing more than 10 m^3/day (or smaller systems if it is part of an economic activity). It also applies to water used in the food-processing industry. This directive included

48 indicator, chemical, and microbiological parameters. Member states of the European Union must adhere to these quality standards and can also set additional standards [45].

The policy's goal is to protect human health over a lifetime of water consumption through the setting and revision of standards according to up-to-date scientific studies. It is part of more general European Union water and health policies and includes provisions for monitoring, assessment, enforcement, and communication with consumers. The Directive provides baseline standards and minimum monitoring requirements to achieve a level of consistency in drinking water quality among member states but also allows for autonomy for individual member states with regard to setting more stringent standards, standards for additional contaminants, and more frequent monitoring requirements [46]. It includes a requirement for reviewing standards every 5 years.

A web page for the drinking water section of the European Union's Directorate-General for the Environment site provides information about legislation and implementation related to drinking water standards [44]. Links to the websites for the European Union member states' official Drinking Water Directive implementation plans also are available [47].

The European Union's Water Information System for Europe (WISE) is a partnership among "the Group of Four" (Go4): the European Environment Agency, the Directorate-General for the Environment, Eurostat, and the Joint Research Centre. It provides information about, among other things, European Union water policies [48].

7.4 China

In 2011, 95 % of China's urban population had access to piped water on the premises, with another 3 % depending on another source of improved water and 2 % on unimproved water [17]. In rural areas, 45 % of the population had access to piped water on the premises and 40 % to another source of improved water, with 13 % dependent on an unimproved source and 2 % on untreated surface water. For the entire country, these figures are 70 % with access to piped water on premises, 22 % using another source of improved water, 7 % using an unimproved source, and 1 % depending on surface water. This represents a significant improvement since 1995, with 25 % of China's population having gained access to piped water on the premises between 1995 and 2011.

China's drinking water health standards, issued in 1985 (GB5749-85), were updated in 2006 by a set of mandatory standards (GB5749-2006), which implemented 13 national standards for drinking water testing [49]. The new requirement increased the number of parameters to be measured from 35 to 106, including 6 microbial indicators, 21 inorganic compounds, 20 sensory properties and general physical and chemical indicators, and 53 organic compounds.

The 2006 revision of standards also united rural and urban standards and applied to all types of centralized and distributed drinking water supplies.

According to the Ministry of Water Resources of the People's Republic of China [50], in 2005 about 300 million people in China did not have access to safe drinking water. About 63 million people in China are supplied with drinking water that exceeds their National Health Standards for fluorine. Another 38 million people drink brackish water, and 11 million people are at risk of waterborne diseases because of the quality of their drinking water. In rural populations, about 190 million people use drinking water that contains other harmful substances at levels exceeding health standards. China's National Safe Drinking Water Program for Rural Areas is being implemented through a series of 5-year planning periods, with the most recent (the eleventh 5-year plan) focused on the problems of high fluorine, high arsenic, brackish water, waterborne diseases, other pollution problems, and water shortages. Its goals are to provide access to safe drinking water to another 160 million rural residents during this planning period and to all rural residents by 2015.

7.5 Australia

The *2011 Australian Drinking Water Guidelines* represents the most recent revision by Australia's National Health and Medical Research Council in collaboration with the Natural Resource Management Ministerial Council. This document, the new edition of which includes new information about pharmaceuticals and endocrine disruptors, pesticides, microorganisms, and monitoring, can be found on the Research Council's website [51].

These guidelines are non-mandatory and are developed by teams of specialists. Regulatory frameworks are developed at the state level. The Victorian government, for example, passed a Safe Drinking Water Act in 2003, the first such legislation in Australia [52], and regulations went into effect in 2005, under the authority of the Essential Services Commission. According to the 2013 WHO-UNICEF report [17], all of Australia's population has access to piped water on the premises.

Quality is key to a sustainable future for Australian water resources, as it is elsewhere in the world [53]. Australia's major water quality problem is nonpoint source pollution; the country's population is primarily coastal, and point sources (industries and wastewater treatment plants) discharge into estuaries and oceans instead of into freshwater sources. Activities contributing to nonpoint source pollution include widespread clearing of native vegetation, irrigation, feedlots, and other agricultural activities.

According to an assessment published as part of Australia's State of the Environment technical papers series, Australian drinking water supplies are not, for the most part, obtained from sources affected by chemical industries [54]; this is very different from drinking water sources in North America, South America, Europe, China, and other regions of the world. The major tap water quality concerns identified in this report include carcinogenic disinfection by-products; color, taste, and odor; corrosion of pipes and fittings and the leached products of such corrosion; hardness; salinity; toxic algae; toxic inorganic substances; and turbidity. The report authors point out that although many measurable parameters can serve as quality indicators, just a few are usually enough to provide a reliable overview: turbidity, color, total dissolved solids, water hardness, coliform bacteria, and a few chemical variables "have proved to be remarkably robust in their ability to track complex underlying water quality problems" [54].

7.6 Kenya

In Kenya, a Water Services Regulatory Board was established in 2003, in response to the Water Act of 2002, to oversee the provision of water and sewer services [55]. The Water Services Regulatory Board sets rules and enforces standards; it issues licenses to Water Service Boards, which contract with Water Service Providers to provide water services in their jurisdictions. The National Environment Management Authority (NEMA) lists 17 parameters and their maximum allowable Guide Values (pH, suspended solids, nitrate, ammonia, nitrite, total dissolved solids, *E. coli*, fluoride, phenols, arsenic, cadmium, lead, selenium, copper, zinc, alkyl benzyl sulfonates, and permanganate) [56]. Some of these standards are above and some below the WHO guidelines.

Like other developing countries, Kenya faces significant challenges with regard to drinking water. Instituting standards and a regulatory framework is a giant step, but often financial resources to implement standards, enforce regulations, and ensure compliance are lacking. A Water Services Regulatory Board performance review [57] shows that between the 2005/2006 reporting period and the 2010/2011 reporting period, the percentage of people living in urban areas who had access to safe drinking water increased from 40 % to 52 %, a significant increase but still far from the Board's goal of reaching 80 % urban coverage by 2015. Only 7 of the country's 65 urban Water Service Providers have reached the 80 % coverage benchmark. Growing population pressures in urban centers requires more investment in water services; especially underserved are low-income areas, and the 2012 review recommended extending coverage to these urban neighborhoods through water kiosks and yard taps.

In 2010/2011, 90 % of required tests for residual chlorine were submitted by 65 urban Water Service Providers, up from 84 % the year before. The rate of compliance in test results, however, decreased slightly over the same period. For bacteriological standards, the number of tests increased from 62 % to 76 % between 2009/2010 and 2010/2011, and the rate of compliance in test results dropped from 94 % to 87 %. Only 23 % of the Water Service Providers fell within the acceptable range for this test.

Although safe drinking water is becoming available to more Kenyans, the country, like the rest of the world, is working against increasing degradation of its water resources. Many sewage treatment plants do not work properly and discharge untreated sewage into surface water; sediments, nutrients, and agrochemicals from farming threaten water quality; uncontrolled industrial discharges contribute to the deterioration of Kenyan waters; and saltwater intrusion caused by overuse of aquifers is contaminating groundwater supplies [58].

7.7 India

According to the 2013 WHO-UNICEF report, India has made significant progress over the past decades in providing safe drinking water to its citizens [17]. In 1954, India launched a national water supply program to build village systems. India's Ministry of Health includes the Central Public Health Environmental Engineering Organization, which runs the national drinking water supply program.

India's set of drinking water standards and a document called the *Uniform Drinking Water Quality Monitoring Protocol (2013)* [59, 60] together provide guidance for the provision of safe drinking water. The *Protocol* is a set of guidelines, not a set of regulations; each Indian state has its own rules and requirements. The document provides details about which parameters must be monitored and at which regulatory levels [60]. At the state laboratory level, there are 78 parameters to be monitored, including 6 physical parameters, 36 chemical parameters, 4 microbiological parameters, 18 individual pesticides, and 15 other specific parameters. At the district and subdistrict laboratories, 13 basic water quality parameters must be routinely monitored: total coliforms, thermotolerant coliform or *E. coli*, total alkalinity, total hardness, total dissolved solids, pH, turbidity, chloride, sulfate, iron, arsenic, fluoride, and nitrate. Drinking water standards include requirements for frequency of sampling; in India the timing of sampling and monitoring with respect to the monsoon is important.

India's monsoon climate affects more than just sampling schedules; water has to be stored for use during the dry season, and, as in many countries, water's various uses conflict. For example, despite increasing amounts of money dedicated to village water supplies in India, the increased use of groundwater for irrigation all over the country resulted in new village boreholes and hand pumps that did not always provide water.

Three percent of the government funding for India's National Rural Drinking Water Programme has been allocated for water quality monitoring and surveillance, and the *Uniform Drinking Water Quality Monitoring Protocol* provides information about sampling and testing procedures; equipment, supplies, chemicals, and personnel requirements; building space; and other details related to water testing [61].

The *Protocol* also lists the acceptable limits for 23 important parameters, along with the limit that is permitted in the case of no available alternative source of drinking water. Another useful set of tools is provided in the section on sanitary inspection forms, with specific questions appropriate to piped water, hydrants and tanker trucks, gravity-fed piped water, boreholes with either mechanized or hand pumps, protected springs, rainwater collection and storage systems, and dug wells.

The government of India has long been committed to providing "safe water and sanitation for all" and took an active role in the United Nations MDG of reducing by half the population without safe water by 2015 [62].

7.8 Israel

According to the 2013 WHO-UNICEF report [17], all of Israel's residents have access to piped water on the premises. Israeli drinking water standards are based on the guidelines and standards developed by the WHO, the EPA, and the European Union Environmental Directorate [63]. A guidance document was replaced by the Drinking-Water Quality Regulations issued by the Ministry of Health in 1974. The regulations, updated about every 10 years, include microbial, chemical, physical, and radiological standards along with requirements for monitoring. Israel's standards are generally consistent with international norms and include both required and recommended levels. Although Israel's water resources have been undermined by contamination and salinization, the quality of its drinking water has improved with more stringent regulations and effective water management interventions.

Israel's approach to improving the safety of its drinking water incorporated a gradual adoption of increasingly stringent standards, an approach later followed in Palestine, where water treatment experts envisioned "a steady process of ratcheting down drinking-water contaminant levels" as resources to monitor and treat water and enforce regulations became available. The Palestinian experience can be compared to Israel's [64]: "Initial Israeli drinking-water standards were low and gradually became more demanding as the country's economic conditions improved. For instance, Israel understood that a standard of 90 mg/L was desirable for nitrates but couldn't afford it. Today it can make this commitment." Israel's nitrate standard today is 70 mg/L [65], closer to the WHO standard of 50 mg/L [33] than to the standard of 10 mg/L in the United States.

8 Emerging Standards and Regulatory Challenges

New contaminants in drinking water—and new threats to human health—will continue to appear as long as humans continue to develop new chemicals for industry and agriculture, mine new areas of the earth, and dispose of pharmaceutical and other wastes in such a way that they can end up in water sources. Contaminants of concern also can take the form of already existing contaminants about which new information becomes available; already existing contaminants detected by new, more sensitive analytical techniques; and already existing contaminants that interact or combine with others in ways that create a threat to human health.

Because of the limitless potential for new contaminants [7], the United States and many other countries have built into their drinking water regulations provisions for the assessment and inclusion of new contaminants [66]. The WHO *Guidelines* are subject to a rolling revision; the European Union Directive requires reviewing standards every 5 years; and the EPA is required to review and revise standards every 6 years and to publish a list of nonregulated contaminants every 5 years [46]. This Contaminant Candidate List (CCL) is generated by evaluating data sources that identify potential microbial and chemical contaminants and serves to identify contaminants of concern for possible regulatory action [67].

The determination of risk for any contaminant requires extrapolating from studies on laboratory animals to humans and from experimental doses to the concentrations found in drinking water supplies [2]. Regulatory challenges include balancing the benefits of the use of various chemicals with the risks posed by their presence in water supplies and balancing the costs of monitoring and removing contaminants with the benefits of their removal.

This section provides information about some categories of emerging contaminants that pose significant regulatory challenges. More information is available in a later chapter of this book.

8.1 Disinfection By-Products

In the nineteenth century, when chemists were working to analyze water [20], they wondered whether the analyses would change or affect what was in the water being tested. Their concern was well founded. Scientists know now that some of the treatment methods used in contemporary water treatment can create other potentially dangerous contaminants [7].

One example of this is the suite of chemicals generated by disinfection. These disinfection by-products (DBPs) have been associated with bladder cancer, birth defects, and miscarriage [68]. Although several DBPs are regulated in the United States and in other countries, many others are not, and researchers are still finding new DBPs. In a project under way in the European Union, researchers are investigating the health impacts of long-term exposure to DBPs, looking both at the epidemiology of adverse pregnancy outcomes and at chemical and biological analyses of water from different types of water treatment plants from 11 cities in 5 European countries [69]. More than 70 DBPs have been identified as part of this work, including many that are not regulated and others that had not previously been reported, and research continues.

A specific example of a disinfection by-product is *N*-Nitrosodimethylamine (NDMA), one of a group of very potent carcinogens. NDMA is formed during wastewater chlorination and can enter drinking water supplies via municipal wastewater reuse, direct industrial contamination, and chlorination processes [70]. In finalizing its third Contaminant Candidate List in 2009, the EPA added to the CCL draft two disinfection by-products, chlorate and bromochloromethane [67].

8.2 Pharmaceuticals

Advancements in analytical instrumentation and new methods of analysis have allowed detection of smaller concentrations of contaminants in water [71–75]. One of the groups of contaminants that have received increasing attention in recent decades is pharmaceuticals, which enter drinking water sources through wastewater discharges from sewage treatment plants and from leaking sewer lines, landfills, and animal wastes [71, 72].

About 3,000 different substances are used as pharmaceutical ingredients [73]. One concern about pharmaceuticals is that the release of antibiotics into the environment can generate bacterial resistance, the so-called Super Bugs. Another fear is that some pharmaceutical compounds can disrupt the endocrine systems of both humans and wildlife. Illegal drugs also have been detected in drinking water sources. Methamphetamine and MDMA, or ecstasy, have been found in U.S. water sources, and cocaine was found in a river in Italy in 2005. Other illicit drugs now reported in water sources include morphine and other heroin metabolites, marijuana metabolites, codeine and metabolites, and methadone and its metabolites. Among drinking water contaminants that most people will recognize are caffeine; tobacco by-products; ibuprofen, also known as Advil, Nuprin, and Motrin; and acetaminophen, or paracetamol (APAP, Tylenol) [72, 74].

Chemist Christian Daughton reported in a 2010 review [72] that no toxicological risks have been documented for any of the pharmaceuticals detected in drinking water at the low concentrations detected. But contaminants present in only trace amounts may become a greater concern in the future, as we move toward indirect and direct water reuse, and combinations of various pharmaceuticals may present currently unknown risks. Pharmaceuticals also can form new contaminants in response to disinfection and other treatment processes. Ten pharmaceuticals, the antibiotic erythromycin and nine hormones, were added to the EPA's Contaminant Candidate List as it went from draft to final form in 2009 [67].

8.3 Emerging Pathogens

Waterborne diseases also present new challenges. The microbes responsible for disease can evolve, new diseases can be discovered, and the importance of previously known diseases can increase [76]. Resistance to antibiotics, also related to contaminants in water [73], can complicate treatment of patients suffering from waterborne diseases. Research shows that some bacteria grow in water distribution systems and home plumbing pipes, creating new threats after water has left the treatment plant [77].

Researchers studying zoonotic pathogens—pathogens carried by animals—have found that although many of these pathogens affect humans, there are five that frequently cause illness worldwide: *E. coli* 0157, *Giardia*, *Campylobacter*, *Salmonella*, and *Cryptosporidium* [18]. Emergent or as-yet-unrecognized zoonotic pathogens are unlikely to be problematic contaminants in water supplies in which these five pathogens are successfully controlled. Controlling for zoonotic pathogens continues to be critical, however, as 85 % of the world's fecal waste is produced by domestic animals—sheep, pigs, cattle, poultry—and that waste, carrying pathogens, often makes its way to water sources. The increased use of wastewater for agricultural applications also increases the danger of outbreaks of waterborne disease [3].

The extreme weather events associated with global climate change will pose challenges. A review of waterborne disease outbreaks following such weather events found that heavy rainfall and flooding were implicated in more than half the outbreaks and that *Vibrio* and *Leptospira* were the most common pathogens involved [8]. Twelve microbial contaminants are listed on the EPA's Contaminant Candidate List [67]. They include adenovirus, caliciviruses, enterovirus, and the Hepatitis A virus, along with *Campylobacter jejuni*, *E. coli* 0157, *Helicobacter pylori*, *Legionella pneumophila*, *Mycobacterium avium*, *Naegleria fowleri*, *Salmonella enterica*, and *Shigella sonnei* [67]. *Legionella* and *Mycobacterium* are among the microbial contaminants known to multiply in plumbing systems [77].

9 Global Drinking Water Quality Goals

A global water policy framework can be traced back to 1972 and the Stockholm Declaration, and the first international forum on water was in 1977. At this international forum in 1977, the United Nations recognized the right to water as a human right [25]. Between 1990 and 2010, according to the United Nations, the MDG drinking water target was met, halving the proportion of the world's population that had no access to safe drinking water. More than two billion people gained access to improved drinking water sources over those decades [26], although definitions of "improved" and methods of measuring access make it possible that the number of people using safe water worldwide has been overestimated [27].

WHO and UNICEF have facilitated the formulation of drinking water goals for the future [17]. The Joint Monitoring Programme for Water Supply and Sanitation, known as the JMP and run by WHO and UNICEF together, plans to collect baseline data by 2015; this data set will be used to evaluate progress toward the goals. More information about the conferences that generated these targets, the working groups involved, and the proposal document itself can be found online [78]. The goals include:

- Target 1: By 2025, open defecation will be a practice of the past.
- Target 2: By 2030, everyone will have access to a basic drinking water supply and hand washing facilities at home, at school, and at health centers. A *basic drinking water supply* is defined as access to an improved drinking water source for which water collection takes 30 min or less, round trip. *Improved* is defined

as adequately protected by its construction from outside contamination, especially fecal matter.

- Target 3: By 2040, everyone will have adequate sanitation at home, the proportion of those without an intermediate drinking water supply at home will have been reduced by half, and the human waste from at least half of homes, schools, and health centers with adequate sanitation will be safely managed. An *intermediate drinking water supply* is defined as access to an improved drinking water source on the premises that meets basic microbiological standards (less than 10 colony-forming units of *E. coli* per 100 mL) and was available in acceptable quantities for at least 12 of the past 14 days.
- Target 4: The delivery of all drinking water supply, sanitation, and hygiene services will become more affordable, environmentally and economically sustainable, and accountable.

Each of the targets includes the progressive reduction of current inequalities in access to services and will be accompanied by a set of unambiguous indicators. The 2013 report listing the targets explains them this way: "Based on the simple inspirational vision of the universal access to safe water, sanitation and hygiene, they focus on the poor, disadvantaged and those excluded at the individual and household level, as well as in schools and health centres. Pursuing the elimination of inequities and inequalities, the targets seek to both increase the number of people using water, sanitation and hygiene as well as progressively improve levels of service."

10 Conclusions

As the demand for water increases all over the world, we will increasingly use water sources that we have avoided in the past—sources that are more likely to be contaminated either naturally or by human and industrial wastes and overuse. Population increase, increased need for food production, the movement of the world's population to cities, increasing uncertainties about precipitation, extreme weather events that result in water supply contamination, and continuing degradation of water quality all increase water stress, and half of the world's population will be living in areas of water stress by 2025 [5]. Urban/rural disparities and inequities associated with poverty continue to affect access to safe drinking water, and work is needed especially in sub-Saharan Africa and the Pacific, where many people do not have safe sources of drinking water [79].

Unfortunately, we still live in a world where many people drink water that does not meet established drinking water standards. This is particularly true in countries that have not yet developed standards or that lack the regulatory framework and resources to treat and monitor water quality and enforce regulations. However, this is also sometimes true in developed countries. In the United States, for example, most community water supply systems are 50–100 years old, and most of their annual budgets are used for repairs [7]. Many systems cannot afford to implement advanced treatment technology. When a regulated pollutant is found above the standard, the public is warned, allowing consumers to purchase bottled water or use home filtration or treatment systems but not necessarily providing safe water from the public water supply [7]. As occurs elsewhere in the world, financial and political problems can prevent the provision of safe drinking water.

Many people in developed countries use water that is not required to meet standards; the SDWA, for example, does not affect private wells or water systems that provide drinking water to fewer than 25 people [80]. Among the 30 Organization for Economic Co-operation and Development (OECD) countries, the percent of the population that is connected to a public water supply, and thus probably protected by a set of drinking water standards, ranges from 74 (Turkey) to 85 (Poland, Slovak Republic, and the United States) to 90 (Finland, Mexico, and Ireland) to 100 (Italy, Luxembourg, and the Netherlands) [81]. As in the United States, the OECD countries have increasing problems of aging treatment systems, communities with systems not conforming to new and more stringent regulation, and lapses in service quality [81].

The regulation of drinking water in developing countries is hampered by the same problems that faced nineteenth-century England. How to set, implement, and enforce regulations and how to get customers to pay for an uncertain and possibly unclean supply of water are issues that are still being worked out in many countries. For example, the Chief Executive Officer of Kenya's Water Services Regulatory Board, Robert Gakubia, includes the following problems in his list of the "huge challenges" that face Kenya with regard to water services [57]: low efficiency and effectiveness of investments, slow progress in coverage, financing gaps, resistance to compliance, and high levels of Non-Revenue Water, the water that is lost from the system through theft, metering inaccuracies, leaks, and other routes that bring the provider no money.

The existence of sets of standards and examples of regulatory frameworks in place in a variety of countries, along with the guidance of WHO and UNICEF, should ease the path toward the adoption of drinking water standards worldwide. Although the WHO/UNICEF goals for drinking water do not at this point specify standards beyond a basic microbial limit, they allow us to envision a future in which drinking water standards and regulations are relevant and protective of human health all over the world.

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