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Water Security in a Changing World

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4.1 Introduction

> *Water is at the core of sustainable development*
>
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> Sustainable Development

The global human population, currently estimated at 7.3 billion, is expected to increase by 33% to 9.7 billion by 2050. Under present conditions and policies, this is projected to require a 60% concomitant increase in agricultural production and 15% increased demand for water to meet the food needs of a projected world population of 9 billion people (World Bank, 2017). And the United Nations (UN) has estimated that, under current practices, the global water demand in developing nations alone will have increased by 400% by 2050 (United Nations World Water Assessment Programme, 2015). Combined with rising gross domestic product (GDP) in virtually all nations, which leads to increased demand for electricity, these increasing needs for water come at a time when long-term droughts are having impacts in highly (e.g., southwestern USA, western Canada), moderately (e.g., Brazil, Columbia), and less-developed (e.g., Malawi) nations alike. Global climate change adds additional uncertainly to the future regional availability of water. Often, poor policies and lack of regulations promoting water conservation lead to wasteful use, exacerbating droughts caused by natural phenomena and disproportionately affecting the poor and disenfranchised.

Herein we address two aspects of water security: water quality and water quantity. Recent decades have seen increased access to safe drinking water. By 2010, 89% of the global population were using potable water, which was an increase in over two billion people in the previous 20 years. Still, nearly one billion people lack access to sufficient quantities of safe water for drinking, food preparation, and hygiene. The UN Committee on Economic, Social and Cultural Rights, through the adoption of General Comment No. 15 (United Nations, 2002), recognized the human right to water, further defined as "the right to sufficient, safe, acceptable and physically accessible and affordable water for personal and domestic uses." More recently, the UN General Assembly, through adoption of Resolution 64/292, recognized the human right to clean drinking water and sanitation (United Nations, 2010). Access to safe water goes hand in hand with proper sanitation and treatment, which is lacking in some regions.

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As we will show, exposure to water contaminated with pathogens and toxicants is not limited to underdeveloped nations.

Sustainable population and economic growth into the future will require that industry, energy, and agriculture make smarter use of a smaller share of finite water resources. We examine the water/energy/food nexus and discuss how improvements in efficiency and waste reduction are needed on both ends of the supply chain. Ensuring the sustainability of global water resources will require multidisciplinary consideration of region-specific needs, resources, and limitations in the production of energy and food.

4.2 Waterborne Pathogens and Contaminants: Technologies for Drinking Water Treatment and Management of Water Safety

Safe drinking water, which is free from harmful microorganisms and substances, is essential for public health and linked with adequate sanitation. At the global level, the access to safe drinking water has improved remarkably during the last 25 years and now more than 91% of the world's population has access to safe drinking water (http://www.who.int/wsportal/casestudies/en/). This improvement has also contributed to the 50% decrease in deaths due to communicable diseases of children younger than 5 years of age during the 15 last years. However, at the same time the target level set for sanitation improvement by the UN's Millennium Development Goals (MDGs) has not been met (United Nations, 2015). One-third (2.4 billion) of the world's population is still without proper sanitation, and more than 900 million do not have access to designated toilets or latrines (http://www.who.int/wsportal/casestudies/en/).

Despite many positive achievements, people still get ill and die because of unsafe drinking water, primarily in developing countries, but also in countries having organized and controlled drinking water supplies and sanitation systems. Unsafe drinking water is still an important single source of gastroenteric diseases, mainly due to fecally contaminated raw water, failures in water treatment processes, or recontamination of treated drinking water (Medema et al., 2003; WHO, 2011). It has been estimated that, across the globe, 842 000 deaths every year are attributable to unsafe water supply and poor sanitation and hygiene. The World Health Organization (WHO) has estimated that a total of 3.5% of all disability-adjusted life years (DALYs) are caused by unsafe drinking water and water-related diarrheal diseases.

A significant portion of the water-related disease burden, primarily vector-borne diseases, is attributable to the problems in management and use of water resources. Additionally, many water sources are also used for leisure and recreational activities, agriculture, and food production, which can be microbiologically or chemically contaminated and pose health risks through those endeavours (Cabelli et al., 1982; van Asperen et al., 1998; Schönberg-Norio et al., 2004). Access to safe water, sanitation, and hygiene is also critical in the prevention and management of 16 out of the 17 neglected tropical diseases, including trachoma, soil-transmitted helminths, and schistosomiasis. These diseases affect more than 1.5 billion people in 149 countries, causing blindness, disfigurement, permanent disability, and death. The One Health approach – the recognition that human, animal, and ecosystem health are inextricably linked – combines expertise in public health, human and veterinary medicine, and drinking water management and provides a strong network for reaching the goal of safe drinking water (Courtenay et al., 2015).

4.2.1 Waterborne Pathogens

Surface water sources (e.g., lakes and rivers) are often contaminated microbiologically by treated or untreated sewage water or fecal discharges of domestic or wild animals, often exacerbated by extreme weather conditions, like heavy rains or floods. *Ground water* sources (e.g., wells, borehole wells) are usually of good microbiological quality. However, ground water can also become contaminated, either by surface water containing animal or human fecal material after heavy rain or snow melt, or by sewage leakages, and become the source of community-based outbreaks, especially if improper or no disinfection treatment has been applied (WHO, 2011).

The most important waterborne microbial pathogens include:

- bacteria (e.g., *Campylobacter* spp., *Escherichia coli*, *Salmonella* spp., *Shigella* spp., *Vibrio cholerae*, and *Yersinia enterocolitica*);
- viruses (adenoviruses, enteroviruses, hepatitis A, hepatitis E, noroviruses, sapoviruses, and rotaviruses); and
- protozoa (*Cryptosporidium parvum*, *Dracunculus medinensis*, *Cyclospora cayetanensis*, *Entamoeba histolytica*, *Giardia duodenalis*, and *Toxoplasma gondii*) (WHO, 2011).
- nematodes (*Dracunculus medinensis*).

Selected microbial pathogens and their characteristics are presented in Table 4.1.

In the mid-1800s, large waterborne disease outbreaks in Europe were caused by *V. cholerae*. The famous outbreak investigations done in London in 1854 by John Snow greatly expanded understanding of the epidemiology and prevention of waterborne diseases (Vinten-Johansen et al., 2003). *V. cholerae* is still a significant cause of waterborne infections, especially in developing countries, where most of the victims are often children under 5 years of age (WHO, 2002, 2003; Ashbolt, 2004). In developed regions, such as the northern European countries, the most important waterborne pathogens are noroviruses and *Campylobacter jejuni* (Guzman-Herrador et al., 2015). Noroviruses and several other waterborne viruses have low or extremely low infectious doses to cause gastroenteritis and they are shed in feces in very high numbers even if the infected person remains or becomes asymptomatic. Viruses do not multiply in the environment but they can persist in water for long periods. Therefore, inadequate disinfection of fecally contaminated drinking water could easily lead to large outbreaks (Gall et al., 2015).

Enteric parasites, such as *Giardia* spp. and *Cryptosporidium* spp., are well recognized as emerging pathogens transmitted through drinking water and being able to cause severe waterborne gastroenteritis, especially in immunocompromised persons (Franzen and Muller, 1999; Szewzyk et al., 2000; Stuart et al., 2003). One of the largest waterborne outbreaks ever seen was caused by *Cryptosporidium parvum* in Milwaukee, USA, in 1993, where 403 000 persons were infected. Also countries such as the UK and Sweden have experienced large *Cryptosporidium*-associated waterborne outbreaks (Chalmers, 2012).

4.2.2 Antibiotic-Resistant Bacteria in Source and Drinking Water

As a result of decades of usage of antibiotics and other antimicrobial agents in human and veterinary medicine, antimicrobial-resistant bacteria and their resistance genes are common and widespread contaminants of raw water. Many enteric bacterial pathogens and fecal bacteria, such as *E. coli.*, *Klebsiella*, and fecal enterococci, carry genes associated with multiple resistances. Currently, special interest is directed to extended-spectrum beta-lactamase producing *Enterobacteriaceae* (ESBL) or carbamase-producing Gram-negative bacteria, which are especially common in countries where antibiotic usage is uncontrolled (Zurfluh et al., 2013; WHO, 2014). In these countries, resistant bacteria are common in sewage water and surface water causing the risk of further spread. However, these bacteria are also detected in surface waters in highly developed countries (Zurfluh et al., 2013) and they are spreading globally by travel, thus posing an increased human health risk worldwide (WHO, 2014). Antibiotic-resistant bacteria, among other bacteria, are destroyed by adequate drinking water treatment (see Table 4.1).

Table 4.1 Selected waterborne pathogens and their characteristics.

	Health significance				Examples of reduction by various water treatment technologies	
Pathogen	**Relative infectivity**	**Persistence in water supply**[a]	**Important animal source**	**Resistance to chlorine**	**Chlorine (time for 2-log/99% reduction using 1 mg/L at pH 7.5, $T = 20$ °C)**	**UV (dose for 4-log/99.99% reduction)**
Viruses						
Hepatitis A	High	Long	No	Moderate	~16 min	7–186 mJ/cm^2 for all viruses
Hepatitis E	High	Long	Potentially/yes	Moderate		
Polioviruses	High	Long	No	Moderate		
Adenoviruses	High	Long	No	Moderate		
Noroviruses	High	Long	No/potentially	Moderate		
Rotaviruses	High	Long	No	Moderate		
Bacteria						
Campylobacter jejuni	Moderate	Moderate	Yes	Low		0.65–230 mJ/cm^2 for all bacteria
Escherichia coli	Low	Moderate	Yes	Low	<1 min	
E. coli, EHEC	High	Moderate	Yes	Low		
Shigella spp.	High	Short	No	Low		
Vibrio cholerae	Low	Short/Long	No	Low		
Yersinia enterocolitica	Low	Long	Yes	Low		
Protozoa						
Cryptosporidium parvum	High	Long	Yes	High	~9600 min	<1–60 mJ/cm^2 for all protozoa
Entamoeba histolytica	High	Moderate	No	High		
Giardia intestinalis	High	Moderate	Yes	High	~45 min	
Toxoplasma gondii	High	Moderate	Yes	High		
Helminths						
Dracunculus medinensis	High	Moderate	No	Moderate		
Schistosoma spp.	High	Short	Yes	Moderate		

Data based on WHO, 2011.

a) Short means that infective stages have been detected in water at 20 °C for up to a 1-week period, moderate is 1 week to 1 month; and long is over 1 month.

4.2.3 Chemical Hazards in the Drinking Water

A wide array of hazardous toxic compounds can be present in raw source water as well as in drinking water. According to their suspected toxicity, permitted concentrations of chemicals are regulated in national drinking water regulations, which are commonly based on the guideline values evaluated and published by WHO (2011). The toxicants and other chemicals affecting water utility originate from various sources. To develop control measures to decrease their concentrations to acceptable levels, it is necessary to recognize the major sources of contaminants. Chemical contaminants are often grouped according to their origins:

- Naturally occurring in rock or soils characterized by geology (e.g., arsenic, aluminum, uranium, fluorine, iron, and manganese).
- Industrial activities (e.g., organic solvents, benzene, a large group of organic chlorinated compounds, and cadmium).
- Agricultural activities (e.g., nitrates, pesticides, antibiotics and other pharmaceuticals).
- Human activities, such as pharmaceuticals and cosmetics.
- Formation during water treatment, such as disinfection by-products (DBPs) – often organic halogen-containing compounds and residues of coagulation chemicals (aluminum).
- Leakage or dissolution from water storage or distribution materials (e.g., acrylamide, lead).

Some toxins are also produced by microbes, such as microcystins produced by cyanobacterial growth in surface waters.

4.2.4 Pharmaceuticals in Wastewater and Raw Water Sources

Residues of pharmaceuticals and their metabolites have been present in waters for decades but the monitoring for their levels in wastewater, wastewater effluents, and water-bodies has only recently started. These compounds are acknowledged as emerging hazards to ecosystems and human health since they may enter into drinking water from contaminated raw water source (WHO, 2012; Rivera-Utrilla et al., 2013). Pharmaceutical compounds originate from both human usage and agriculture. In addition, through their manufacturing processes pharmaceutical industries release these compounds into wastewaters and the environment. Pharmaceuticals and personal care products, and their metabolites, are also excreted by people or by domesticated animals through feces and urine into wastewater or directly into the environment. Recent advances in sensitive analytical techniques have ensured detection of trace concentrations (usually present in nanograms per liter) of these chemicals and their transformation products (Riviera-Utrilla et al., 2013). However, there are limited data available on the occurrence and concentrations of these compounds in drinking water (WHO, 2012) and even full-scale wastewater treatment systems do not have the capacity to remove these residues. Their significance for ecosystem and human health is largely unknown and more research is warranted. Discussion for the need and feasibility for regulation of pharmaceutical compound has started in international organizations and in national authorities (WHO, 2012).

4.2.5 Water Treatment Methods

The general purpose of drinking water treatment is to make it safe (potable) by removing or inactivating the pathogenic organisms, their toxins and other hazardous chemicals entirely or to a level that causes no harmful effects (Backer, 2002). *Disinfection* is a process in which harmful microbes are inactivated, chemically or physically, while *purification* refers to removal of harmful substances from drinking water. The aim of water treatment is also to remove unwanted odor, taste, and color and to make water physically and chemically fit for distribution and use (e.g., hardness and pH).

The multiple barrier approach is essential in water treatment, since only in exceptional cases is a single treatment step capable of removing or inactivating all different types of pathogenic microbes or toxins (Stanfield et al., 2003; LeChevallier and Au, 2004). In practice, the multiple barrier concept means a combination of two or more different treatment methods to minimize the possibility that harmful microbes or toxins will enter the drinking water through ineffectiveness or failure in some treatment stages (WHO, 2011). Traditionally, a large-scale water treatment process includes pre-treatment steps using various filter methods and storage, followed by coagulation, flocculation, and sedimentation of impurities, continued by final filtration, and ending with chemical or UV disinfection. Some of the treatment techniques are described below in more detail. The choice of methods will depend on the source water quality, the cost of the treatment process, and the quality and safety standards for the processed water.

4.2.5.1 Thermal Treatment

Thermal treatment, that is, letting the water (rolling) boil at 100 °C for some minutes, is the oldest means of killing microbes and is a simple way to treat smaller amounts of water under field and emergency conditions (Backer, 2002). The "boil water" advice is also a common practice when contaminated drinking water is suspected to cause an acute waterborne outbreak in a community. At 100 °C, all pathogenic vegetative bacteria, protozoa, and viruses are destroyed; only microbial spores, for example, spores of *Clostridium* and *Bacillus*, and heat-resistant toxins, such as some cyanobacterial toxins, survive or maintain their toxicity (Backer, 2002). *Distillation* is a method for producing pure (deionized) water through boiling and then condensing the steam in a clean container; the temperature of boiling water is also effective against microbes and heat-sensitive toxins. *Vacuum distillation* is a method for distilling the water under negative pressure (and therefore a temperature lower than 100 °C is needed). This method is used to produce drinking water from seawater but due to the low temperature it may not be effective against pathogenic microbes (Al-Kharabshed and YogiGoswami, 2003).

4.2.5.2 Chemical Disinfection

Chemical disinfection of drinking water includes the use of chlorine, iodine, silver, or ozone. The efficiency of chemical treatment is a function of dose, contact time, temperature, and pH (Stanfield *et al.* 2003). The efficiency is described usually by the concentration time (CT) concept, which is a product of the residual chemical concentration and the contact time (Stanfield et al., 2003). The efficiency of all chemicals is reduced by organic material such as humic substances in water. A proportion of the added chemical is bound to the organic material (so-called chemical demand) and cannot act against microbes; only the free residual chemical is effective in microbial inactivation. All chemicals are most effective at moderate temperature (15–20 °C) and at a pH of 6–9 (Backer, 2002). In addition to their antimicrobial effect, certain chemicals, especially ozone, can act as strong oxidants and also oxidize and remove harmful chemicals from drinking water.

Chlorination is the oldest and most commonly used disinfection method in both the developed and developing world (Stanfield et al., 2003; WHO, 2011). It is used as compressed elemental gas, sodium hypochlorite solution ($NaOCl$), or solid calcium hypochlorite ($Ca(OCl)_2$. It is relatively simple to use as hypochlorite solution also in emergence situations. However, chlorines are also highly toxic and their use requires that personnel should know and follow the handling and safety instructions.

In general, chlorination is effective against bacteria and viruses but less effective or even ineffective against protozoa and algae at the concentrations normally used in drinking water, typically 0.5–1 mg/L (parts per million, ppm) of free residual chlorine (Table 4.1). So-called *shock chlorination* can be done using high doses of chlorine (e.g., 10–50 mg/L) for disinfecting drinking water pipelines or storage tanks. Chlorine combined with amine (chloramine) ensures protection against recontamination of treated drinking water under storage and distribution. Chlorine can react with organic material, especially with humus in the water, and mutagenic (carcinogenic) by-products can be formed. However, the antimicrobial benefits of the chlorination have been estimated to exceed the negative health effects, namely, production of DBPs (Ashbolt, 2004). The formation of by-products can be minimized by removing organic material (humus) before chlorination and controlling the chlorine concentrations used (WHO, 2011).

Iodine can also be used as a water disinfection chemical and its performance is mainly similar to chlorine (Backer and Hollowell, 2000; Goodyer and Behrens, 2000). The *silver* ion has some bactericidal effects, but the use of silver ion products is better suited for preserving previously treated water (Backer, 2002). The silver ion is also used in many filtering devices as an antimicrobial coating (Backer, 1995).

Ozone is a powerful oxidant and effective against bacteria, viruses, and even protozoa. In addition to microbes, ozonation is also effective against cyanobacterial toxins, such as microcystins (Hoeger et al., 2002; LeChevallier and Au, 2004). Ozonation may produce bromate as a harmful by-product (WHO, 2011).

4.2.5.3 Filtration

Filtration is a physical method to remove organisms and other particulate matter from drinking water based on particle and sieve size (Figure 4.1). Particle (also referred to as granular or sand media) filtration is a widely used drinking water treatment, usually combined with coagulation, using organic (e.g., polyamine) or inorganic (e.g., alum) compounds, flocculation using anionic or cationic compounds, and sedimentation. For primitive conditions, a simple sand filter can be easily constructed, for example, from a bucket and fine-grained,

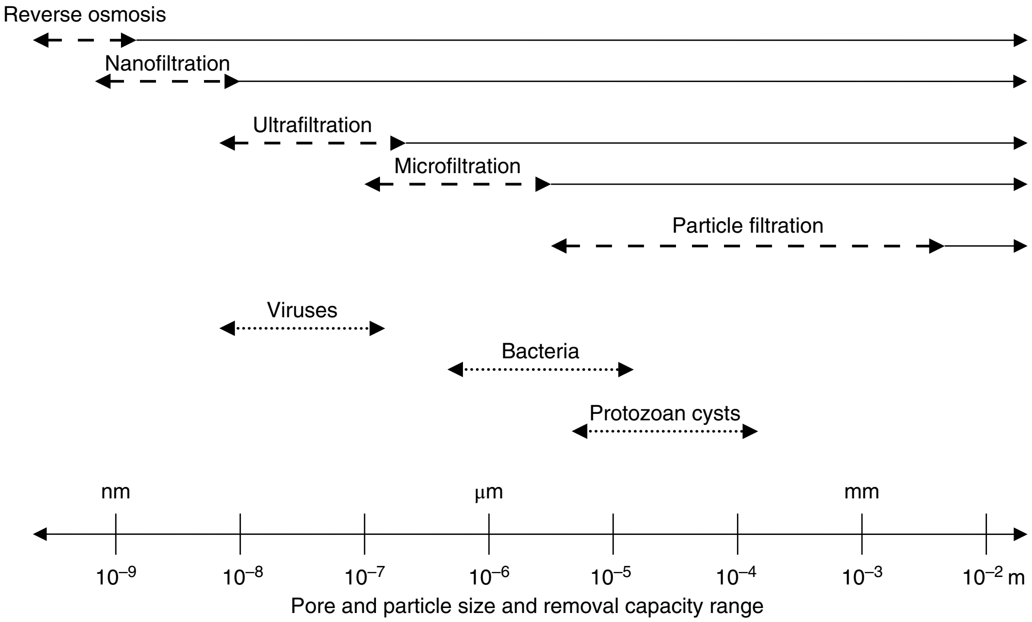

Figure 4.1 Pore size (dashed lines) and range of removal capacity (solid lines) of various filtration methods and general size range of microbial particles (dotted lines).

heated and washed sand. Primitive filters can also be constructed, for example, from used woven and multilayered fabrics.

In addition to particle granular media, filtration media can be made of ceramics or special membranes. A smaller pore size and thus removal of smaller particles can be achieved by ultra- or nanofiltration and reverse osmosis (RO) technology. The RO technique is also effective for removal of monovalent ions and organic compounds of molecular weight greater than 50 (WHO, 2011). RO is the most commonly used technique for desalination of seawater.

4.2.5.4 Other Treatment Methods

Ultraviolet (UV) radiation, especially in the UV-A and UV-B bands, is effective against microorganisms; the optimal wavelength is approximately 265 nm (LeChevallier and Au, 2004). The permeability of UV radiation is reduced by, for example, organic and cloudy material and humus in water (LeChevallier and Au, 2004). Under primitive conditions solar UV radiation can be utilized for drinking water treatment, for example, by exposing the water bottles to direct sunlight for some hours (McGuigan et al., 1998).

Activated carbon is used, for example, in water filters, usually in either powdered or granular form (WHO, 2011). Activated carbon absorbs taste and odor compounds, cyanobacterial toxins, and other organic chemicals (WHO 2011). Removal of microbes is only minimal and occurs through adhesion of the microbes on the surface of activated carbon particles (Backer, 1995).

Electrochemical technologies have been investigated for the removal of organic and inorganic contaminants. Key challenges facing these technologies are related to formation of toxic by-products (e.g., perchlorate and halogenated organic compounds). Technologies may be promising but the mechanisms involved in the oxidation of organic compounds and the corresponding environmental impacts have not been fully addressed (Chaplin, 2014).

Ion-exchange techniques are based on the charge exchange between the water phase and the solid resin phase. These techniques can be used to reduce the hardness and remove contaminants such as nitrate, fluoride, arsenic, selenium, and uranium (WHO, 2011).

4.2.6 Surveillance for Waterborne Diseases

Surveillance of waterborne diseases and outbreak investigation is usually the responsibility of the local, state, regional, or national public health authorities. A successful investigation requires close collaboration between public health, medical, and environmental authorities together with laboratory, veterinary medical, and water treatment plant management expertise applying the One Health concept.

The WHO defines a waterborne outbreak as an episode in which two or more persons experience a similar illness after ingestion of the water from the same source and when the epidemiologic and laboratory evidence implicates the water as the source of the illness (WHO, 2011). The main concern of water safety is focused on the acute illnesses that are typically caused by pathogenic microbes. However, chemical toxicants may also cause acute illnesses (intoxications), for example, after chemical accidents or industrial releases. But, more typically, they cause chronic diseases like cancers after prolonged exposure to elevated concentrations. Based on the strength of the epidemiologic and laboratory findings, the source of the outbreak can be classified as suspected or confirmed. A sufficient number and volume of samples collected from the suspected drinking water at *the early stages of investigation* are essential to catch the possible cause and prove the connection between the exposure and the outbreak (Hunter et al., 2003).

4.2.7 Requirements for Drinking Water Quality

The WHO has established revised guidelines for drinking water quality that can be applied to national standards and legislation, taking into account the national climatic, geographic, socioeconomic, and infrastructural characteristics, as well as national health-based targets (WHO, 2011). In general, water intended for human consumption "must be free from any micro-organisms and parasites and from any substances which, in numbers or concentrations, constitute a potential danger to human health" at the point of compliance (Council of the European Union, 1998).

Since the analysis of all possible enteropathogens can be laborious and require special analytical techniques, several indicator organisms have been proposed, among the earliest being *E. coli* (Ashbolt et al., 2001), which is abundant in human and animal feces. Total coliform and *E. coli* counts are used worldwide as indicators for fecal contamination of drinking and recreational bathing water (Edberg et al., 2000; Havelaar et al., 2001; Rompre et al., 2002; Scott et al., 2002). A microbiological criterion for drinking water hygiene used commonly worldwide requires that *E. coli* or fecal enterococci should not be detected in a 100-mL water sample. Requirements for sampling and limits for tolerated concentrations of various chemical toxicants are given in international or national regulations and are based on the national risk assessment and WHO guidelines (WHO, 2011).

4.2.8 Water Safety Plans (WSPs)

The purpose of drinking water treatment and drinking water hygiene is to minimize the adverse health effects for the consumer, although in practice it is impossible to reduce the risks to zero under all circumstances (Hunter and Fewtrell, 2001). The acceptability of risk is dependent on the given population, circumstances, and time; a risk accepted in a community is not necessarily accepted in another community.

In 2004 the WHO introduced the Water Safety Plans (WSP) approach for ensuring safe drinking water supply. The WSPs draw on many of the principles and concepts from other risk management approaches, in particular from the multi-barrier concept and from the Hazard Analysis of Critical Control Points (HACCP) approach. The WSP should be developed and implemented for individual drinking water supply systems by using a comprehensive risk assessment and risk management approach that includes all steps in the water supply from catchment to consumer (Figure 4.2) (WHO, 2011). The WSP strategy has recently been adopted as a regulatory requirement in many countries.

Water Safety Plans combined with Quantitative Microbiological Risk Analysis (QMRA) will help drinking water producers and public health authorities set and manage health-based targets for drinking water. Only a few countries, among them The Netherlands and the USA, have set quantitative guideline values for the acceptable annual risk. In The Netherlands, health regulators have set requirements for drinking water companies such that the annual risk for water-associated gastrointestinal illness is less than one person affected per 10 000, 95% of the time (Smeets et al., 2009, 2010; Schijven et al., 2011). The US Environmental Protection Agency (USEPA) has introduced a health-based target in which less than one new infection per 10 000 persons should occur annually, using *Giardia* as a reference organism (Macler and Regli, 1993). The logic behind this requirement is that *Giardia* is more resistant to drinking water disinfection than other microbial pathogens. The requirement is based on the numbers of annually reported cases of giardiasis in the USA at present.

Even though the WSP concept was implemented more than 10 years ago, only limited scientific evidence is available on its impact in improving water safety and health (Dyck et al., 2007; Mudaliar, 2012). In Iceland, a WSP was adopted into legislation in 1995. Recent Icelandic surveillance data showed that both the microbiological quality of tap water was improved (heterotrophic counts < 10 CFU/mL) and the incidence of diarrhea in the population was decreased significantly (Gunnarsdottir, 2012), thus demonstrating the positive impact of an implemented WSP.

The WSP concept can be implemented in all water treatment systems, both large and

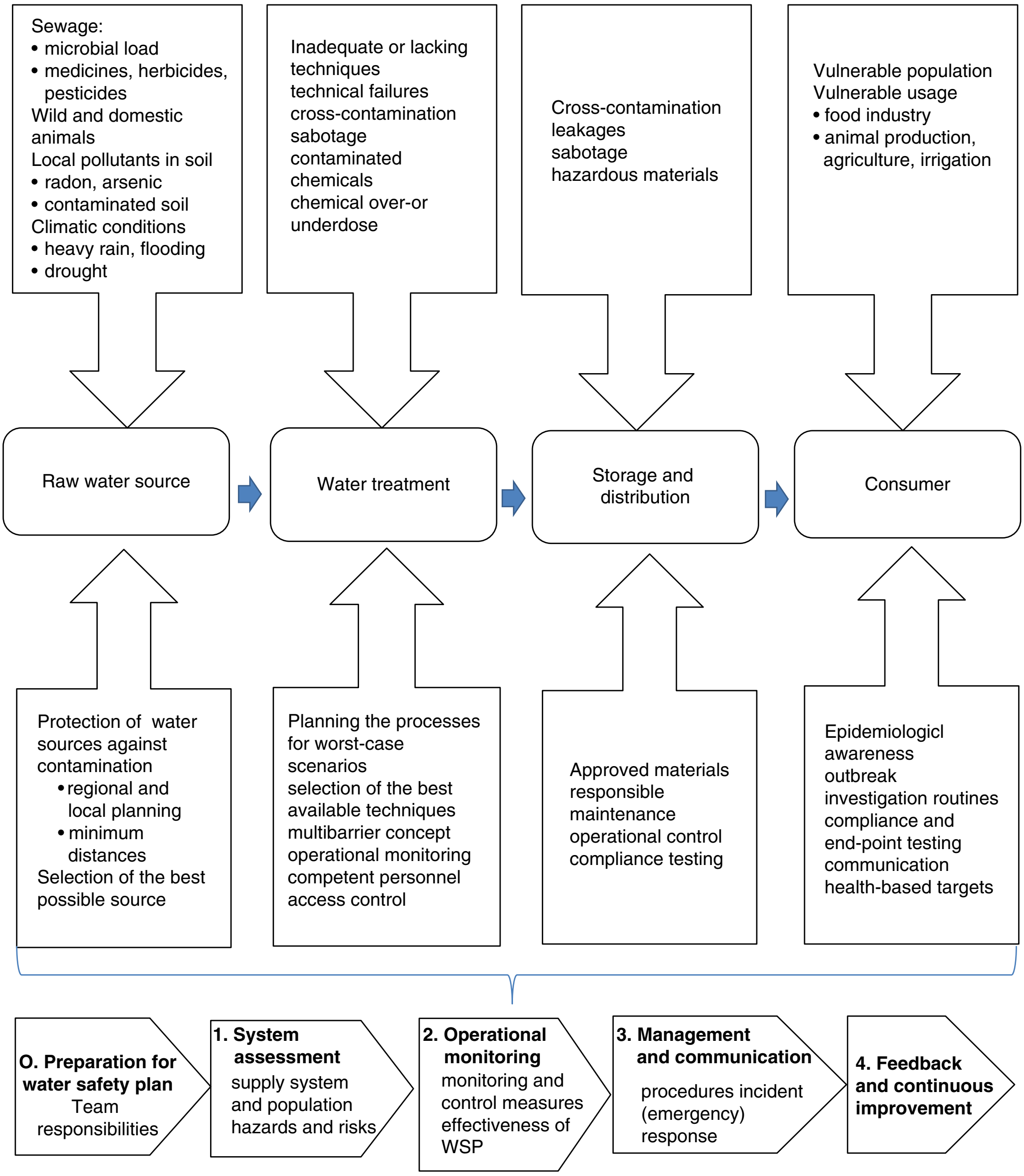

Figure 4.2 Schematic illustration of the water supply system from raw water source to water consumer (in the middle) combined with the hazards and risk factors (arrow boxes downwards) and risk management options (arrow boxes upwards). Hazards and risk factors may have direct or indirect impacts on drinking water safety and increase the risk consequences and severity. Risk management includes actions that intend to reduce and manage the hazards and risk factors. Steps 0–4 of the Water Safety Plan (WSP) represent fundamental parts of the WSP taking into account the whole water supply system from the raw water to the water consumer.

small, and in developed and developing regions, since it is based on the local infrastructure, socioeconomic and environmental conditions, and on nationally decided health-based targets (WHO, 2011). However, the development and adoption of the WSP system may require education, improved knowledge of the water supply system, and improved cooperation between different stakeholders and experts. Furthermore, technical and financial resources are required to improve the treatment and distribution infrastructure, even in developed regions. Designing and ensuring a safe drinking water supply system is a multi- and interdisciplinary challenge, where close collaboration and cooperation between veterinary, public health, and medical professionals, together with experts on security and quality, water engineering and communication, is essential (Rose, 2002; IWA, 2004; Meinhardt, 2005; Courtenay et al., 2015).

4.3 The Water/Energy/Food Nexus: Mitigating Global Risks

Water is vital not only for human consumption, but also for agricultural production, electricity generation, and manufacturing. The accelerated global population increase in the past century combined with the acceleration of gross domestic product (GDP) growth (especially in developing nations) has placed significant stress on global water supplies. This discussion surrounding the water/energy/food nexus attempts to highlight these stresses in an effort to mitigate the risks associated with stressed global water supplies. Ignoring these risks can have catastrophic consequences from both social and economic perspectives.

There are a number of challenges that hamper the ability to mitigate threats to this nexus on a global scale. These challenges are due to myriad factors, including the characteristics of the global economy combined with the need for different solutions for different regions, depending on the nature of the challenges specific to those regions. For example, many manufacturing processes are being shifted to developing nations due to their lower labor costs. These processes can stress existing water supplies, thus diverting water from agricultural uses. Agriculture in many regions utilizes large quantities of water: as much as 90% of the water usage in some Gulf Cooperation Council (GCC) countries is for agriculture (Dziuban, 2011). Water is also vital in most areas of the world for the production of electricity.

Water issues can cross boundaries and regions across the globe. For example, the Middle East has 5% of the world's population, but only 1% of the world's renewable water resources. Per capita availability of water is the lowest, rates of withdrawal already the highest, and more water storage has been installed than in any other region of the world (Granit, 2010). On the other hand, the state of Illinois would seem to have abundant water sources (e.g., it is bordered by one of the Great Lakes and the Mississippi River). However, despite its location and typical climate, Illinois has been susceptible to drought (Figure 4.3; Illinois State Water Survey, 2015). In some other areas, especially the western states of the USA, the issue is related to groundwater recharge rates for aquifers (Meixner et al., 2016). Average declines of 10–20% are expected across the southern High Plains aquifers (Figure 4.4; Meixner et al., 2016).

4.3.1 Water/Energy Nexus

Before we examine the water/energy nexus, it is important to recognize that there is a direct relationship between electrical energy consumption and GDP. This energy-GDP nexus has been recognized by a number of authors for a variety of countries. Mohanty and Chaturvedi (2015) provided clear evidence of this nexus in the growth of the Indian economy (Figure 4.5). The results from this study clearly demonstrated that electrical energy leads economic growth, that is, increase in GDP, and that growth in economies leads to increased electricity consumption (Figure 4.6). However, this relationship is changing over time for more developed nations such as the USA (USEIA, 2013). It is projected that by 2040 growth in electricity consumption (0.9%) will be less than half the growth in GDP (2.4%). This projection reflects a change as compared to

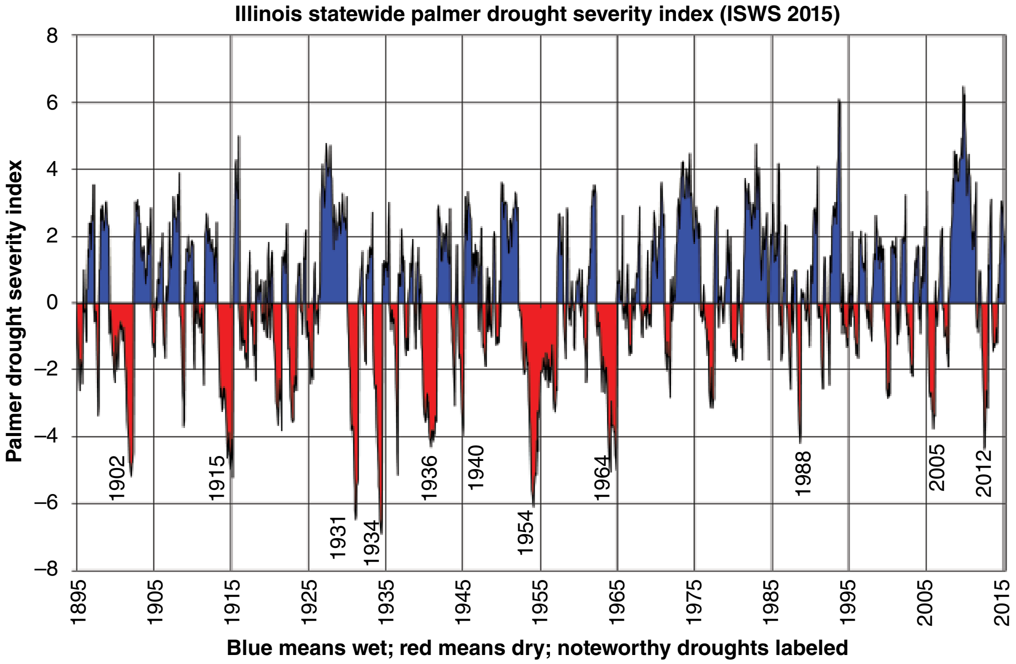

Figure 4.3 Incidence of drought within the state of Illinois. *Source:* Illinois State Water Survey, 2015. Reproduced with permission of Dr Jim Angel.

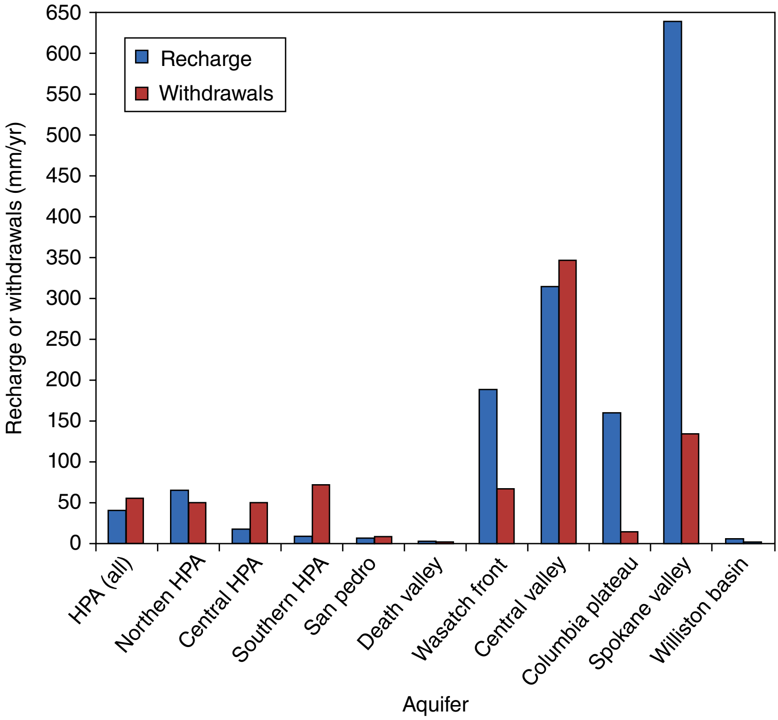

Figure 4.4 Recharge and withdrawals from aquifers across the western USA. HPA, High Plains aquifers. *Source:* Meixner et al., 2016. Reproduced with permission of Elsevier.

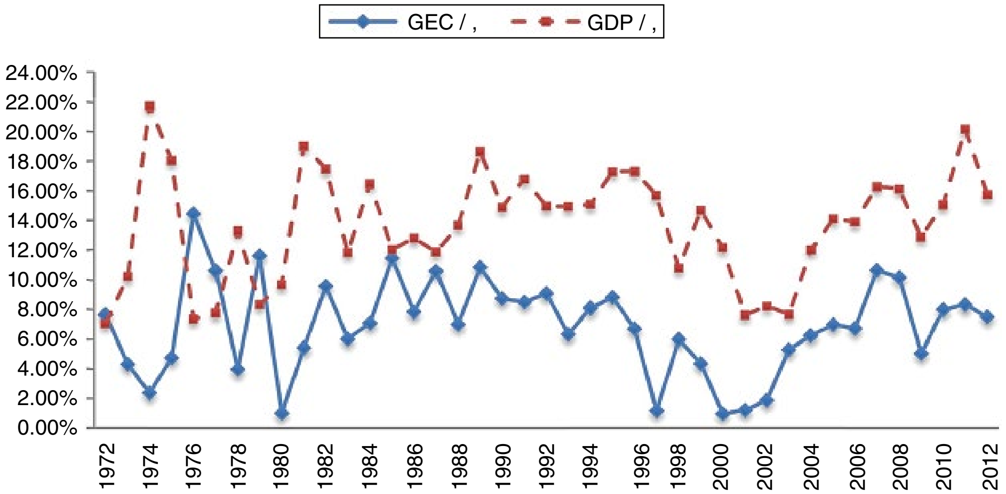

Figure 4.5 Annual growth in electricity consumption (GEC) and nominal gross domestic product (GDP) for India. *Source:* Mohanty and Chaturvedi, 2015. Reproduced with permission of Dr Asit Mohanty.

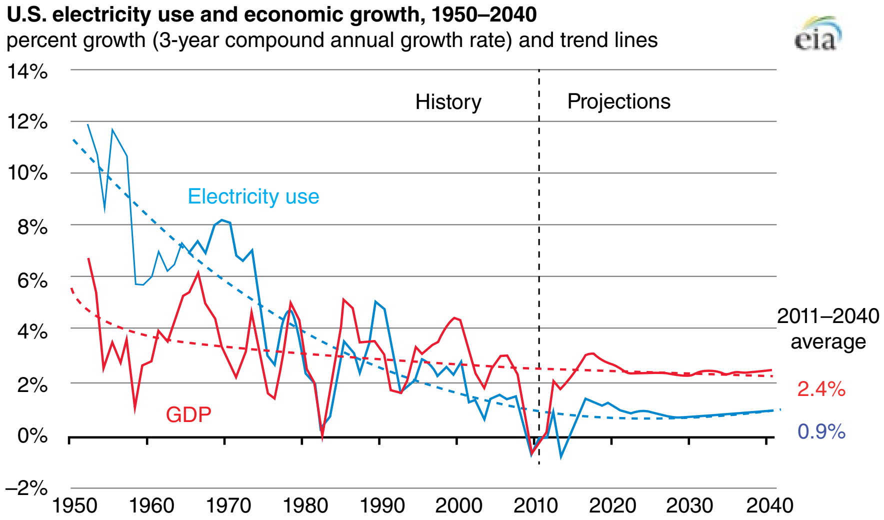

Figure 4.6 Relationship between energy consumption and gross domestic product (GDP) for the USA. *Source:* USEIA, 2013.

the time frame prior to 1975 when growth in electricity consumption outpaced GDP, and between 1975 and 1995 when the growth rate for these factors were nearly identical. This change for the USA is attributed to a number of factors including aggressive energy efficiency policy and investments along with shifts toward less energy-intensive industries.

Now let us bring water into the energy equation. A prominent component of this nexus is the amount of water required for electricity generation. Large quantities of water are typically withdrawn from the environment in traditional methods to generate electricity. *Withdrawal* is defined as water removed from the ground or diverted from a surface-water source for use (Kenny et al., 2009). This water is typically used as a heat-exchanging medium. In other words, it is used to absorb waste heat and is then discharged back into the environment. *Consumption* of water for these applications is defined as water that has been withdrawn and is not returned to the environment after use. This consumption could be due to evaporation, process loss, and so forth (Faeth and Sovacool, 2014).

Faeth and Sovacool (2014) compared water consumption (m^3) per megawatt hour (MWh) of electricity produced from a variety of sources (Table 4.2). Using renewable energy sources in place of nuclear, coal, and natural gas to generate electricity significantly reduces the amount of water required for electricity generation. Nuclear generation of electricity both withdraws and consumes the greatest amount of water. Coal and natural gas generation of electricity both withdraw orders of magnitude more water than solar photovoltaic (PV) and wind. Water consumption for coal and natural gas is approximately the same and is four times greater than solar PV, while wind is exponentially less as water consumption is negligible (Faeth and Sovacool, 2014; Li et al., 2012). This is a major advantage for renewables and provides a means to reduce the amount of water used in the generation of electricity, thereby reducing risks to food and water security.

The implication of the water/energy nexus can be illustrated by examining trends in the Gulf Cooperation Council (GCC). Electricity needs in the GCC have been growing at a rate of 5–8% per year. Electricity consumption per capita (10 000 kWh/capita) and water consumption per capita (850 m^3/year/capita) within the GCC are exceptionally high (Economist Intelligence Unit, 2010). Based on these facts, it is critical to reduce the amount of water used in the generation of electricity. For example, if approximately 1000 MWh of electricity was produced using renewable energy, the amount of water saved would be equivalent to the amount of water produced by two to three desalination plants!

There are a number of projections, based on revising the global portfolio for energy generation, that would significantly impact global risks surrounding the water/energy nexus. It is important to note that water consumption as well as carbon emission reductions should be considered when altering existing electricity generation portfolios. Many of the positive scenarios listed below will require a combination of technological advancements along with policy initiatives.

4.3.1.1 Nuclear

Nuclear power is the largest source of low-carbon electricity generation, yet it suffers from the stigma of such disasters as Chernobyl (1986, Ukraine), Three Mile Island (1979, Pennsylvania, USA), Stationary Low-Power Reactor Number One (1961, Idaho, USA), and more recently the Fukushima Daiichi nuclear power plant accident in 2011 (International Energy Agency and Nuclear Energy Agency, 2015). In addition, the management of the nuclear waste generated from plant operation creates the issue of where, how, and for how long to dispose of the spent fuel rods that are still highly radioactive. Even with its torrid history, nuclear power is expected to account for 17% of global electricity production by 2050 (World Nuclear Association, 2016). Major growth of the nuclear generation market is expected to occur in China, India, the Middle East, and the Russian Federation. Increased research and development (R&D) in nuclear safety, advanced fuel cycles, waste management, and innovative designs are necessary to achieve the projected growth.

As pointed out earlier, another significant issue with nuclear generation of electricity is that, whereas the carbon emissions are low, it is one of the worst in terms of water withdrawal and consumption (Table 4.2). The majority of water used by a nuclear power plant is withdrawn for cooling and about 98% is returned but, due to the large volumes withdrawn, there is still a substantial amount of water consumed. It will be critical to implement technologies that reduce these water consumption and withdrawal requirements. A few examples of water reducing

Table 4.2 Water usage per electricity generation method.

	Withdrawal (m^3/MWh)	Consumption (m^3/MWh)
Nuclear	168	1
Natural gas	43	0.4
Coal	86	0.4
Solar PV	0.1	0.1
Wind	0	0

Source: Faeth and Sovacool, 2014. Reproduced with permission of Paul Faeth.

methods include using reclaimed wastewater for cooling such as the Palo Verde nuclear power station near Phoenix, AR, USA, and dry cooling such as the Bilibino power plant which is above the arctic circle in Russia (International Atomic Energy Agency, 2012).

4.3.1.2 Coal

Currently, coal-based electricity generation is the predominant method globally, and often the cheapest form of energy generation in many regions, because the coal is easy and cheap to mine and burn to create electricity (*The Economist*, 2014). But a global slowdown in coal demand has been observed and is projected to continue due to stringent environmental policies designed to reduce CO_2 emissions (International Energy Agency, 2017). Because electricity generation from coal requires large quantities of water, this trend would decrease global water demand for electricity generation.

There are a number of R&D initiatives underway to deploy High-Efficiency Low-Emission (HELE) technologies to improve the efficiencies of coal plants along with decreasing primary pollutants (e.g., SOx, NOx, etc.) (International Energy Agency, 2012). It will also be necessary to deploy carbon capture and sequestration systems to reduce CO_2 emissions to meet future required levels (International Energy Agency, 2013a). However, another challenge is that many coal-fired plants are old, inefficient, and beyond their designed lifetimes, in addition to using especially high volumes of water.

4.3.1.3 Natural Gas

Electricity generation through the use of natural gas is displacing coal-based electricity production in certain regions of the globe. Relatively low costs for natural gas have also aided this trend. This trend looks promising from the standpoint of reduced CO_2 emissions from electricity generation, yet it will have a relatively small impact on water usage because both coal and natural gas have similar water consumption. And consideration needs to be given to the broader environmental footprint of natural gas production through hydraulic fracturing or hydrofracking, which can cause problems with water contamination and disposal (Vaidyanathan, 2016; Llewellyn et al., 2015).

4.3.1.4 Renewables

At the same time, due to technological advances, electricity generation from renewables is predicted to rise substantially. Some report that photovoltaic (PV)-based electricity generation could achieve a global share of electricity generation of 16% by 2050 (International Energy Agency, 2014). In fact, combining PV (panels directly convert solar energy to electricity) and solar thermal (solar energy used to create heat to run heat engines to create electricity), solar technologies could become the leading source for electricity even earlier, by 2040 (International Energy Agency, 2014). These scenarios would significantly reduce the stress of electricity generation on water sources, but there are a number of caveats for these scenarios. It is assumed that transitional policy support mechanisms are put in place in some markets to enable PV electricity costs to reach competitive levels with existing technologies. In addition, the variability of solar generation needs to be addressed through a number of means. This requires advances in interconnection to the grid, demand-side response, flexible generation, and energy storage

(Kenny et al., 2009). The proportion of electricity generated from renewable sources has varied widely across European countries, though on the whole it has steadily increased from 2004 through 2014 (Figure 4.7).

Electricity generation by wind is predicted to reach 15–18% by 2050 (International Energy Agency, 2013b). This scenario again would reduce stress on global water sources. The caveats surrounding this scenario are that a significant amount of R&D must be funded to improve design, materials, manufacturing technology, and reliability to optimize performance and reduce uncertainties for plant output (International Energy Agency and Nuclear Energy Agency, 2015). Just as with solar, transitional policy support mechanisms will need to be put in place. The issue of intermittence and changes to grid infrastructure will also need to be addressed in order for wind to reach the levels predicted. It will also be important to adapt wind plant design to cold climates and low-wind velocity sites.

4.3.1.5 Water/Energy Nexus Summary

The challenge of the water/energy nexus becomes apparent when the results from the studies above are compared:

- Electricity consumption drives economic growth. And although for developed nations growth rates of energy consumption might be less than GDP growth, the relationship still exists.
- It is important to have reliable and low-cost electricity in order to drive economic growth. This requirement has hampered the penetration of renewables in certain regions of the globe.
- Water consumption in electricity generation is highly reliant on the means of generation.
- Non-renewable sources for electricity generation tend to consume higher quantities of water than renewable resources.
- Renewable resources have the greatest potential to reduce water usage during electricity generation.
- While the amount of renewable generation capacity has increased worldwide, the majority of generation is still accomplished through use of resources (e.g., coal and nuclear) that require large quantities of water.
- Solutions to the water/energy nexus must include a combination of demand-side reductions, as well as further efforts to drive down the costs for renewable energy sources.

4.3.2 Water/Food Nexus

An example of the water/food nexus and its relationship to regional water supply and demand can be illustrated by again examining trends in the Gulf Corporation Council (GCC). The combination of a growing population and increased food production has resulted in great demands on water supplies in the GCC. For example, Saudi Arabia (KSA) quadrupled its domestic food production during the 1980s and early 1990s with a major focus on wheat production, a grain that relies on heavy use of water resources (World Bank, 2016a; Elhadj, 2014). Much of this production has now been moved outside KSA because of the severe depletion of the ground-water supply (Sfakianakis et al., 2010). The impact of agriculture on water is especially evident by the fact that, within KSA, dairy farms require on average 2300 gallons (8.7 m^3) of water to produce one gallon of milk (Dziuban, 2011).

This example illustrates how water supply and demand can directly impact food production and supply chains. This direct supply-demand relationship is analogous to the one observed for water/energy. Just as regions with low water supplies should consider electricity generation methods that require low water demands (i.e., solar PV and wind), regions with low water supplies should focus on regional food supplies that have low water demands.

Despite these similarities, there are some differences between the water/energy and water/food nexus. Energy efficiency methods

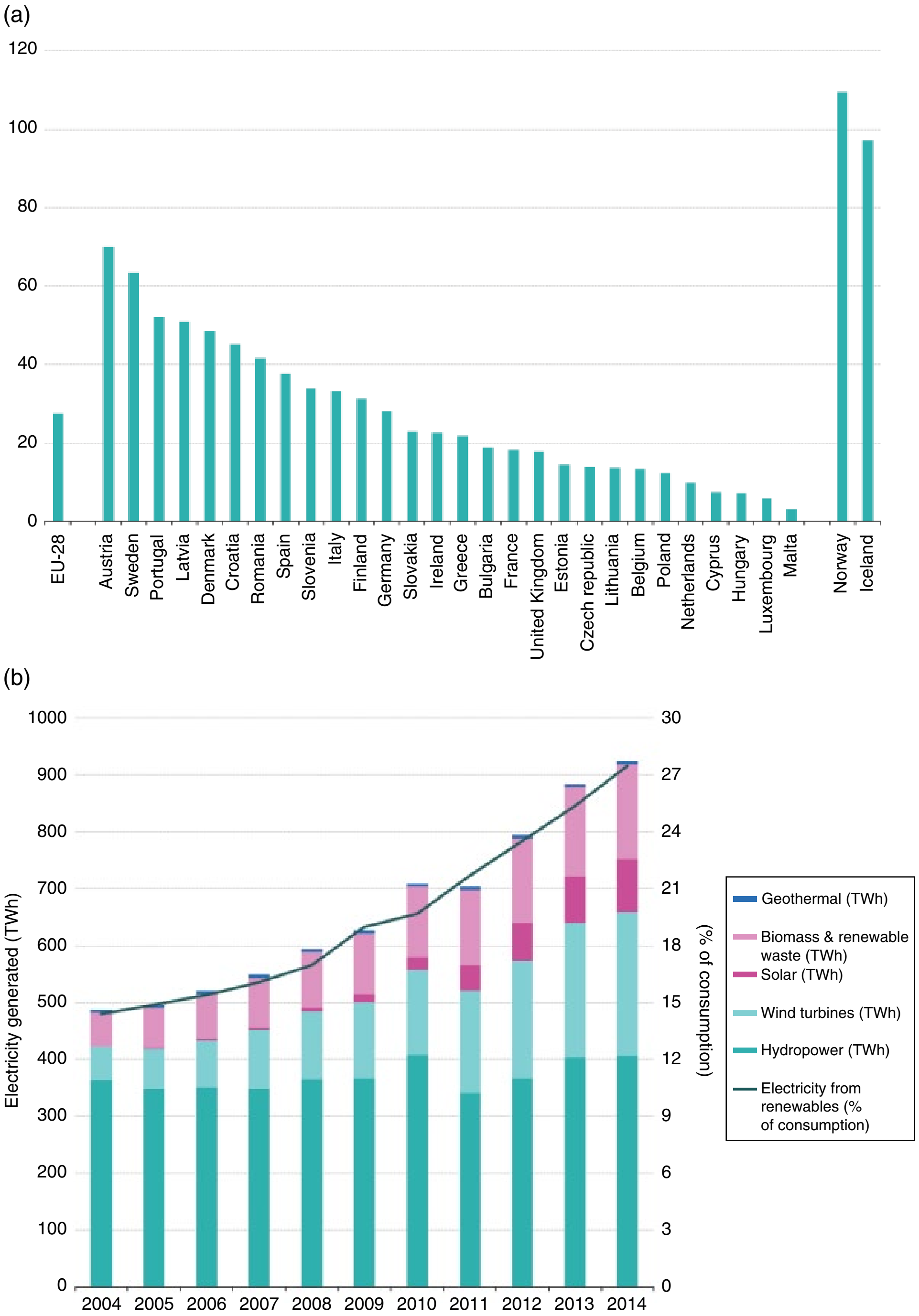

Figure 4.7 Renewable infrastructure trends across Europe. (a) Proportion of electricity generated from renewable sources, 2014 (% of gross electricity consumption). (b) Electricity generated from renewable energy sources, EU-28, 2004–14 YB16. *Source:* Eurostat, 2016.

can reduce water consumption for electricity production, thereby directly reducing water demand. However, the introductions of efficiencies within the food supply chain impacts water in a more indirect fashion. The magnitude of current inefficiencies (or losses) in the food chain can best be understood by considering that "one-third of all food produced for human consumption in the world is lost or wasted" (FAO, 2013a).

The Food and Agriculture Organization (FAO) of the United Nations goes on to say:

> The global volume of food wastage is estimated to be 1.6 gigatonnes of "primary product equivalents", while the total wastage for the edible part of food is 1.3 gigatonnes. This amount can be weighed against total agricultural production (for food and non-food uses), which is about 6 gigatonnes. … The blue water footprint (i.e., the consumption of surface and groundwater resources) of food wastage is about 250 km^3, which is equivalent to the annual water discharge of the Volga River, or three times the volume of Lake Geneva.
>
> *FAO, 2013a*

The FAO defines food wastage as "any food loss due to deterioration or waste" (FAO, 2013a). They explain:

> Food loss refers to a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in the food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, and lack of access to markets. In addition, natural disasters play a role. Food waste refers to food appropriate for human consumption being discarded, whether or not after it is kept beyond its expiry date or left to spoil. Often this [wastage] is because food has spoiled but it can be for other reasons such as oversupply due to markets or individual consumer shopping/eating habits.
>
> *FAO, 2013a*

Food wastage can be divided further into an upstream and a downstream component. Upstream losses occur in the production phase, while downstream losses occur in the consumption phase (FAO, 2013a). It has been shown that food wastage is very dependent on the nature of the local conditions with a region or country. This regional attribute is also complicated by the fact that the source of food wastage (upstream vs downstream) depends on the overall income of the region (FAO, 2013a). For example, developed regions tend to have the greatest wastage downstream, while developing regions tend to have the greatest wastage upstream. The relationships between water and food outlined demonstrate the importance of decreasing food wastage. Reductions in food wastage will reduce the overall blue water footprint reported previously. The specific solutions deployed to reduce wastage and hence reduce the water footprint will vary not only by region, but also by regional income. A number of countries are implementing strategies to combat food waste. For example, in the USA, USEPA is conducting several studies on how to reduce food waste and use food waste as a value-added product (USEPA, 2016). The European Commission's new Circular Economy Package has food waste prevention as an important part (http://ec.europa.eu/food/safety/food_waste/eu_actions/index_en.htm).

The discussions above outline the additional complexities of the water/food nexus as compared to the water/energy nexus. Another consideration for the water/food nexus is not only food wastage but also activities that decrease the *quality* of the water supply. Regions may have sufficient water supply but if that supply is contaminated, it is not usable in the food supply chain unless decontamination procedures are deployed. The challenge is that activities that contaminate the water supply can range from industrial releases to the everyday use of pharmaceuticals and personal care products (PPCPs). These sources represent two extremes and are indicative of the complications of clean-up and management of water supplies.

Another unique aspect of the water/food nexus is that the means to mitigate risks related to water and food can be designed also to impact the water/energy nexus. One example relates to the management of food waste. Nearly 40% of the food produced within the USA is not consumed, but instead becomes food waste (Gunders, 2012). It has been shown that food waste can be collected and used as an input stream to anaerobic digesters (Nazaroff and Alvarez-Cohen, 2001; Smith, 2009). These digesters can be located at wastewater treatment facilities. The net result impacts both water and energy. The food waste is repurposed and used as a feed stock for the anaerobic digester instead of being sent to a landfill. The anaerobic digester produces biogas that is then used as an energy source within the wastewater treatment facility (Fulton, 2014; USEPA, 2016).

4.3.2.1 Water/Food Nexus Summary

The interdependencies of the water/food nexus become obvious when the results from the discussion above are summarised:

- Regional water resources directly influence the type of food production and how long it can be sustained; therefore regions with low water supplies should focus on regional food supplies that have low water needs.
- Good quality water is important for food production.
- Reductions in food wastage will dramatically decrease water consumption.
- Food waste could be used as a value-added product to generate energy without using additional water resources.

4.3.3 Water/Energy/Food Nexus: Summary and Next Steps

The water/energy/food nexus demonstrates the risks associated with climate change on a global basis. Risks, and therefore their mitigation strategy, will vary based on the specific region of the globe. As indicated previously, regions will modify their electricity generation portfolio based on water considerations as well as CO_2 emission reduction considerations. Food security and resiliency issues will also vary with the specific region of the globe. The challenge with the water/food nexus is the need for not only *quantity* but also *quality* of water. These requirements illustrate why water management will be crucial in driving the economies of the future. The resulting interlinkage between water, food, energy, cities, and the environment motivates the suggestion of defining an “expanded water nexus” to emphasize water dependency (World Bank, 2016b).

Geopolitical events also help to create risks related to this nexus. They demonstrate the need to include resilience factors when examining potential solutions. It is important to start considering solutions that impact *all three components* (water, energy, food). Too often solutions are being pursued that reduce risks around one aspect (e.g., water/energy) but have a neutral or negative impact on the other aspect (e.g., water/food). It also is important to develop solutions that start with “low hanging fruit” approaches, such as efficiency, and then transition to more costly or complex solutions. In the food waste management world, this solution methodology is defined as the food waste pyramid. It suggests starting with *reducing* waste, then exploring *reusing, recycling or recovering*, followed only by the least environmentally friendly solution of *landfill* (FAO, 2013b). It means always starting with *efficiency* improvements that will inherently reduce overall demand.

This approach requires organizations that have the ability to benchmark current resources, estimate their level of resilience, and then understand how climate change, geopolitical events, and other factors can impact the resources. Organizations such as the Prairie Research Institute (PRI; www.prairie.illinois.edu) at the University of Illinois are engaged in this systematic analysis, which enables various scenarios to be examined. Typical activities conducted by PRI and that should be done globally include:

- Tracking weather, water, and soil data such as done by the PRI's Water and Atmospheric Resources Monitoring (WARM) program.
- Water planning.
- Water use and reuse.
- Disaster response scenarios.
- Energy efficiency.
- Alternative energy sources.
- Food wastage reduction and management.

The water/energy/food nexus provides a major challenge at a global scale, yet it must be addressed at a regional level with region-specific solutions. It requires coordination across utility and market sectors that have had limited coordination in the past. Failure to coordinate this effort will not only impact economic growth, but also could ignite civil unrest. As indicated by the World Bank (2016b) in their report: "…water management will be crucial in determining whether the world achieves the Sustainable Development Goals (SDGs) and aspirations for reducing poverty and enhancing shared prosperity."

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