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Water and Health

A Dynamic, Enduring Challenge

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6.1 Introduction

Health outcomes have been a primary motivator for many developments in the water sector, particularly in water supply, sanitation and water resources development. The evolution of water research over past centuries in Europe and North America, where reliable and abundant quantities of water are widely accessible, made water quality and acute health outcomes a primary concern. The priorities of the sector have shifted since then as research expanded into different geographies and development challenges. In recent decades, the sector was influenced by the Millennium Development Goals (MDGs) to focus on delivering improved water facilities. Currently, it is being strongly directed by the Sustainable Development Goals (SDGs; see Chapter 1), and the dialogue that preceded the goals, to consider levels of service provision.

In this chapter, we first explore in Section 6.2 the established approaches for classification and measurement of water-related health outcomes, with an emphasis on infectious diseases. In Section 6.3, we provide some examples of shifts in the water sector where new innovations (in measurement and treatment methods) and knowledge (particularly evidence of emerging diseases) have substantially impacted public health. In Section 6.4, we explore how knowledge of water and health linkages is being enriched by research into chronic drinking water related diseases. And finally, in Section 6.5 we issue a challenge to future water researchers, from all disciplines, framing three major areas where innovation is needed to overcome seemingly intractable water-related health problems.

6.2 Classifying and Measuring Health Outcomes

Infectious diseases were the initial driver for health-related water research taking place in areas with relatively abundant water, in Europe and North America. This focus on infectious diseases was extended to other parts of the world, and in 1972, as part of the

Water Science, Policy, and Management: A Global Challenge, First Edition. Edited by Simon J. Dadson, Dustin E. Garrick, Edmund C. Penning-Rowsell, Jim W. Hall, Rob Hope, and Jocelyne Hughes.

seminal Drawers of Water study in East Africa, a functional water-related disease classification was created (White et al. 1972; Table 6.1). This classification, which is sometimes referred to as the Bradley classification, for the first time considered diseases not by their causal microbes or symptoms of infection, but by their transmission pathways. This was done to enable consideration of the impact of interventions. It was also intended to highlight the importance of water quantity in the communities of East Africa, where the study was based. The classification was designed to differentiate the water-related diseases that are associated with water resource developments (such as dams and irrigation canals), including the insect vector-borne disease of malaria and water-based diseases such as schistosomiasis.

Our understanding of the transmission cycles of many water-related diseases has greatly improved in the decades since this classification was first developed. Transmission is a more complex and sophisticated process than we imagined – for example, the ability of *Legionella* to proliferate intracellularly in free-living freshwater amoebae was only recently understood. It is scarcely possible to capture this complexity and retain a simple and robust categorization. Nevertheless, the original four-category system is now inadequate and many advances in our understanding of water-related disease, several of which are discussed by Bartram and Hunter (2015), must be considered in modern classifications. For example, pathogens in water can directly enter the human body via the respiratory tract as well as via the gastrointestinal route. Indeed, *Legionella*, which now accounts for half the reported waterborne outbreaks in the USA, often enters via the respiratory tract in aerosols. Secondly, the role of handwashing with soap in reducing transmission of conventional respiratory pathogens, such as the influenza virus and other highly infectious diseases, creates a further subsection of water-washed diseases. As raised by Gerba and Nichols (2015), the categorization of water-based diseases

Table 6.1 The Bradley classification of water-related diseases.

Category	Definition	Example
I Waterborne	Where water acts as a passive vehicle for an infecting agent (e.g. faecal-oral diseases).	
a) Classical		Typhoid
b) Nonclassical		Infectious hepatitis
II Water-washed	Where infections decrease as a result of increasing the volume of available water, irrespective of water quality.	
a) Superficial		Trachoma, scabies
b) Intestinal		Shigella dysentery
III Water-based	Where a necessary part of the life-cycle of the infecting agent takes place in an aquatic animal such as a snail.	
a) Water-multiplied percutaneous		Schistosomiasis
b) Ingested		Guinea worm
IV) Water-related insect vectors	Where infections are spread by insects that breed in water or bite near it.	
a) Water-biting		Gambian sleeping sickness
b) Water-breeding		Onchocerciasis

Source: Adapted from White et al. (1972).

merits further attention as well. With the guinea-worm approaching extinction owing to its successful control, a better subdivision of the water-based diseases may be between diseases with an aquatic intermediate host(s) and pathogens that also live non-parasitically in freshwater.

To further complicate classification attempts, gains in knowledge have somewhat blurred the boundary between classical waterborne disease agents and freshwater microbes that can become pathogenic, especially in immunologically compromised hosts. The increase in people experiencing deliberate immunosuppression (e.g. for transplanted organ survival) or suffering immunological damage (e.g. from diseases such as HIV) has widened the range of opportunistic pathogens (Bartram 2015). Additionally, some free-living microorganisms that proliferate greatly in water under certain conditions can produce toxins of public health importance (e.g. some cyanobacteria that cause 'algal blooms' produce neurotoxins). These toxins sit more comfortably within a classification system that includes chemically toxic metals (e.g. arsenic). It remains important, however, to distinguish between infective replicating agents and the vast array of toxic chemicals. The health impacts of toxic chemicals are better understood now (as discussed in Section 6.4) than they were when the Bradley classification was originally developed. At that time, toxic chemicals in water were not considered a critical issue compared with acute infectious disease.

Diarrhoea is an indicator of acute infectious waterborne diseases, and self-reported diarrhoea remains a key method used to measure health risk associated with water supply and sanitation, despite many limitations. Diarrhoea is caused by a range of pathogens, with the majority of childhood deaths from diarrhoea associated with rotavirus, shigella, adenovirus, cholera and *Cryptosporidium*, according to the Global Burden of Disease study (GBD 2018). Diarrhoea remains a major cause of disease internationally: it is the eighth leading contributor to mortality, causing an estimated 1.6 million deaths in 2016. Unsafe water and sanitation are amongst the leading risk factors for diarrhoea, with 72% and 56% of diarrhoea deaths in children younger than five years attributed to unsafe water and poor sanitation, respectively.

6.3 Politics and Innovation in Water and Health

The water and health field changed rapidly over the previous century, constantly evolving to deal with new evidence, changing risks and environments, but also in response to changing societal concerns and political agendas (see Chapters 8 and 19). The drivers of implementation in any sector are strongly political, and water and health is no different, but the sector's work has also been heavily influenced by disruptive innovations. In water-related health research (and health-related water research), innovations in the science of detection and treatment and changes in knowledge have rapidly shifted academic discussions into action. They have changed the way that researchers and practitioners in the sector work. Whilst there have been many innovations in the broad field of water and health (Bartram 2015), in this section we draw from David Bradley's experience of working in the sector across six decades to explore some of his key reflections on the politics and innovations that have driven agendas and shaped the sector. Understanding these drivers of change is helpful for reflecting on how impact can be achieved.

6.3.1 Measurement: Understanding the Role of Malnutrition and Infection in Diarrhoea

In the 1920s, research into infectious diarrhoeal disease and nutrition began to overlap. The role of nutrition in modifying host resistance to infection was recognized and initially overestimated, drawing considerable research attention in the following decades (Scrimshaw et al. 1959). Research focused on the impacts of nutrition on infections, with comparatively few studies examining the reverse – how infections impact nutrition. By the 1960s, the complexity of infection–malnutrition interactions was better understood, but the relative importance of infection versus nutrition was still debated. It was recognized that in cases '[w]here both malnutrition and infection are serious … success in control of either condition commonly depends on the other' (Scrimshaw et al. 1959, p. 396). Yet, research and interventions continued to focus more on nutrition, in part because determination of causal agents (pathogens) remained out of reach for many diarrhoeal cases.

In this case, disruptive innovation took the form of increased measurement capability, which enabled the detection and quantification of faecal–oral pathogens in faeces. Technological innovations increased detection of aetiological agents: first of bacteria with better culture methods, then with electron microscopes viruses were identified on and in gut tissue. Innovations in tissue culturing techniques for detection in later decades helped to expand virus vaccine programmes (College of Physicians of Philadelphia 2019). Some of these changes were very rapid: *Cryptosporidium* was first detected in Bangladesh immediately following news of a paper that reported a new method for staining the parasite cysts (David Bradley, personal communication). These innovations were supported by collaborations between microbiologists and nutritionists, such as the ground-breaking work in Guatemala tracking the impact of infections on growth faltering in malnourished children (Mata et al. 1972). Identifying pathogenic causes of diarrhoea helped to balance the debate about the relative importance of infection versus nutrition and pushed the conversation towards treatment and environmental interventions.

6.3.2 Treatment: Oral Rehydration Therapy (ORT)

Cholera is one of the most researched diarrhoeal diseases. It can spread rapidly through a population, causing severe fluid loss through diarrhoea and vomiting, and leading to death if not treated. Before the nineteenth century, if you contracted cholera there was a 70% chance you would die. Cholera originated in South Asia and travelled to Europe and North America as trade increased. More recently, the 'seventh pandemic' has spread the disease to many areas across the globe. Large cholera outbreaks in Europe and North America have been identified as drivers of the sanitation revolution in the industrialized world (Guerrant et al. 2003). With the recognition that dehydration was the cause of death from cholera infections in the 1830s, treatments started to include intravenous fluid replacement (Guerrant et al. 2003), reducing the mortality rate to 40%. This required many litres of sterile intravenous fluid, however, with a significant production and storage chain to maintain during epidemics.

In the 1960s, new research identified the importance of glucose in enabling the uptake of sodium in cholera patients, sparking the development of ORT, with the first trials taking place in what is now Bangladesh in 1970. ORT use rapidly went from trial to implementation as the 1971 Bangladesh war of independence resulted in cholera treatment being needed for high numbers of refugees – higher than could be supplied by intravenous methods. Mortality was reduced with ORT down to 3.6% (Guerrant et al. 2003), with intravenous treatment largely replaced except in cases with vomiting. Over time the success of ORT as a low-cost intervention, capable of being delivered in settings with limited medical facilities, has enabled the transformation of cholera from a disease endemic in Bangladesh, to one that has been observed to be underreported in specific areas where there is good access to ORT as most cases can be treated at home.

Cholera remains a very serious disease, with regular outbreaks across the world. It is considered an 'indicator of inequity' because it typically impacts the poorest who are malnourished and lack adequate water and sanitation. Research on ORT and cholera has continued, broadening the solution from sugars to carbohydrates more generally. But whilst the timing of outbreaks remains difficult to forecast, and environmental or human reservoirs of the disease are debated, ORT has enabled rapid and cost-effective responses that have saved countless lives. In this case innovation occurred rapidly, driven by a case overload associated with displacement to poor living conditions during the war (Guerrant et al. 2003).

6.3.3 Knowledge: Emerging Health Issues

Health policy narratives are influenced by the available knowledge. We highlight this here as it is a major challenge to delivering progress in water-related health, but also to inspire future researchers about the dynamic nature of the challenge. Climate change has been an area that has strongly influenced health policy and research in recent years. To determine future needs for health systems and technologies, we now need to understand much more about the climatic factors that influence health outcomes through changing environmental conditions, human behaviour, and vector habitats. These changes include the emergence (and re-emergence) of infectious diseases, such as the Zika virus outbreaks in South America in 2015, and environmental transmission of mosquito-borne diseases re-emerging in Europe. Determinants of disease are understood in the context of the climate conditions and behaviours that spread them.

Here the system has been disrupted by the changing environment; however, it is the disruption of the sector motivated by this knowledge that we are highlighting. The new evidence on climate and health has driven policy responses and research. This process of knowledge influencing priorities does not always rely on external disruption – changes in public health patterns have themselves led to new knowledge that is influencing policy and ongoing research. As we succeed in treating acute diseases and our life expectancy increases, our understanding of health vulnerabilities changes. Chronic health conditions gain relative importance, and policies and research become more focused on long-term exposures and immune system changes.

Although scientific knowledge is important for influencing sector priorities, it is crucial to acknowledge that political context and the potential for success are equally if not more important factors determining policy formation, traction and effectiveness. Accordingly, in the next section we give an example where politics rather than science led disruptive change in the water sector.

6.3.4 Politics and the Pace of Disruption

Not all disruption is rapid, nor scientifically driven. Some ideas historically have taken much longer to move from academia to practical implementation. One commonly taught to students, in many different disciplines, is John Snow's theory of waterborne disease, which stemmed from London's 1854 Broad Street pump cholera outbreak. Snow's work is now recognized as ground-breaking epidemiology. When he initially reported that cholera was waterborne, however, it took longer for his theory to be widely accepted than it did for 'the most advanced and elaborate sewage system in the entire world' to be constructed and largely operational in London by 1866 (Johnson 2006, p. 208). The delay to sewer construction was largely political, rather than due to a lack of knowledge that clean water was important.

The prevailing belief at the time was that disease spread through bad air (the miasma theory), but this belief and belief in the importance of clean water were not mutually exclusive. Long before science provided an explanation, societies were aware that water and illness were linked. That awareness was reason enough for Scotland and northern British industrial towns to construct extensive waterworks by 1850 to combat shortages and provide cleaner water (Soloman 2010). In London, a filtration system was introduced for Chelsea in 1828 – preceding Snow's theory of waterborne cholera by decades.

After the first cholera outbreak in England, a commentator in a medical journal stated that 'there was never a real panic' because it was quickly realised that the great majority of cholera victims were amongst 'the poorest of the poor' (Inglis 1971, p. 272). London was experiencing a sanitary crisis and it was a reflection of social inequality. It was also 'an early manifestation of an inherent dilemma in the industrial market economy': the lack of an internal mechanism to ensure environmental sustainability (Soloman 2010, p. 260). Furthermore, there was ongoing debate over the rightful role of London's government as the administrative class and industrial magnates had risen to prominence, heralding a shift from self-serving aristocratic ideals towards Victorian ideals of 'social conscience and civic pride' (Plumb 1963, p. 97). So, London's eventual sanitary revolution was not driven as much by scientific understanding of waterborne disease as it was by political motivations (e.g. the Great Stink) and ideals of civic pride.

Even as the science of waterborne disease has advanced in the many decades since, these historic sociopolitical debates are still reflected in current efforts to tackle cholera and other waterborne diseases amongst the urban poor. The persistence of these debates underscores the importance of political will for enabling positive change in the water sector. Innovation and advances in knowledge are important, but not sufficient to move the sector forward without political backing.

6.4 Beyond Outbreaks: The Underreported Health Burden of Inadequate Water Supplies

Historically, research tackled the acute health burden of infectious disease, as discussed in Section 6.2. Health problems resulting from long-term exposure to infectious diseases received substantially less attention and remain underreported. Similarly, salinity and chemical contaminants such as arsenic, fluoride, lead and manganese, which typically have significant health effects only after long-term exposure, have been overlooked in traditional classifications of water-related health issues. To date, there has been no global assessment of the health burden from chemical contaminants in water, although there is enough evidence to know that the impacts are varied and widespread.

In recent years, research has increasingly directed attention towards the health burden of long-term exposure to both infectious diseases and chemical contaminants rather than solely to their acute effects. This new focus on chronic conditions is changing the way researchers and practitioners think about water and health. As the collection of research expands, researchers and practitioners in the water sector gain a better understanding of the importance and complexity of health outcomes from long-term consumption of contaminated drinking water. In this section we explore five growing areas of research: the chronic impacts of infectious diseases through enteric environmental dysfunction (EED); visible physical effects of chemical exposure such as skin and skeletal damage (e.g. due to hyperkeratosis, peripheral neuropathy, and fluorosis); less visible physical effects of chemical exposure such as hypertension and cancer; cognitive impairment; and psychosocial distress. These are all relatively young areas of research in which additional studies have high impact potential.

6.5 Enteric Environmental Dysfunction

Increasingly in recent years, the chronic impact of infectious diseases has been recognized. EED is the term used to describe inflammation of the gut from chronic exposure to pathogens associated with poor drinking water quality, poor hygiene, and high faecal contamination from humans and animals in the environment. This inflammation leads to malabsorption of food and malnutrition, which increases both susceptibility to further infections and the risk of stunting (Figure 6.1). The impact of EED on the gut is also associated with lower effectiveness of oral vaccines, such as the oral rotavirus vaccine (Korpe and Petri 2012). Whilst the relationship between individual infections and stunting was first demonstrated in Guatemala by Mata et al. (1972), researchers have only recently begun to realise the cumulative impact of clinical and subclinical asymptomatic infections via EED and stunting.

Stunting affects an estimated 165 million children under five years of age, many in areas with poor access to water and sanitation (Prendergast and Humphrey 2014). Although height is a linear measure, stunting is also associated with growth retardation in other areas of the body. Consequently, it can result in increased mortality and morbidity, including reduced cognitive development. Furthermore, it is associated with chronic non-communicable diseases, including metabolic disorders, such as diabetes, and cardiovascular diseases, as well as adult obesity (Guerrant et al. 2013).

Stunting has lifelong implications for those directly affected; it also has intergenerational impacts. Impacts on cognitive development reduce the potential for educational attainment and employment. Increased health costs and risks place economic burdens on families. These reinforce an intergenerational cycle of poverty, which is exacerbated because women who were stunted in childhood are biologically more likely to have stunted offspring (Prendergast and Humphrey 2014).

6.5.1 Visible Disease from Chemical Exposure

Arsenic and fluoride are two of the best-known environmental contaminants of concern for drinking water, in part because they cause visible physical damage. Hazardous concentrations of these elements are generally associated with groundwaters in the

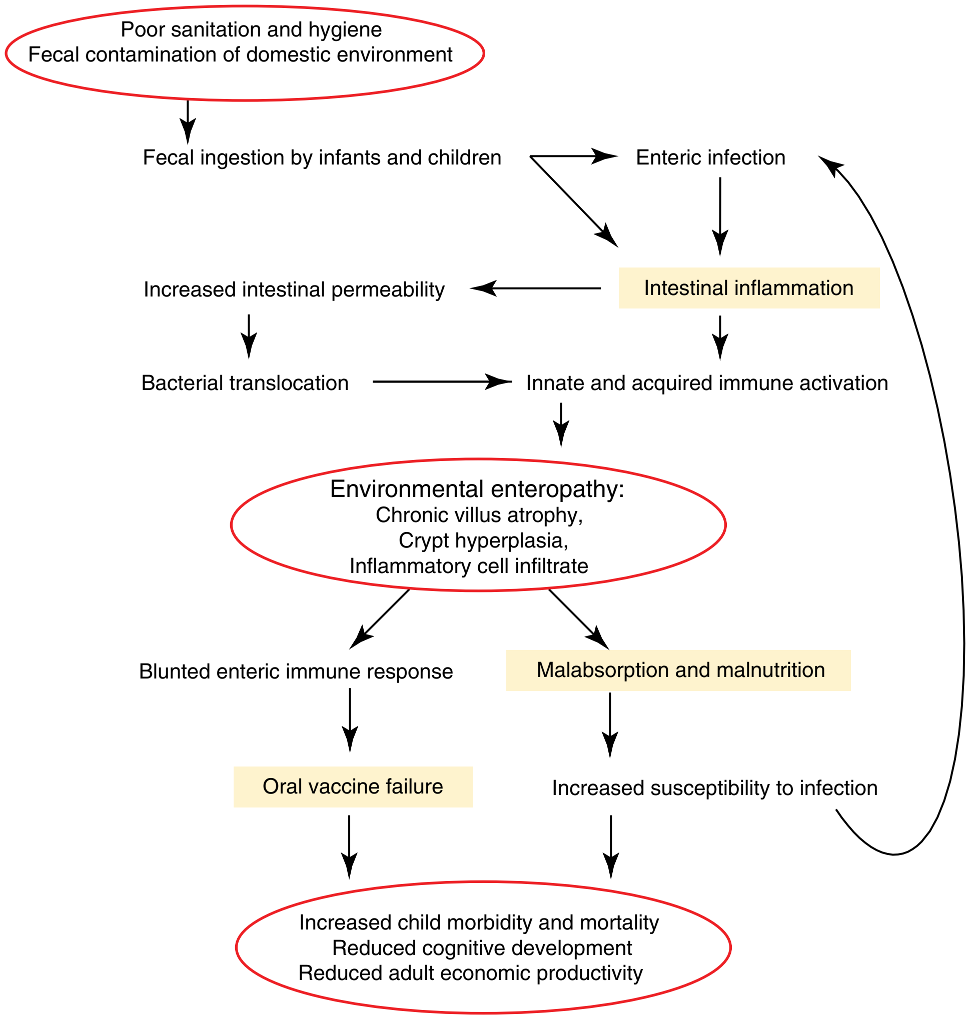

Figure 6.1 Model of the mechanism of development of environmental enteropathy. *Source:* Korpe and Petri (2012). Reproduced with permission of Elsevier Ltd. (*See color representation of this figure in color plate section*).

Indian subcontinent, China, Central Africa and South America, although the geology in most parts of the world can create localized areas of high concentration. Both arsenic and fluoride are readily absorbed through the human gastrointestinal tract (WHO 2017).

The most-documented health impacts of absorbed arsenic are dermal lesions in the form of changed pigmentation, hyperkeratosis (overproduction of keratin in the skin causing thickening in places and resulting in a sandpaper-like texture of the skin), and peripheral neuropathy (which results in weakness, numbness and pain due to peripheral nerve damage). Arsenic poisoning can also cause peripheral vascular disease (PVD) – a blood circulation disorder that produces pain and fatigue as well as visible symptoms such as reddish blue or pale colouration of legs and arms, and wounds or ulcers that will not heal. PVD also increases blood clot formation, which can lead to organ damage and loss of fingers, toes or limbs (WHO 2017). There are no known benefits of consuming arsenic, and considerable uncertainty remains 'over the actual risks at low concentrations' (WHO 2017, p. 315). As a result, concentrations in drinking water should ideally be zero (the WHO gives a provisional guideline of 0.01 mg/l as a concentration that can reasonably be achieved by treatment and detected with current analytical methods).

Unlike arsenic, there is clear evidence that fluoride may be a beneficial nutrient. At low concentrations (0.5–2 mg/l), it has been shown to improve dental health (WHO 2017), leading to fluoridation of some municipal water supplies and fluoride being added to dental products. High fluoride intake is detrimental, however, especially for children during their development. It can cause fluorosis – a condition marked by discoloured and pitted teeth, weakened bones (which are more susceptible to fracture) and immobilized joints. Dental fluorosis is associated with long-term consumption of water with concentrations as low as 0.9 mg/l, whereas skeletal fluorosis is associated with concentrations around 3–6 mg/l, with crippling cases usually resulting from greater than 10 mg/l (WHO 2017). The severity of fluorosis is determined by the cumulative absorption of fluoride over time, but fluorosis symptoms can improve if fluoride consumption stops or is reduced. Food and airborne particulates can also be significant sources of fluoride, so the safe amount of fluoride in drinking water is dependent on the volume consumed and the contribution of fluoride from food and air. Although the WHO provides a drinking water guideline for fluoride of 1.5 mg/l based on epidemiological evidence, the organization also emphasizes the need for context-specific water quality standards that account for total fluoride intake from water as well as food, airborne particulates, and dental care.

6.5.2 Hypertension and Cancer

Beyond very visible physical effects from arsenic and fluoride intake, drinking unsafe water that contains high levels of salinity and heavy metals can increase the likelihood of developing hypertension and cancer. It is widely recognized that high dietary sodium chloride intake raises blood pressure and can lead to hypertension (Institute of Medicine 2005), which increases the likelihood of preeclampsia and cardiovascular and renal diseases. Despite this recognition, the WHO has not developed a health-based guideline for salinity in drinking water for two main reasons (WHO 2017). Firstly, there is an assumption that salt intake from food substantially outweighs intake from water. Since salt is detectable by taste, acceptability limits are generally reached before salinity becomes a health concern. Consequently, people will elect not to drink water that is hazardously salty, assuming that they have another option. The second reason that no health-based drinking water guideline is available for salinity is that '[n]o firm conclusions can be drawn concerning the possible association between sodium in drinking water and the occurrence of hypertension' (WHO 2017, p. 416). There have been relatively few studies examining the relationship between blood pressure and sodium in drinking water, and most were conducted in developed countries.

One exception is a small collection of studies from coastal Bangladesh that have examined the impact of high-salinity drinking water on blood pressure. Scheelbeek et al. (2017), for example, found that drinking water was a significant source of daily sodium intake and that the concentration of salinity in drinking water was highly associated with blood pressure and the likelihood of hypertension in consumers. The assumption that taste-based acceptability thresholds direct people to drink water with limited salt content holds true in many places, particularly in the developed world; however, there are water-insecure coastal zones and dryland, groundwater-dependent regions where people – especially impoverished people – have few options besides drinking saline water.

Salinity is not the only component of drinking water quality that can impact cardiovascular health: stunting from EED is associated with cardiovascular problems and a growing number of studies have reported associations between hypertension and intake of environmental toxins such as arsenic, cadmium, mercury (Martins et al. 2018) and lead (USEPA 2013). For arsenic in particular, studies have reported associations between concentrations in drinking water and hypertension (Abhyankar et al. 2012) and cardiovascular disease (Moon et al. 2012), although a dose–response relationship has not been established.

In addition to being a risk factor for cardiovascular and renal diseases, 'there is overwhelming evidence that consumption of elevated levels of arsenic through drinking water is causally related to the development of cancer' in the skin, lungs, bladder and kidneys (WHO 2017, p. 316). Studies have also pointed to a possible association between fluoride in drinking water and cancer, but the evidence is considered inconclusive and more data are needed – particularly for bone cancer, given the impact of fluorosis on bone development (WHO 2017). Whilst low-cost water treatment is available for arsenic and fluoride, as well as pathogens, there is little evidence of sustainable use at the household or community level in low-income settings (Waddington and Snilstveit 2009).

6.5.3 Cognitive Impairment

Chronic exposure to contaminated drinking water can also impact brain function. Stunting from EED and intake of heavy metals such as arsenic, lead, and possibly manganese can affect cognitive development. These impacts have been found to be most severe for children, although the mechanisms of cognitive impairment are not well understood. For arsenic, studies have demonstrated an inverse relationship between arsenic intake and intellectual function amongst children and adults (Wasserman et al. 2004; Bryant et al. 2011).

For lead, the USEPA (2013) recognizes that even low concentrations in the blood of children can damage their central and peripheral nervous systems and cause lower intelligence quotient scores, behavioural problems and learning disabilities. Unlike arsenic and fluoride, which are naturally occurring environmental contaminants, lead in drinking water usually leaches out of lead piping in municipal distribution systems. This was the cause of the water crisis in Flint, Michigan, that began in 2014 when the city changed the raw water source and treatment practices for their municipal supply, resulting in lead leaching from pipes into their drinking water.

In addition to arsenic and lead, a few epidemiological studies have pointed to an association between manganese in drinking water and learning difficulties in children – more work is needed to strengthen these findings and demonstrate a causal relationship (WHO 2017). Food is usually a more important source of manganese than water, but some surface and groundwater sources can be significant if they have sustained anaerobic conditions (under which manganese is more soluble). As with salinity, elevated manganese in drinking water (more than 0.1 mg/l) can cause an undesirable taste that may discourage people from drinking the water if they have a better-tasting alternative (WHO 2017).

6.5.4 Psychosocial Distress

In addition to the aforementioned physical impacts, people with chronic health conditions often have their suffering compounded by loss of ability – ability to be productive, to earn an income, to fit a social role. This loss of ability can have immediate and long-term impacts on individuals, families and communities. Both the experience of the disease itself and its follow-on effects have important psychological consequences. A few studies have examined the psychosocial dimensions of inadequate water supplies. For example, Wutich and Ragsdale (2008) found that emotional distress was significantly associated with water insecurity in a Bolivian squatter settlement; Brinkel et al. (2009) reviewed literature on the social and mental health effects of arsenic exposure and found them to be numerous; and Thomas and Godfrey (2018) identified emotional distress associated with intrahousehold conflict around limited water services in rural Ethiopia. Psychosocial distress is a growing area of public health research. When applied to the water sector, acknowledging this health dimension further emphasizes the importance of securing reliable, safe and affordable water supplies.

6.5.5 Revisiting the Water-Related Burden of Disease

Chronic conditions resulting from long-term exposure to bacteriological and chemical contamination in drinking water create a far-reaching, often intergenerational health burden. This burden is unevenly distributed, with geography, wealth, age, gender, race, and other axes of inequality being important factors. Those with education, and who can afford more costly alternatives, and those with access to better nutrition can reduce their exposure or moderate the impacts – for example, a diet high in calcium can somewhat mitigate the impact of fluoride and lead ingestion (USEPA 2013; WHO 2017), and a high potassium diet can moderate the blood pressure increase from high sodium intake (Institute of Medicine 2005). The chronic conditions described in the preceding sections are generally more severe if people are exposed as children, although elderly people are more at risk from blood pressure increases. Brinkel et al. (2009) reported that Bangladeshi women suffer more from arsenic-related ostracism than do men. In the United States, African-Americans are reported to have above average prevalence of salt sensitivity and therefore higher risk of hypertension (Institute of Medicine 2005). These many inequalities add another layer of complexity for understanding and combating the health burden of inadequate water supplies.

This burden has considerable implications for meeting development aims, including the SDGs. The extent and impacts of EED and chemical contamination demonstrate that a more nuanced understanding of the complexities of water and health interactions is needed. Focusing on diarrhoea in children under five as the primary outcome of water, sanitation and hygiene (WASH) interventions does not adequately represent the complex benefits of good WASH. Although a shift has been made to focus on anthropometric measures, such as stunting, this still does not capture the full burden of poor WASH nor the potential benefits of improving WASH. It is worth noting that cost–benefit studies still rely heavily on diarrhoea risk reductions as the main source of data on health benefits and health cost-savings. A more holistic understanding of the water-related burden of disease may greatly increase our ability to implement effective water interventions for improved long-term, multigenerational benefits.

6.6 Water and Health Challenges in the SDG Period

Improvements in water-related health have been significant over the past decades. We know much more about infectious diseases, how to interrupt their transmission pathways, and how to treat them. These gains in knowledge have enabled substantial reductions in diarrhoeal diseases, malaria, schistosomiasis and other water-related diseases. Additionally, as highlighted in Section 6.4, we are beginning to understand the importance of chronic water-related health problems and the need for approaches that better reflect the complexity of water-health systems. In light of this complexity and the ambitious SDGs, addressing water-related health raises important interdisciplinary challenges.

In this section we frame three current research challenges where innovative thinking is needed: meeting higher service levels for WASH; developing new technologies for testing water quality; and building institutional capacities to decrease inequalities in global water supply. These challenges are central to achieving the water SDG, but they are not all-encompassing. The future will also see water and health researchers focusing on other important challenges, for instance: identifying and managing emerging diseases and contaminants including endocrine-disrupting chemicals; dealing with the increasing use of human and animal antibiotics and the resulting rise of antimicrobial resistance; addressing declining water infrastructure; and tackling previously unrecognized inequalities in developing and developed countries.

The greatest conceptual difference between the water MDG and the water SDG is the shift from thinking about infrastructure to thinking about services – a shift from considering things to considering people. The drinking water SDG is Target 6.1:

> *By 2030, achieve universal and equitable access to safe and affordable drinking water for all.*

'Safely managed' is the gold standard by which progress towards Target 6.1 will be judged (Table 6.2). The ladder of service levels is presented rather than a single standard, so that monitoring can reflect important intermediate steps as well as progress in achieving the gold standard (WHO/UNICEF 2015). Whilst the focus here is on water quality, it is important to note that the new category of 'safely managed' also addresses quantity, a critical factor for ensuring health gains, through reducing the burden of collection that often physically restricts water use, and through ensuring water is available when needed.

Explicit inclusion of water quality in the definition of 'safely managed' is an important aspect of the shift in emphasis from infrastructure towards more holistic service provision. The old infrastructure approach was often characterized by discrete investments with little follow-up after construction; in contrast, ensuring good water quality in the long term requires ongoing management to maintain and verify water safety measures. In the MDG period, progress towards safe water provision was measured only by the

Table 6.2 The WHO/UNICEF Joint Monitoring Programme (JMP) monitoring levels for drinking water.

Service level	JMP definition
Safely managed	Drinking water from an improved[a] water source that is located on premises, available when needed and free from faecal and priority chemical contamination.
Basic	Drinking water from an improved[a] source, provided collection time is not more than 30 minutes for a round trip, including queuing.
Limited	Drinking water from an improved[a] source for which collection time exceeds 30 minutes for a round trip, including queuing.
Unimproved	Drinking water from an unprotected dug well or unprotected spring.
Surface water	Drinking water directly from a river, dam, lake, pond, stream, canal, or irrigation canal.

Source: Adapted from WHO/UNICEF (2017).
[a] Improved sources are supposed to be protected from faecal contamination by nature of their design/construction. The category includes: piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.

prevalence of 'improved' water sources. The move to include water quality explicitly was informed by several studies, including a meta-analysis by Bain et al. (2014) that showed the inadequacy of 'improved' infrastructure as a proxy for safe water. These studies indicated that the achievement of the water MDG (Target 7c), which was celebrated in 2010, was less of a triumph than initially thought because 'improved' infrastructure is not consistently free from faecal contamination. For the SDGs, safe water will be judged by water quality tests and, in recognition of the importance of chronic health issues, priority chemical contamination will be considered in addition to faecal contamination (priority in this case depends on context, but arsenic, fluoride and lead are high-profile contaminants). Thus, the SDG focus on services is especially pertinent to the relationship between water and health.

6.6.1 Improving Service Levels

The move to the service-oriented SDGs and the addition of the JMP's service ladder has coincided with more nuanced investigation into the health outcomes associated with different service levels and the health benefits achieved by different interventions. It has also enabled water and health research to be situated in a clearer policy context. A rigorous WASH randomized control trial recently conducted in rural Kenya and Bangladesh tried to unpack some of the uncertainties around WASH effectiveness, focusing in particular on impacts on infants. These trials found no significant additional benefit from WASH interventions being added to nutrition programmes (Luby et al. 2018; Null et al. 2018). This is consistent with earlier evidence from Fewtrell et al. (2005), who conducted a number of reviews and meta-analyses of studies of water, sanitation and hygiene interventions that suggested multipronged interventions (i.e. those addressing a combination of water supply, quality, sanitation and hygiene aspects) did not have a greater impact on health than did individual interventions.

A meta-analysis by Wolf et al. (2018a) showed that having high-quality piped water leads to a much greater reduction in diarrhoea than interim service levels. Increasingly, studies are highlighting problematic limitations and variability in WASH service levels. The benefits of piped water supply can be realised only if supplies are reliable (e.g. Majuru et al. 2016). For non-piped supplies, service levels vary based on intermittent water availability due to poor maintenance and related governance issues (see Chapter 9). Additionally, users often choose to switch between different water sources based on seasonality and other factors, often switching to less microbially safe surface water sources during rainy seasons (Thomson et al. 2019). It is clear that the relationship between health outcomes and a water source type or category of infrastructure is heavily mediated by the level of service supplied.

Wolf et al. (2018b) cautioned against interpreting a minimal reduction in diarrhoea as indicative of an ineffective intervention, as a particular intervention may only target one of many pathways of faecal–oral transmission, making the individual intervention a necessary but not sufficient condition for reducing diarrhoea morbidity. Unless these multiple pathways are targeted simultaneously, the faecal exposure is often unlikely to be reduced sufficiently to result in a reduction in enteric disease (Robb et al. 2017). The relationship between higher levels of service and better health outcomes is positive but complex and nonlinear. Further research to understand this complexity is vital for designing WASH programmes and interventions that ensure the most effective use of inevitably limited resources.

6.6.2 Improving Water Quality Testing Methods

The purpose of drinking water quality testing is to reduce uncertainty about the wholesomeness of water for consumption, thereby promoting health-protective management of supplies and prioritization of interventions. The water SDG, in particular the 'safely managed' gold standard, has highlighted the importance of water quality testing; however, generating water quality information is costly, time-intensive and rife with uncertainty. It can be particularly difficult in low-resource settings and where organizational structures are not in place to conduct monitoring programmes or make use of water quality data.

There are many different pathogens – bacteria, protozoa and viruses – that spread by faecal contamination of water supplies. Although methods have significantly advanced, many pathogens remain difficult to detect without intensive, expensive molecular methods – even then, it is difficult to determine which individual micro-organisms are infectious. For the last century, instead of testing for pathogens directly, monitoring programmes have used culturable coliform bacteria as indicators of faecal contamination risk. The preferred indicator, *Escherichia coli*, continues to be widely used, but it has some important limitations:

- It takes 18–24 hours for test results to be available.
- Traditional culturing methods require experienced technicians as well as sterile working conditions and access to a power supply for refrigeration and incubation of growth media and samples.
- The cost of consumables may prohibit frequent sampling where budgets are constrained, but frequent sampling is important to understand and manage temporal and spatial changes in water-related health risks.
- Viruses and protozoa are physiologically distinct from *E. coli* and thus have different environmental transport and survival patterns, so absence of *E. coli* does not guarantee safety (Leclerc et al. 2001).

- *E. coli* can survive and reproduce in soils, sediments, water, and biofilms on infrastructure (for example Brennan et al. 2010) – so their presence is not necessarily indicative of recent faecal contamination.

In addition to these limitations, the purpose of *E. coli* testing is often misunderstood: instead of interpreting results within a risk assessment framework, there is a tendency to equate *E. coli* in general (a common enteric species, the majority of which are non-pathogenic) with *E. coli* in its pathogenic form, and therefore to interpret tests as direct assessments of pathogen presence.

In recent years, new approaches have been developed to get around some of the limitations of traditional *E. coli* sampling. For example, simple methods for most probable number assessment of culturable *E. coli* have been developed and marketed for application in low-resource and emergency settings by companies such as Aquagenx (https://www.aquagenx.com). Moving further from the traditional approach, emergence of a new paradigm in DNA sequencing has the potential to lower barriers to direct analysis of pathogens (Jain et al. 2016) – although clinical applications are more prevalent than environmental monitoring applications to date. A third approach has been to use a well-established form of measurement (fluorimetry) in a new way. This approach attempts to use tryptophan-like fluorescence, an indicator of microbial activity in water, as a measure of faecal contamination risk (e.g. Nowicki et al. 2019). Although each of these approaches has certain strengths, they all have limitations and do not provide universally applicable solutions for microbial water quality monitoring.

We have focused here on microbial water quality monitoring, but innovation to improve chemical water quality monitoring capacities could also have widespread implications. Especially with increasing attention on water quality testing in light of the drinking water SDG, research into new approaches to testing for chemical and pathogenic contamination has relevance and far-reaching impact potential.

6.6.3 Leaving No One Behind

The SDGs are accompanied by the oft-repeated imperative to leave no one behind and to prioritize those who are most difficult to reach. For SDG 6.1, those who are most difficult to reach are poor inhabitants of rural areas. As of 2015, it was estimated that only 24% of people in sub-Saharan Africa (SSA) had safely managed water and most of them were living in urban areas. One of the criteria for safely managed water is for it to be supplied on premises. This is a difficult standard to meet in rural areas where supplies are typically decentralized, and low-density settlements make extensive piped networks prohibitively expensive under current cost–benefit considerations. When only the water quality criterion is accounted for, the estimate for total population with good quality water rises to 42%, but there is insufficient data to make an estimate for the rural areas.

Identification methods exist for the pathogens and chemicals discussed in this chapter; however, even where tests are affordable, in low-resource settings useful water quality data are often not readily available to managers of non-utility supplies, whether at the household, community or government level. In rural areas of SSA, where community-led models of water management predominate, drinking water quality is rarely tested. In SSA, rural areas will require the most 'attention and additional resources to achieve regulatory compliance for water quality monitoring' (Peletz et al. 2016).

Monitoring is only part of the challenge. Once water quality data are generated, water safety planning processes must be in place to act on them. But the prevalence of decentralized community management is a barrier to increasing water safety because community-level water managers rarely have the training or access to resources that are required for water quality testing and designing and implementing water safety plans.

Safe, community-managed water supplies require a dual approach where water quality information and community management are both priorities. To align these priorities, communities must be supported in understanding and managing the safety of their drinking water. As elaborated in Chapter 9, recent literature promotes institutional pluralism as a strategy for improving rural water service provision. The challenges for achieving the SDG targets for sanitation, which is necessary for reducing stunting and the infectious disease burden, are similarly complex (see Chapter 16). The core concept is that appropriate sharing of responsibilities between the government, private sector, communities, families and individuals can take advantage of the differing strengths of each domain. Indeed, even as 'leaving no one behind' points to the needs and rights of everyone for water, so too there are responsibilities towards the management of water at every level of society, and 'everyone playing their part' points to the responsibilities that accompany rights. Such an approach could provide an opportunity to include an effective, health-protective water quality monitoring element as part of the wider management of rural drinking water services.

6.7 Conclusions

Despite many advances, and a much deeper understanding of the complexity of intersections between water and health, it remains a relevant area and a critical challenge for delivering the SDGs. In this chapter we have reflected on historical context and the current state of knowledge, framing three challenges for future scholars that underpin the delivery of the SDGs: achieving high service levels, safe water, and universal access. To achieve these, we need disruption. It has been clear from the start of the SDGs that these ambitious targets of universal coverage of basic water and sanitation will not be achieved within the time-frame (and available finances; see Chapters 15 and 17) of current approaches; it is even less likely that access for all will be achieved with a high level of service.

Disruption in the water sector is not always rapid. Change has come from different pathways as a result of innovation and learning, of crisis, and of political will. Reflecting on these historical developments helps us to consider how change happens, and that opportunities for innovation can be shaped by processes far removed from technological advancement and scientific understanding.

Acknowledgements

This work is an output from the REACH programme (www.reachwater.org.uk) funded by UK Aid from the UK Department for International Development (DFID) for the benefit of developing countries (Aries Code 201880) and the Gro for GooD project (UPGro Consortium Grant: NE/M008894/1 (NERC, ESRC and DFID). However, the views expressed, and information contained in it are not necessarily those of or endorsed by DFID, which can accept no responsibility for such views or information or for any reliance placed on them.

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