

Chapter 2

Waterborne Disease Outbreaks and the Multi-barrier Approach to Protecting Drinking Water

2.1 Introduction

Drinking water outbreaks have occurred throughout the world, causing varying illnesses and even death. This chapter reviews past outbreaks of microbial contaminants and the associated lessons that have been learnt. Only the most recent outbreaks are considered, as these are probably the most relevant for policy purposes. The publication, *Safe Drinking Water: lessons from recent outbreaks in affluent nations*, written by Hrudehy and Hrudehy (2004), summarize the occurrences of 69 drinking water outbreaks. They begin in January 1974 in Richmond Heights (Florida), and continue up to March 2002 in Transtrand (Sweden). The Hrudeys have made a significant contribution to the topic of drinking water safety through the detailed account of these outbreaks, and their overall analyses. Their book emphasizes the impact of the Walkerton contamination of 2000, and also describes the lessons that have been gained as a result. While taking the Hrudeys' work into consideration, the objective of this chapter is to include outbreaks that have occurred since 2002, and to expand upon their conclusions.

A variety of contaminants have caused water outbreaks, but a few in particular are a primary concern. *Cryptosporidium parvum*, *Giardia lamblia*, *Campylobacter jejuni*, and *Escherichia coli* (*E. coli*) have caused the largest and most significant outbreaks, and therefore are the main focus. *Toxoplasma gondii* is also included, but this pathogen is very rare and does not pose the same level of risk. These disease-causing contaminants are most commonly transmitted into water sources by animal or human fecal matter. The three categories of microbial contaminants in drinking water are protozoa, bacteria, and viruses. Protozoa and bacteria contaminants have had the most significant impacts and are the focus of this review.

Outbreaks can occur because of an array of factors. The multi-barrier approach is the primary strategy for enhancing safety of drinking water systems. This approach is designed to provide the best quality of water by using a number of checkpoints throughout a water system. If a contaminant enters the water system, it is the goal of

the multi-barrier approach to detect and treat the contaminant before it reaches the consumer. A failure in one or more of the barriers can lead to the spread of contamination, which results in an outbreak if not detected in the remainder of the system. Most outbreaks in the history of drinking water contamination have been a result of barrier failures. Failures can occur anywhere within the system, including source water, operations, treatment, and distribution. Outbreaks are an indicator of weaknesses within a water system. The number of outbreaks and their severity reflect poorly on the ability of an overall system to provide safe drinking water. Also, the weather frequently plays a key role in outbreaks by introducing contaminants into water sources, often by runoff from either a heavy rainfall or spring melt. Surface water is particularly vulnerable to weather occurrences because it is easily accessible, in contrast to groundwater sources that have natural filtration through the soil, and therefore incur less contamination than surface water, in general. Over time, with the knowledge gained through the experience of past outbreaks, fewer outbreaks would be expected to occur as water systems improve to prevent future contamination. However, this has not been the case, as contamination continues to be a major concern throughout the world, and surprisingly even in developed countries such as Canada, the United States, and Europe.

This chapter is organized as follows: Protozoa contaminants of *Cryptosporidium*, *Giardia*, and *Toxoplasma* are discussed first. This is followed by a discussion of bacterial contaminants of *Campylobacter*, and *E. coli*. For each contaminant a description is included as well as the predominant outbreaks that each has caused. Furthermore, a number of principles of watershed management are reviewed in Sect. 5.

2.2 Protozoa

2.2.1 *Cryptosporidium*

Cryptosporidium is a frequent microbial cause of drinking water outbreaks. This is because as a protozoan it is resistant to chlorine disinfection, which allows it to spread undetected throughout the distribution system to the consumer. Chemical disinfection is a critical barrier in the multi-barrier approach to prevent the possible spread of contamination, but alternative treatment is necessary for systems to be effective against *Cryptosporidium*. Alternative treatments including coagulation, sedimentation, filtration, ozone and ultra-violet light treatment have been determined to be effective against *Cryptosporidium* (Rose 1997, p. 149). Communities that rely solely on chlorine are the most vulnerable to an outbreak of cryptosporidiosis, the disease caused by *Cryptosporidium*. Severe diarrhoea is the main symptom of cryptosporidiosis. The majority of the outbreaks are related to treatment failures within the water system, often a heavy reliance on chlorine and a failure to provide filtration. Filtration is extremely important in removing *Cryptosporidium*, particularly in communities that rely on surface water sources. This is

because of the vulnerability of surface water to potential contaminants in the surrounding environment. Therefore, cryptosporidiosis occurs most commonly in communities that rely on surface water and do not provide filtration.

A well-documented outbreak of cryptosporidiosis occurred in Braun Station, Texas in May–July of 1984. The groundwater source was chlorinated, but was believed to have been contaminated by sewage (Rose 1997, p. 141). The outbreak caused 2,000 cases of reported illness in the community of approximately 5,900 people. A lack of effective treatment was the system failure that caused this outbreak. *Cryptosporidium* is resistant to chlorine and the treatment facility did not provide filtration, which would have been effective against the pathogen.

In January–February of 1987 Carrollton Georgia experienced an outbreak of cryptosporidiosis. The surface water source became contaminated and caused over 13,000 cases of illness. At the time of the outbreak approximately 27,000 people were supplied by the water system in the county of 64,900 people. The source of contamination is believed to have been fecal runoff from nearby grazing cattle and sewage overflow from upstream into the river source (Solo-Gabriele and Neumeister 1996, p. 79). Conventional treatment was used prior to the outbreak, which includes coagulation, flocculation, sedimentation, filtration, and chlorination. Improper flocculation, which is part of the filtration process, allowed the contaminant to spread through the distribution system (Rose 1997, p. 141). This means that the system failure in this outbreak is inadequate filtration. This is a failure in the treatment process of the water system, and therefore could have been prevented by a properly working system. Of course it could be also argued that there was inadequate monitoring since the operators did not detect, and therefore did not fix the improperly working flocculation. Following the outbreak, the treatment system was upgraded in Carrollton with new flocculators, increased filter monitoring, improved chemical dosage, and operational practices (Solo-Gabriele and Neumeister 1996, p. 81). These alterations are significant improvements in an effort to prevent future contamination.

In January–June of 1992, Jackson County Oregon also experienced an outbreak of cryptosporidiosis. The contamination of the surface water sources caused 3,000 cases of defined illness, but is estimated to have affected approximately 15,000 people. The outbreak occurred within two water supplies of Jackson County. The water system of the city of Medford supplied 70,000 people, and the city of Talent's system supplied 3,000 people (Solo-Gabriele and Neumeister 1996, p. 79). The water in Medford came from Big Butte Springs, and was treated with chlorine only. In Talent the water came from a river source that was treated with flocculation, sedimentation, filtration, and chlorination. The source of contamination of Medford's springs is believed to have been contaminated surface water and the source of Talent's river contamination is believed to have been treated wastewater that was received by the river. Drought conditions at the time may have lessened its dilution in the river (Solo-Gabriele and Neumeister 1996, p. 80). Another suggested source for Talent is agricultural runoff that possibly could have entered the river through runoff of rainfall. Again system failures were involved in Medford's outbreak with a lack of filtration and a sole reliance on chlorination, and also in Talent with poor filtration that did not take into account increased in turbidity at the time (Rose 1997, p. 141). Following the

outbreak, Medford flushed its distribution system with chlorinated and filtered river water, and Talent initiated corrections to their system deficiencies such as equipment repairs and treatment alterations (Solo-Gabriele and Neumeister 1996, p. 81).

In January–June of 1992 North Cumbria in England experienced cryptosporidiosis, with an undetermined number of cases. A third of the population of 160,000 was supplied with water from Ennerdale Lake, another third was supplied by Crummock Lake, and the remaining third was supplied by smaller sources (Goh et al. 2004, p. 1007). The contamination occurred in Ennerdale Lake and the source is believed to have been runoff from nearby livestock. The treatment of Ennerdale Lake entailed only chlorination, and therefore a lack of filtration was the system failure that allowed the outbreak to spread in North Cumbria.

From November 1992 to February 1993, Warrington England experienced an outbreak of cryptosporidiosis. There were 47 confirmed cases and an estimate of approximately 1,840 people affected by the contaminated water that was supplied to 38,000 people (Bridgman et al. 1995, p. 557). Only chlorine was used to treat the groundwater supply. No filtration was applied, which is common for groundwater sources because of the natural filtration achieved through the soil. The source of this outbreak is believed to have been agricultural runoff. It is rare to experience *Cryptosporidium* contamination in a groundwater supply, but it is believed that heavy rainfall caused surface water, contaminated from a field with livestock fecal matter, to drain into the groundwater. Research suggests that the use of groundwater sources establishes a low immunity to *Cryptosporidium* so that a contamination will create a more severe outbreak than may occur in communities that have higher immunities from the use of surface water (Frost et al. 1997, p. 10). The system failure in this case was determined to be a lack of monitoring of the water supply. This is likely because of the rarity of *Cryptosporidium* in groundwater sources, and therefore monitoring of the pathogen was not a regular practice.

The most significant drinking water outbreak of cryptosporidiosis was in Milwaukee Wisconsin from March to April of 1993. Two water treatment plants supplying water to Milwaukee used water from Lake Michigan. The southern plant, that supplied southern and central Milwaukee, became contaminated in April 1993. This caused its temporary closure until June 1993. During this period the northern plant was required to supply the entire area (Osewe et al. 1996, p. 298). Both plants use conventional treatment of coagulation, flocculation, sedimentation, rapid sand filtration and chlorination treatment (Solo-Gabriele and Neumeister 1996, p. 81). The outbreak caused over 403,000 cases of illness and 100 deaths out of approximately 840,000 people whom the water system supplied at the time. The source of contamination is believed to have been from cattle runoff and also human sewage that was carried by tributary rivers (Solo-Gabriele and Neumeister 1996, p. 78). Another suggestion, in other research, is that the source was recycled backwash waters (Rose 1997, p. 141). The recycling of backwash waters is commonly practiced to clean filters by flowing water through in the opposite direction to remove captured particles of matter, in efforts to conserve water (Rose 1997, p. 142). The Milwaukee outbreak has been the largest reported outbreak, and its

significance caused changes within the regulation of drinking water in the United States. After the outbreak, the US Environmental Protection Agency enacted the Surface Water Treatment Rule (SWTR). The rule required both disinfection and filtration of all surface waters, as well as groundwaters that are affected by surface waters (Rose 1997, p. 154). Also following the outbreak stricter practices were imposed for chemical dosing and filter monitoring, and long-term improvements were achieved by installing an ozone disinfection facility. Therefore, it can be assumed that the level of filtration and its monitoring must have been inadequate, as it should have been effective at removing or inactivating the contaminant. The contaminants were able to enter the surface source and were also able to pass through the treatment process into the distribution system without detection.

In March 1993, Kitchener/Waterloo Ontario experienced an outbreak of 1,000 cases of cryptosporidiosis. The contamination occurred when the region of approximately 390,000 people switched from a *Cryptosporidium*-free groundwater source to a contaminated surface water source, the Grand River (Frost et al. 1997, p. 10). A newly constructed filtration plant was being used for the conventional treatment of the surface water, with also ozonation treatment. Several other communities had been using the river as a source of water for a number of years, and had not experienced an outbreak. It has been suggested in the literature that this may be related to the low immunity to *Cryptosporidium* that occurs from drinking from groundwater sources (Frost et al. 1997, p. 10). The source of the contamination is believed to have been recycled backwash waters, as suspected in Milwaukee (Rose 1997, p. 141). In the presence of a contaminant, cleaning with backwash water may reintroduce the pathogen into the system. The significance of this outbreak is that it occurred in a large municipality, compared to the majority of drinking water outbreaks that occur in small rural communities.

In 1996, two communities in British Columbia experienced outbreaks of cryptosporidiosis. The first occurred in May in the city of Cranbrook, which has a population of 18,131, causing approximately 2,000 cases of illness. The second occurred shortly afterwards in June in the city of Kelowna, which has a population of 89,442, causing 10,000–15,000 cases of illness. Cranbrook is in the area of southeastern B.C., while Kelowna is in central B.C., 271 km away from Cranbrook (Ong et al. 1999, p. 64). Both cities use surface water sources. Cranbrook uses Joseph Creek and Gold Creek, and Kelowna uses Okanagan Lake. Also, both cities use the same treatment method of only chlorine, without filtration. The majority of water systems in BC are unfiltered and the water is drawn from surface sources, and most also rely on chlorination for simple disinfection (Ong et al. 1999, p. 67). This is a primary concern because of the vulnerability of surface water to contamination. Chlorine is ineffective against protozoan pathogens such as *Cryptosporidium*, and therefore alternative treatment methods, such as filtration, are necessary. The source of contamination in both cases is believed to have been runoff of cattle manure (Ong et al. 1999, p. 63). Treatment failure was the cause of this outbreak because of reliance on chlorine alone. Following the outbreak, the City of Cranbrook decided not to install a filtration plant, but instead has placed monitors into the creeks. Kelowna took more action, possibly because of its larger population and the greater

severity of the outbreak, by approving plans for the construction of an ultra-violet light treatment facility. Ultra-violet (UV) treatment has been proven to be effective against protozoa, and therefore is the right step toward preventing future outbreaks.

In May 2000, August 2000, and April 2001 three outbreaks of cryptosporidiosis occurred in Northern Ireland. Respectively, 230, 117, and 129 cases of illnesses were reported in unrelated cases in different locations within the Belfast Area. These outbreaks are small when considered in proportion to the population of approximately 400,000 people in the greater Belfast area. The source of the first outbreak is believed to have been livestock runoff, the second source is believed to have been human sewage from a septic tank, and the third is believed to have been wastewater from a blocked drain (Glaberman et al. 2002, p. 631). Chlorine is commonly used in Ireland, but in this case it is again proven that chlorine is ineffective against the *Cryptosporidium* pathogen. Filtration was in place in the third outbreak, but the blocked drain would have allowed the contaminated water to enter the finished water supply. Ireland primarily relies on surface water sources for drinking water, and these sources are vulnerable to contamination because of frequent heavy rainfalls and the large numbers of farms with livestock (Zintl et al. 2009, p. 271). This combination poses a serious threat to the safety of drinking water. Although high numbers of livestock are a major concern, only the first outbreak was caused by *Cryptosporidium* of an animal genotype, while the second and third were caused by *Cryptosporidium* of a human genotype (Glaberman et al. 2002, p. 632). With the knowledge of a high likelihood of contamination, whether due to animal or human fecal matter, monitoring and treatment in the area would be necessary in order to avoid future outbreaks. The three outbreaks reflect poorly on the ability of Ireland's water system to monitor and treat their water effectively.

In April 2001 an outbreak of cryptosporidiosis occurred in North Battleford, Saskatchewan. This outbreak caused between 5,800 and 7,100 cases of illness, in the city of approximately 15,000 people. The surface water source of North Battleford is the North Saskatchewan River, which at the time had no protection programs established to prevent source contamination. The treatment at the plant included both chlorination and filtration. It is believed that the source of contamination was sewage from a sewage treatment plant 3,500 m upstream from the intake of the drinking water plant (Hrudey et al. 2002, p. 401). The sewage treatment plant was reported as not meeting operating standards due to old equipment and inadequate practices (Woo and Vicente 2003, p. 261). Another possible source of contamination could be calf feces runoff from the agricultural activity in the area in combination with heavy spring rainfall (Woo and Vicente 2003, p. 261). Again, treatment failure was the main problem within the water system that should have been able to prevent the outbreak. Inadequate coagulation, which is part of the filtration process, was the cause of the outbreak. Also a lack of knowledge and education on the topic of water treatment, particularly concerning the specific pathogen *Cryptosporidium*, was determined to be an issue concerning the capabilities of the plant staff (Woo and Vicente 2003, p. 262). Overall the North Battleford outbreak revealed a variety of problems that allowed the *Cryptosporidium* pathogen to enter the drinking water system.

Cryptosporidiosis then occurred in Gwynedd and Anglesey, Wales in November 2005. Lake Cwellyn was the surface water source for the reservoir that supplied water to approximately 70,000 households. There were 231 cases of illness caused by this outbreak. At first, runoff of animal fecal matter was suspected because of heavy rains prior to the outbreak, but this was not unusual weather for this area. The source of contamination is believed to have been human sewage that entered the reservoir from a sewage treatment system. The human strain of *Cryptosporidium* is more dominant in the autumn, while the animal strain is more frequent in the spring. The treatment of the drinking water included pressurized sand filtration and chlorination, but these methods were not designed to be effective against *Cryptosporidium*. There was no specific treatment failure, but action was taken to add more treatment to the system. UV treatment was installed, and when it was operating effectively, the boil water advisory was removed (Outbreak Control Team 2006, p. 7). This is the largest waterborne outbreak of cryptosporidiosis in Wales. The early issuing of a boil water advisory on November 25 probably contained this outbreak. Only a small proportion of the population became infected, and the installation of UV treatment is a strong preventative measure against future occurrences.

Another outbreak of *Cryptosporidium* occurred in Galway Ireland in February 2007. The outbreak caused approximately 242 cases of illness in the city of approximately 72,000 people. Two treatment plants are used to treat the water supplied from Lough Corrib (a lake) to the city of Galway. One treatment plant was newer and used coagulation and rapid gravity filtration, and the second was older and had no filtration. The water of the two plants is mixed and then distributed to the consumers. The source of the contamination is believed to have been human fecal matter, but the source has not been confirmed. Boil water advisories were issued by four water suppliers that use water from Lough Corrib. Treatment failure from a lack of filtration in the second plant is likely to be the cause of the outbreak. Closures and upgrades have occurred since the outbreak.

Outbreaks of cryptosporidiosis have occurred in both small and large communities, as shown through the history of drinking water outbreaks. This indicates the strength and ability of the *Cryptosporidium* pathogen to overcome standard treatment of water systems of small rural communities, but also urban areas, as seen in Kelowna, Kitchener/Waterloo, Milwaukee, and Carrollton. System failures, particularly in the treatment process, are the main contributing factor that allows outbreaks to occur. Ineffective chlorine treatment, and a lack of or inadequate filtration for surface water sources are the common elements in the outbreaks of cryptosporidiosis.

2.2.2 *Giardia*

Giardia is another common cause of drinking water disease outbreaks. Similar to *Cryptosporidium*, *Giardia* is also a protozoan that causes symptoms of diarrhoea and abdominal pains (Craun 1979, p. 819). *Giardia* is resistant to minimum levels

of chlorine disinfection, and therefore higher concentrations and longer contact times are required for effective treatment, especially in cold water where resistance increases further (Betancourt and Rose 2004, p. 224). Therefore, a reliance on only chlorine disinfection is ineffective and inadequate against the *Giardia* pathogen. Filtration and alternative methods, as with *Cryptosporidium*, are necessary in order to prevent outbreaks.

A significant early outbreak of *Giardia* contamination occurred in November 1974 in Rome, New York. The outbreak in the surface water source caused 4,800–5,300 cases of illness, in the city of approximately 50,148 people. Rome's water supply was from Fish Creek and it is believed that the source of contamination was untreated human waste. At the time of the contamination only chloramine disinfection was used, with no filtration or sedimentation. Chlorine and ammonia were added to the water entering the reservoir, which forms chloramine, and chlorine was added again to the water leaving the reservoir (Shaw et al. 1977, p. 428). Disinfection as the only treatment method is insufficient in preventing outbreaks of giardiasis (Craun 1979, p. 818).

In September–December 1979, an outbreak of giardiasis occurred in Bradford, Pennsylvania affecting 3,500 people. The treatment system for the surface water source included chlorination, but not filtration. Again, in this case minimum levels of chlorine were ineffective against the *Giardia* pathogen. The source of contamination is believed to have been fecal matter from beavers in the watershed. Beavers are common carriers of *Giardia*. Inadequate treatment and monitoring is believed to have caused the spread of the outbreak (Hrudey et al. 2002, pp. 402, 404). Insufficient levels of chlorine that were unable to provide a chlorine residual in the distribution system, the lack of filtration, and the failure to monitor chlorine residual levels allowed the outbreak to occur. Following the outbreak the municipality built a treatment plant with filtration in an effort to prevent future outbreaks.

Another *Giardia* contamination occurred in December 1985 in the water reservoir in Pittsfield, Massachusetts. The outbreak caused 3,800 cases of illness among the population of 50,265 people (Hrudey et al. 2002, p. 399). The source of contamination is believed to have been fecal matter from infected beavers or muskrats. The cause of the outbreak was due to water treatment changes at the treatment plant. Prior to the time of contamination, the city used two surface reservoirs that were chlorinated, but not filtered (Kent et al. 1988, p. 139). During this time a new filtration system was in the process of being installed on the first reservoir, and so a third reservoir was brought online to phase out the use of the first reservoir while filtration was being installed. There was an increase in turbidity in the third reservoir; to make matters worse, chlorine treatment levels were low during that time because of a malfunctioning chlorinator. Therefore, the water was extremely vulnerable to contamination because of lack of disinfection and the filtration had not yet been installed. Following the outbreak the system was hyper-chlorinated and flushed, and chlorine residual levels and contact times were also increased.

In 1986, Penticton British Columbia experienced a drinking water outbreak of over 3,000 cases of giardiasis. The mixed water source, of both ground and surface water, was chlorinated but unfiltered. The source of the contamination is believed to

have been animal fecal matter that entered the water through a spring runoff (Hrudey et al. 2002, p. 400). Treatment failure was the main contributing factor for this outbreak. Filtration, which was not used, is necessary against *Giardia* because of its resistance to minimum chlorine levels.

Treatment failure is the common thread among the outbreaks of giardiasis, just as with cryptosporidiosis. In all the included outbreaks of giardiasis, a lack of filtration is a common factor that enabled the pathogen to spread through the distribution system to the consumer. Outbreaks of giardiasis occur most commonly in communities that rely on surface water. Again, as with cryptosporidiosis, the outbreaks of giardiasis also occurred in both small and large communities. Therefore, these outbreaks show the need to provide effective alternative treatments, instead of relying on chlorination alone.

2.2.3 *Toxoplasma*

Toxoplasma gondii is a rare microbial pathogen that has only caused three recorded drinking water outbreaks. The first occurred in Panama in 1979, the second in Victoria, British Columbia, Canada, in 1995, and the third and largest outbreak occurred in Brazil in 2002 with 209 cases of illness (Dumetre and Darde 2003, p. 654). *Toxoplasma* is resistant to the usual methods of chlorine treatment, but because it is rare, water systems have not been as alert as they should have been.

The outbreak in Victoria, British Columbia occurred from October 1994 to April 1995 in Humpback reservoir. Victoria is supplied by the Humpback reservoir and the Sooke reservoir. The outbreak caused 110 reported cases of illness, although it is believed that the contamination infected 2,900–7,700 people (Aramini et al. 1999, p. 306). The source of the contamination is believed to have been cat or cougar fecal matter (Aramini et al. 1999, p. 307). *Toxoplasma gondii* is also a protozoan pathogen, and therefore is resistant to chemical disinfection, which allows the contamination to spread throughout the water system and into the taps of consumers. The water system in B.C. relied on chloramine disinfection without filtration, enabling the survival of the pathogen within the reservoir (Dumetre and Darde 2003, p. 654). This was Canada's first and only reported outbreak of toxoplasmosis, and is also the first outbreak of toxoplasmosis in a developed country.

2.3 Bacteria

2.3.1 *Campylobacter*

Campylobacter jejuni is another cause of drinking water disease outbreaks. *Campylobacter* also causes gastroenteritis illness similar to *Cryptosporidium* and *Giardia*. The main symptom found in humans infected with the *Campylobacter*

pathogen is diarrheal illness. However, *Campylobacter* is a bacterial pathogen, unlike *Cryptosporidium* and *Giardia* that are protozoan pathogens. Chlorine disinfection is effective against bacteria, and therefore outbreaks of *Campylobacter* should be easily preventable. In theory, there should be very few outbreaks since chlorination is the most common chemical disinfection. However, system failures in treatment processes are the main contributing factors that allow outbreaks to occur. *Campylobacteriosis* is more commonly a food borne disease found in raw or undercooked poultry, but there have been several waterborne outbreaks of significance.

In May 1983 in Greenville, Florida, an outbreak of *Campylobacteriosis* occurred. The ground water source supplied the rural community of 1,096 people. Animal fecal matter was determined to be the source of the contamination, causing 865 cases of illness (Sacks et al. 1986, p. 424). The *Campylobacter* pathogen entered the water source through infected bird droppings into open water towers. The system was reported to have other deficiencies, in addition to the open towers, which allowed this contamination to spread undetected. These included an unlicensed operator and insufficient treatment (Sacks et al. 1986, p. 424). The treatment of the system included pre-chlorination, flocculation, and post-chlorination. With effective chlorination the outbreak should have been prevented, but the levels of chlorine in this case were insufficient. The pre-chlorinator failed and the water backed up into the post-chlorinator, which was not effectively chlorinating the water before it entered the underground well. Equipment, operational, and treatment failures all contributed to this outbreak. If the plant had been properly maintained, the outbreak would have been prevented.

In March 1985 the groundwater source of Orangeville, Ontario became contaminated with *Campylobacter*. The outbreak caused 241 cases of illness. The source of the contamination was surface drainage from farming activity that followed a heavy spring rainfall and runoff (Hrudey et al. 2002, p. 399). The treatment of the system did not include chlorination because it was not required at the time for the deep wells. A lack of treatment, especially when considering the proximity of nearby animal farming, in combination with heavy rainfall and runoff, allowed the spread of the outbreak (Hrudey et al. 2002, p. 399). Treatment failure is again shown as the cause of a drinking water outbreak. Following the outbreak, chlorination disinfection has been installed.

In 1998, a groundwater source became contaminated with *campylobacter* in the Haukipudas municipality in Finland. The area of 15,000 people suffered approximately 3,000 cases of illness. The source of the outbreak is believed to have been bird droppings through holes in the water tower. The water supply was not chlorinated; treatment failure from a lack of chlorination is again the major contributor that caused this outbreak to occur.

Outbreaks of *Campylobacteriosis* are not as common as cryptosporidiosis or giardiasis, but *Campylobacter* is still considered a threat to the safety of drinking water. Proper chlorination or other form of disinfection would be effective against the campylobacter pathogen.

2.3.2 *Escherichia Coli*

Escherichia coli is a well-known drinking water contaminant because of the highly publicized drinking water contamination that occurred in Walkerton, Ontario, Canada in 2000. *E. coli*, similar to *Campylobacter*, is a bacterial pathogen that is not resistant to chlorine disinfection. *E. coli* contamination could be easily prevented particularly in smaller rural communities, since chlorine is the most commonly used chemical disinfection for drinking water. Groundwater in the Walkerton case became contaminated with several pathogens, but primarily *E. coli* and *Campylobacter jejuni*, causing over 2,300 cases of illness and seven deaths in the community of approximately 4,800 people (Hrudey et al. 2002, p. 397–398). The source of the contamination was cattle manure. It occurred through a combination of heavy rainfall causing the runoff into the water source, and also system deficiencies such as human error; the water system managers did not detect the contamination, and therefore did not treat it. The Walkerton Inquiry was commissioned following the outbreak, and was released in 2002. The Inquiry discussed the reasons and causes of the outbreak, and also provided recommendations for new and existing legislation to prevent future occurrences. The Inquiry emphasized the necessity of the multi-barrier approach to provide safe drinking water. A common theme among the research on drinking water outbreaks is the failure of barriers in water systems, allowing contaminations to occur and pass through distribution systems to cause illness. System deficiencies, including treatment and operational failures, were the main reasons for the Walkerton outbreak of 2000.

Another case of *E. coli* contamination occurred earlier in Cabool, Missouri in 1989, prior to the Walkerton contamination. The small rural community of approximately 2,090 people reported 243 cases of illness and four deaths. Although not as publicized as the Walkerton incident, Cabool's outbreak was also significant as it also caused death. Cabool uses a groundwater source, but direct source contamination was not believed to have occurred. The source of contamination is believed to have been fecal contamination from sewage. It occurred from a lack of disinfection following replacement of water meters and repairs to broken water mains. Unseasonably cold weather caused the water mains to break. The sanitary sewer system was also vulnerable to storm runoff (Hrudey et al. 2002, p. 403). The introduction of chlorination into the system subdued the outbreak (Rice et al. 1992, p. 38). Again, similar to Walkerton, this outbreak was due to system deficiencies. Treatment, particularly disinfection, is critical to ensure safe drinking water. Proper chlorination would have been effective against the *E. coli* contamination and would have prevented the outbreak.

In both outbreaks of *E. coli*, loss of life was associated with the contamination. The severity of the outbreaks emphasizes the need for adequate treatment, operational practices, and the maintenance and upkeep of equipment. A common thread between the bacteria pathogens, *Campylobacter* and *E. coli*, is that outbreaks most commonly occur in communities with surface sources or groundwater supplies that can come under the influence of surface water and there is inadequate disinfection.

2.4 Lessons from Disease Outbreaks

Drinking water disease outbreaks are the result of multiple failures within a water system. The most common failures that allow outbreaks to occur are improper or neglected treatment and failure to monitor operations. Outbreaks indicate the need for continual vigilance and adequate monitoring in the drinking water production and distribution, as well as continual testing of water quality to maintain adequate quality standards. Outbreaks can be used to gain knowledge and understanding of the techniques and methods that are most effective for providing safe drinking water. Lessons can be learned nationally within countries as well as internationally among countries, as shown here from Canada, the United States, and Europe.

Steven and Elizabeth Hrudehy are able to make conclusions in their book, *Safe Drinking Water* (2004), based on their summary of outbreaks from 1974 to 2002. They conclude that the multi-barrier approach continues to be a requirement for a safe drinking water system. Barriers in place at each stage within the system for the source, treatment, distribution, monitoring, and response are all required to ensure safe drinking water. Both human and nonhuman elements can cause failures throughout the system. Continued emphasis on the multi-barrier approach is necessary in order to detect and treat contamination at all stages before the water is distributed to the consumer. This approach is still the most effective method to provide safe drinking water.

The barrier of treatment is critical to the overall process. If an unknown contamination occurs, the goal of treatment is to inactivate and/or remove the pathogen before the water continues into the distribution system. Chlorine is the most commonly used chemical disinfectant because of its cost-effectiveness. We know that standard chlorine disinfection is effective against bacterial contaminations of *Campylobacter* and *E. coli*, but ineffective against protozoan contaminations of *Cryptosporidium*, *Giardia*, and *Toxoplasma*. *Cryptosporidium* is the most resistant, but all three protozoa are able to surpass simple chlorine treatment, which has been shown to cause numerous outbreaks. In the wilderness it may not be possible to prevent contaminants from entering water sources, especially surface water, but the barriers of filtration and disinfection are critical in preventing the spread of contamination that lead to outbreaks.

Hrudehy and Hrudehy also conclude that microbial pathogens are the primary concern for drinking water safety. All the included outbreaks are caused by pathogens, thus indicating the longevity and persistence of the problem and their dominance among contaminations. Pathogens threaten the safety of drinking water because of the possibility of contamination anywhere throughout a water system and their ability to surpass the treatment process. Pathogens originate from within human and animal fecal matter. Sources deemed to be of high quality could become contaminated with such matter, especially surface water sources. Hrudehy and Hrudehy emphasize the growing occurrence of *Cryptosporidium* since the 1990s up to the Walkerton contamination in 2000. With its high resistance to chlorine, the most commonly used method of treatment disinfection, the threat of *Cryptosporidium*

continues past the Walkerton outbreak to pose the highest risk to water systems. With the extent of research and the numerous outbreaks associated with this dominant pathogen, it is surprising that outbreaks continue to occur.

The Hrudeys also emphasize the effects of a *change* on a drinking water system. A system that is adaptable to change will be more capable of providing safe drinking water. Change can include changes in the weather, changes within the community, and changes within the water system. This is a contributing factor in many of the mentioned outbreaks. Change in the weather, either due to season changes or severe rainfalls associated with climate change, prior to the occurrence of outbreaks is a common event, such as in the outbreak of Carrollton Georgia in 1987, Warrington England in 1992, Cranbrook B.C. in 1996, and Galway Ireland in 2007. Change in a community can occur from human activity, such as farming. Agricultural runoff from farming activity was the specified cause in outbreaks such as Jackson County Oregon in 1992, Warrington England in 1992, and in Galway Ireland in 2007. Change in a water system contributed to outbreaks such as Kitchener in 1993 when the water system switched from a groundwater source to a surface source, and also in Pittsfield Massachusetts in 1985 when a filtration plant was in the process of being installed. Change should act as a warning to system operators of possible contamination. Monitoring should be heightened during times of change, and precautions may be necessary.

The conclusions by Hrudey and Hrudey (2004), based on outbreaks prior to 2002, emphasize that the Walkerton outbreak should have served as a major landmark in the history of contaminations. However, it does not seem that water authorities have absorbed lessons from that outbreak, as outbreaks have continued to occur since then. The conclusions and lessons described by the Hrudeys in their book can therefore be further expanded with new information by including outbreaks after 2002. The outbreak in Gwynedd and Anglesey, Wales in 2005 and the outbreak in Galway Ireland in 2007 are the most recent outbreaks. Including these cases provides the opportunity to consider whether outbreaks have changed patterns after Walkerton. Considering the patterns among the outbreaks is important in determining what factors contribute to the occurrence of an outbreak.

From the analysis of outbreaks reported here, we can conclude that there are no seasonal patterns to outbreaks. Contaminations have continued to occur during spring runoff from winter thaws and with higher amounts of rainfall. However, outbreaks can occur at any time during the year. This can be observed from the outbreaks reported here, as over half of the outbreaks surveyed here did not occur in the spring season. Spring runoff and rainfall are natural events, but improper practices by system operators can also cause outbreaks. Frequent human failures that cause outbreaks include improper and ineffective treatment, insufficient monitoring, and inadequate training of operators.

We can also conclude that outbreaks do not follow a pattern based on the size of a water system. In contrast to what may be a common belief, outbreaks are not specific to only small rural areas. Although outbreaks may be more frequent in smaller towns because of lower maintenance and less efficient water systems, due to lack of finance, this does not mean that larger systems are immune from failure.

This survey of waterborne disease outbreaks makes it clear that outbreaks can occur in both large and small communities. As mentioned above, Milwaukee with a larger population of 840,000 served by the water system and North Battleford with a smaller population of 15,000, have both experienced outbreaks of cryptosporidiosis. The major difference is that an outbreak among a larger population is likely to have a more significant impact, as more people are affected. The outbreaks that have occurred after Walkerton in 2000 also indicate that large communities are also susceptible to contamination.

Another factor that seems to stand out in the outbreaks is the reliance on chlorine. Communities that rely heavily and especially those that rely solely on chlorine disinfection are vulnerable to contamination. This chapter suggests that the most dominant microbial contaminant of the outbreaks referred to here is a protozoan pathogen, namely *Cryptosporidium*. The ability of protozoa to infiltrate and pass through many drinking water systems is because of their resistance to chlorine. Alternative treatments that are effective against protozoa are filtration, ozone treatment, and UV light treatment. Communities that have experienced problems of *Cryptosporidium* contamination often rely heavily or solely on chlorination. This is a significant limitation in the use of chlorine. Another disadvantage of chlorine is the byproducts that can result from its use. Trihalomethanes (THMs) form through a reaction between chlorine and organic compounds. These are known as disinfection by products (DBPs) and can have long-term health effects (Moghadam and Dore 2012). Chlorine can also create a distinctive taste if high levels of disinfection are required, which is often strongly disliked by receiving communities. Alternative methods of disinfection should be considered to avoid the problem of ineffective disinfection and the occurrence of THMs.

Multi-use watersheds involve a variety of activities and operations that could all contribute to a contamination. It is clear that farming operations often result in animal fecal matter contaminating water courses. Sewage treatment plants are another common cause of contamination. Animal and human fecal matter is the most common source of contamination in the drinking water outbreaks. The increase of human activity in a watershed also increases the possibility of contamination. Consequently multi-use watersheds need to increase the scrutiny of their water quality.

Boil water advisories (BWAs) are issued in order to prevent disease and drinking water outbreaks. A BWA requires all citizens of the specified community to boil their water prior to consumption in order to kill the possible pathogens within the water. BWAs are issued at the local level by the water authority of a community often following the detection of contamination, as a precautionary measure. Used wisely a BWA can prevent an outbreak. A BWA is effective when the detection of a pathogen in a water system is confirmed. However, a BWA can be ineffective when uncertainty of the water quality results in a continuous use of BWAs. A BWA is also ineffective when it is used as an alternative by water systems rather than providing the necessary treatment and equipment maintenance to be able to supply safe drinking water. A BWA should not be issued to avoid the responsibility of proper treatment and maintenance, but continuous and long-

standing advisories indicate that this occurs, particularly in small communities. Continuous BWAs are more common in smaller rural communities that are unable to maintain or upgrade their systems, often due to financial inability. Many residents are known to disregard a BWA, as some BWAs last many years.

Overall, the issue of drinking water quality will continue to remain a primary concern worldwide. Contamination and outbreaks can occur at any time and anywhere regardless of season or size of water system. The patterns among the outbreaks clearly show the ineffectiveness of chlorine against the threatening *Cryptosporidium* pathogen, the vulnerability of multi-use watersheds, and the failures of BWAs that are often overused. There is no substitute to proper treatment for safe drinking water.

What is the first step in preventing waterborne disease outbreaks? In the multi-barrier approach, the first component is the establishment of protection of source waters. This may require a watershed protection plan, including legislation to support watershed protection in the law of the land. Implementing watershed protection requires an understanding of the key principles of watershed management. The next section provides a succinct statement of the principles; the risk management component of watershed management is covered in Chap. 6.

2.5 Principles of Watershed Management

A watershed is an area within which all water bodies such as rivers and streams accumulate and eventually find an outlet. A watershed may also have one or more sub-watersheds. Watersheds are naturally cohesive hydrological units, encompassing a large area of land. The successful management not only aids the hydrological system, but also benefits the socio-ecological entity. We now summarize the core principles based on successful watershed management in the past.

1. A Good Understanding of Natural Ecosystems

Watersheds are defined by the topographic boundaries including natural ecosystems and urbanized landscapes, or elements of both (United States Environmental Protection Agency (USEPA) 2013, p. 7). The natural processes refer to the dynamic physical and chemical interactions, which form the landscape of the watershed, as well as its water quality. According to their characteristics, watersheds can be classified into three management zones (USEPA 2013, p. 8):

- *Upland zones* are land areas above high water level that intercept and transport rain or storm as groundwater.
- *Water-body zones* are surface water bodies, such as stream, river, and ocean, which provide the living environment for aquatic and terrestrial birds and mammals.
- *Riparian zones* are border surface water bodies that filter the surface water runoff.

The communities of humans, plants, and animals rely heavily on the watersheds, but to some extent damage them at the same time. It is an interaction effect between human activities and natural forces, which directly or indirectly changes the conditions of the water and land. More especially, with urban impervious surfaces such as roads and highways, storm-water flowing across the surfaces picks up contaminants that are carried directly in the storm-water drains and eventually enter the watershed (USEPA 2013, p. 13). In addition, the discharged and untreated water carries pollutants such as fertilizers, motor oil, PCBs and heavy metals, which also end up in the watershed; it impacts the water quality as well as public health. Thus, a good understanding of natural systems helps to achieve a harmonious relationship between human activities in the watershed and natural processes.

2. A Watershed Management Framework with the Involvement of Partners and Stakeholders

Building a watershed management framework is necessary in order to prevent environmental problems in advance. The framework describes the goals or problems and outlines the protective actions. Essentially, the framework focuses on a continued process for partners and stakeholders to work together and supports the watershed plans (USEPA 2013, p. 17). These partners and stakeholders make decisions on all the aspects of the framework that includes (a) resource standards (i.e. water quality standards), (b) watershed management approaches, and (c) watershed management projects. Eventually, the coordinated efforts in watershed management facilitate the development of the environment and the economy. For example, in 1992, three major chemical companies (Amoco, Dupont, and Bayer) collaborated with US fish authorities and other professional associations and even local citizens, in reconstructing successfully the ecosystem in the Cooper River region, and also enhanced local economic growth (USEPA 2013, p. 5). Moreover, using sound science in watershed management helps to achieve sustainable goals. For example, in trying to relieve the pressure of water demand due to increasing urban population, adequate water is required for the future in a sustainable manner. Furthermore, making use of scientific management approaches such as sustainability analysis and other tools to improve water productivity will be required to satisfy the water demands in the future.

3. Continuous Improvement Based on the Integrated Watershed Management

The overlapping of multiple jurisdictional boundaries in a watershed and the various environmental and economic interests of stakeholders result in a complexity of watershed management, and thus an integrated management approach applied to the watershed is required to improve the effectiveness of management (USEPA 2007, p. 1). To meet multiple objectives, integrated management refers to all stakeholders utilizing their respective disciplinary approaches to address the priority problems within a given watershed. Specifically, a government agency may be responsible for implementing a watershed management plan, as well as assessing and managing water quality and supply, while a local watershed association may be interested in solving a sedimentation problem in a small watershed, or making sure

farming in the region does not have an adverse impact on water quality in the region. A good integrated management approach should connect all the initiatives and actions of government agencies as well as local watershed associations (USEPA 2013, p. 17). Additionally, the process of integrated management is continuous, cyclical, and endless; it includes data gathering, assessment, targeting, implementation, and monitoring (USEPA 2013, p. 15).

4. Flexible Approach in Watershed Management

The watershed management approach is not one size fits all. Because each watershed landscape is shaped by a blend of climate, geology, hydrology, soils, and vegetation, a targeted approach should be applied to support the watershed management depending on different regions of the country (USEPA 2013, p. 20). In practice, watersheds can change over time, due to (for example) the emergence of serious diseases or a change in water flow patterns or due to a change in use patterns. The objectives and approaches of watershed management should be adjusted to adapt to changes in water and land use.

5. Application of Ecological Risk Assessment to Watershed Management

The US has strong regulations on point source pollution such as farms with animals. With the reduced impact of point source pollution (e.g. cattle manure from a specific farm) on source water quality via multiple legislation or regulations in the US, the issue of controlling nonpoint source pollution (pollution sources that cannot be identified) is becoming increasingly important both environmentally and economically (USEPA 2007, p. 6). Due to the limitations of being able to find pollution sources and pathways, nonpoint source pollution problems are not being corrected by existing regulations (USEPA 2007, p. 6). For this reason the EPA recommends an alternative approach, which is the application of Ecological Risk Assessment (ERA) to watershed management. In practice, the primary principles of watershed ERA assist the watershed managers to make decisions on such factors as total maximum daily load of contaminants, resource planning, and land use zoning, and how to mitigate these expected harmful effects. Since the sources of pollution are not known, it is a matter of assessing the risks that emerge from a variety of causes. In the mid-1990s, USEPA's Risk Assessment Forum and the Office of Water collaborated on testing the application of the ERA approach and recorded all the details during the experiment by choosing five watersheds that possessed abundant ecological resources, available dataset, and multiple stressors (USEPA 2007, p. 6). According to the EPA Risk Assessment Forum and the Office of Water, several researchers found that the application of ERA had been beneficial for watershed management (USEPA 2007, p. 6). A complete description of ERA is given in Chap. 6, which covers all aspects of risk management.

The key issue in the risk assessment of point source pollution is an adequate record of agricultural and commercial activity that could impact water courses within the watershed. Where the agricultural activity involves a large number of animals (for example cattle or pigs), there have to be clear animal manure management plans that ensure that none of the manure ends up in the water courses. For

nonpoint sources (for example wild animals or birds dying in water bodies at unknown locations, or contaminating the water with their feces), a good overview of the wildlife is necessary, and risks of contamination must be estimated. It would also help if there were water quality monitoring stations, so that when a quality problem arises, the authorities can try to identify the location of the contamination and remove it. If the contamination shows up in groundwater, it may be next to impossible to trace the source of the contamination. But if the frequency has been calculated, then risk assessment methods can be used and “high risk” areas can be mapped to warn local residents of the dangers of contamination of unknown origin.

In the US, a set of best management practices for animal farming are mandatory for large farms. For nonpoint source pollution, the US uses the method of Ecological Risk Assessment, on which more details are considered in Chap. 6. The principles of watershed protection outlined above should be reflected in legislation, wherever these principles are taken seriously. In other words, “voluntary” watershed protection is impossible and all watershed protection practices should be embodied in legislation.

2.6 Conclusion

The key lessons are: (a) a water system cannot rely exclusively on chlorine; (b) water systems must institute careful monitoring of conventional water treatment technology, particularly of flocculation and of chlorination; (c) water systems must be vigilant over the possibility of animal or human fecal material seeping into the water supply at all stages; (d) there is a need to institutionalize a regular protocol of sampling of water quality and the reliability of such sampling, and (e) a determined policy of continual modernization of all components of the complete water treatment train, by investing in newer and safer treatment technologies (see Chaps. 3 and 4).

As a first step in preventing waterborne disease outbreaks, institute a multi-barrier approach, of which the first component is the establishment of a sound watershed management plan that prevents contamination of water courses. The second step in the multi-barrier approach is a clear understanding of drinking water treatment technologies, which is the subject of Chaps. 3 and 4.

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