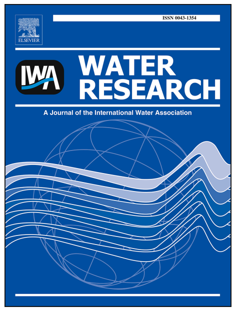

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Extreme Weather Events: Should Drinking Water Quality Management Systems Adapt to Changing Risk Profiles?

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Abstract

Among the most widely predicted and accepted consequences of global climate change are increases in both the frequency and severity of a variety of extreme weather events. Such weather events include heavy rainfall and floods, cyclones, droughts, heatwaves, extreme cold, and wildfires, each of which can potentially impact drinking water quality by affecting water catchments, storage reservoirs, the performance of water treatment processes or the integrity of distribution systems. Drinking water guidelines, such as the Australian Drinking Water Guidelines and the World Health Organization Guidelines for Drinking-water Quality, provide guidance for the safe management of drinking water. These documents present principles and strategies for managing risks that may be posed to drinking water quality. While these principles and strategies are applicable to all types of water quality risks, very little specific attention has been paid to the management of extreme weather events. We present a review of recent literature on water quality impacts of extreme weather events and consider practical opportunities for improved guidance for water managers. We conclude that there is a case for an enhanced focus on the management of water quality impacts from extreme weather events in future revisions of water quality guidance documents.

Keywords: Climate change; drought; flood; cyclone; hurricane; wildfire.

Abbreviations:

WHO World Health Organization

ADWG Australian Drinking Water Guidelines

IPCC Intergovernmental Panel on Climate Change

WSP Water Safety Plan

DOC Dissolved organic carbon

CT Concentration-exposure time

1. Introduction

Drinking water guidelines, such as the Australian Drinking Water Guidelines (ADWG) (NHMRC & NRMMC 2011) and the World Health Organization (WHO) Guidelines for Drinking-water Quality (WHO 2011), provide guidance for the safe management of drinking water. The contemporary editions of these documents focus primarily on the development and application of water quality risk management systems. The ADWG refer to this system as the "*Framework for the Management of Drinking Water Quality*" (ADWG Framework), while the WHO Guidelines refer to the "*Framework for Safe Drinking-water*" and the development and application of "*Water Safety Plans*" (WSPs). Both documents provide guidance on maximum contaminant concentrations ("guideline values") considered to be appropriate for the protection of human health. While the WHO Guidelines provide some guidance on managing water quality during emergencies and disasters, the focus of both documents is on day-to-day management under expected (or previously experienced) variability in climatic conditions. As such, guideline values for many chemical contaminants were derived based on assumptions of long-term continuous exposure.

The tragic consequences of the waterborne disease outbreak that occurred in Walkerton, Canada in 2000 are a well-known case study for many water quality risk managers (Hrudey et al. 2003, Ritter et al. 2002). Indeed, the Walkerton outbreak is cited numerous times in the ADWG and provided considerable inspiration for the adoption of risk management concepts that are fundamental to the contemporary ADWG and WHO Guidelines. While there were numerous contributing factors, a key aspect of the Walkerton outbreak was its association with extreme weather conditions. The preceding 5-day rainfall accumulation was equivalent to a once-in-60 year event in Walkerton, and a once-in-100 year event in the heaviest rainfall area to the south of Walkerton (Auld et al. 2004).

Despite the importance of the Walkerton case study and its association with an extreme weather event, the ADWG and WHO Guidelines deal only very briefly with the specific circumstances of extreme weather events. Among diverse specific water supply circumstances identified in the WHO Guidelines, it is observed that:

> *"Over an extended period of time, climate change may foster greater extremes in weather, including more frequent and longer spells with much higher peak temperatures, droughts, frequency of heavy precipitation and violent storms".*

Indeed, there is now broad scientific consensus that, with the continuation of greenhouse warming over the 21st century, it is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions (IPCC 2014). These climate change impacts will amplify existing risks, and create new risks for natural and human systems. The Intergovernmental Panel on Climate Change (IPCC) has identified important key risks for various global regions, including in some cases, increased drought-related water shortages, as well as increased damage from floods and wildfires (IPCC 2014).

Current evidence indicates global increases in the frequency and magnitude of high temperature extremes, together with more frequent and intense heavy rainfall events in many, but not all, global regions (Goodess 2013). Consequently, some regions are projected to become more prone to more intense rainfall and others more prone to drought (Cook et al. 2014). Recent evidence suggests that already about 75% of the moderate daily hot extremes, and about 18% of the moderate daily precipitation extremes over land, are attributable to climate change (Fischer and Knutti 2015). Pacific Ocean *El Nino* events are a prominent feature of climate variability and are associated with severely disrupted weather patterns, leading to tropical cyclones, drought, wildfires, floods and other extreme weather events worldwide (Cai et al. 2012). Recent modelling has revealed evidence for a doubling in *El Nino* event occurrences in the future as a result of greenhouse warming (Cai et al. 2014).

The WHO Guidelines state that there may be a number of possible water quality changes resulting from these types of events, including impacts to sediment loading, chemical composition, total organic carbon content and microbial quality (WHO 2011). Gastrointestinal illness following extreme weather events is a common occurrence and often results from the disruption of potable water supplies (Ivers and Ryan 2006, Watkins 2012). A recent systematic review identified eighty-seven waterborne outbreaks involving extreme water-related weather events (Cann et al. 2013). Heavy rainfall and flooding were the most common extreme weather events preceding outbreaks, which were often the result of the contamination of drinking-water supplies (Cann et al. 2013). Developing countries tend to be disproportionately affected by extreme weather events due to a lack of resources, infrastructure, and disaster-preparedness programs (Watson et al. 2007).

The risk management principles enshrined in the ADWG Framework and WHO WSPs are applicable to all specific water supply circumstances. However, it is arguable that many extreme weather situations will challenge most water suppliers, beyond what is currently considered during current risk management planning for abnormal weather events. As such, it is appropriate to consider the case for the review of water quality management guidelines with specific attention being paid to managing the potential impacts of extreme weather events on drinking water quality.

2. Water Quality Impacts

Extreme weather conditions have long been associated with a diverse range of water quality impacts and associated waterborne diseases. A systematic review has revealed that the average odds of identifying *Cryptosporidium* oocysts and *Giardia* cysts in fresh surface waters were increased between 2-3 times during and after extreme weather events, compared to normal conditions (Young et al. 2015). Similarly, the average concentrations of *Cryptosporidium* and *Giardia* identified under these conditions were also higher (Young et al. 2015). Consistent with these observations, drinking water-related waterborne infections have been observed to be associated with extreme events such as increased precipitation and temperature (Herrador et al. 2015, Semenza et al. 2011, Thomas et al. 2006). With projected increases in frequency, severity and duration of extreme weather events, it logically follows that the need to manage water quality impacts will increase in accordance with climate change (Delpla et al. 2009, Moors et al. 2013).

Direct impacts to water quality from extreme weather may be relatively simple to identify, but indirect impacts from extreme weather or changing trends over time can be overlooked, especially when they occur months, or even years, after the onset of the particular event (Stanford et al. 2014). Changes to temperature and precipitation patterns can increase the potential for wildfires, encourage invasive species, or increase forest mortality, resulting in both short-term impacts on water quality and long-term impacts to water catchments (Stanford et al. 2014).

In some cases, extreme weather events can impact water supply systems, such that normal household water services may not be maintained. These circumstances may also have public health impacts. For example, temporary loss of water supply and low water pressure following a freezing weather event in the USA led to increased rates of acute gastrointestinal illness in affected households (Gargano et al. 2015). Furthermore, extreme weather events can damage electrical, communication and transportation infrastructure, leaving water supply systems and operations vulnerable to other water quality impacts (Stanford et al. 2014).

Small scale water services, using surface water resources (rivers and lakes) for drinking water production may be particularly vulnerable to short term transient events due to their low adaptation capacity and their relative lack of support and technical knowledge, compared to major centralised systems (Delpla et al. 2011, Rajib et al. 2012). Despite their additional natural protection, subsurface water supplies, particularly those from karstic aquifers, may also be vulnerable to quality impacts from large rainfall events (Dura et al. 2010).

2.1. Heavy rainfall and floods

From 46 case studies of water quality impacts of extreme weather-related events in Australia and the USA, heavy rainfall was the most commonly reported event and was reported to have the greatest range of potential impacts on water utilities (Stanford et al. 2014).

Drinking water catchments contain various particulate and soluble substances, which may be mobilised to waterways by runoff from rainfall. As a consequence, heavy rainfall and high river flows are commonly associated with elevated turbidity (Goransson et al. 2013) and dissolved organic matter (Hongve et al. 2004, Murshed et al. 2014). In addition to concentration and load increases, substantial changes in the character of organic matter have been observed, with high molecular weight (>2 kDa), UV-absorbing compounds mostly detected in source water during flood periods, but not being evident in waters collected before or afterwards (Murshed et al. 2014). These characteristics, assumed to reflect input of organics from terrestrially derived sources, led in this case to improved treatability (requiring lower alum doses relative to organic carbon concentrations) than organics in waters during non-flood periods.

Transportation of particulate organic matter and dissolved organic matter from forested catchments involves a number of mechanisms and controls, which are only poorly understood for large, intense, storm events (Dhillon and Inamdar 2014). Intensive events may involve mechanisms which may have low relative significance during less intensive events. For example, it has been proposed that intensive rainfall may lead to changes in water pathways in the catchments and thus increased leaching of organic components from the upper soil layer (Hongve et al. 2004).

In urbanised catchments, heavy rainfall can cause combined sewer overflow events, which can lead to sharply diminished chemical and microbial water quality in receiving surface waters (Khan et al. 2014, Passerat et al. 2011). Consequently, increased rainfall, runoff and stormwater overflow lead to more events carrying peak concentrations of waterborne pathogens in surface water (Schijven et al. 2013, Schijven and de Roda Husman 2005). Following flooding of the Ohio River, USA, surface water samples exhibited elevated levels of pathogenic bacteria and viruses, as well as trace metals, including arsenic, copper, iron, lead, and zinc (Yard et al. 2014). Many of these contaminants are indicative of sewage contamination. Heavy rainfall events, resulting in surface runoff, and raw sewage overflows have been predicted as key mechanisms for climate-change induced increases in waterborne pathogens and potential acute gastroenteritis outbreaks (Beaudeau et al. 2011).

As a consequence of diminished runoff quality, water quality in lakes or storage reservoirs may also be impacted during heavy rainfall events. For example, the loading and distribution of suspended matter in storage reservoirs exhibit significant differences during wet and dry periods (Wang et al. 2013). However, water quality impacts to surface water reservoirs with multiple inflow sources may often be difficult to predict and characterise due to variable pollutant loads from the various sources (Aryal et al. 2014).

Following large storm events, residence times in lakes and reservoirs can be greatly decreased, leading to reduced processing of dissolved organic carbon (DOC) and, consequently, an increased quantity of humic substances reaching water treatment plants (Ritson et al. 2014). Severe rainstorms can cause vertical mixing and drastically modify the internal dynamics of some lakes (Kimura et al. 2014). Furthermore, colder or higher salinity inflows from heavy rain events can cause significant short-circuiting in reservoirs as the inflow runs under the main water body towards a dam wall or offtake. This effect can lead to high concentrations of contaminants, including pathogens, reaching drinking water plants (Brookes et al. 2005).

Through increased concentration of organic matter in surface runoff and the subsequent necessary increase in chlorine disinfection doses, increased concentrations of disinfection by-products are a likely outcome in final treated drinking waters (Beaudeau et al. 2011). In circumstances where satisfactory disinfection cannot be maintained, excessive rainfall has been a significant contributor to historical waterborne disease outbreaks in developed countries (Auld et al. 2004, Curriero et al. 2001, Hrudey and Hrudey 2007, Nichols et al. 2009).

In Chennai, India, where water supply vulnerabilities are pronounced, extreme precipitation has been consistently associated with gastrointestinal-related hospital admissions (Bush et al. 2014). Similarly, in Haiti, cholera outbreaks have been significantly associated with heavy rainfall events (Eisenberg et al. 2013). Major flooding events have, in numerous circumstances, led to very serious impacts to drinking water quality. For example, faecal contamination of drinking water sources was shown to be widespread following a 2004 flood in Dhaka, Bangladesh (Islam et al. 2007).

Widespread pathogen contamination of floodwaters was detected following a large urban flood affecting Jakarta, Indonesia (Phanuwan et al. 2006). One out of three groundwater wells that were sampled in the affected area were also shown to be contaminated, indicating that groundwater supplies are not necessarily well protected from surface water contamination. In 2010, flash flooding destroyed basic water and sanitation infrastructure in large areas of Pakistan. Subsequent analysis of drinking water supplies revealed the presence of numerous microbial indicator and pathogenic organisms, as well as known pathogen risk factors, such as elevated turbidity (Baig et al. 2012, Khan et al. 2013). These findings were accompanied by reports of illness following the consumption of contaminated water.

2.2. Superstorms and high winds

Superstorms, such as tropical cyclones, are non-frontal low-pressure systems with closed circulation over tropical or subtropical oceans (Grossmann and Morgan 2011). Coastal areas within the tropical and subtropical bands have become increasingly vulnerable to destruction by tropical cyclones and associated severe floods (Goodess 2013, Grossmann and Morgan 2011). They tend to occur in yearly cycles and affect coastal populations through high wind speeds (destroying dwellings and infrastructure), heavy rainfall sometimes causing floods and landslides, and storm surges and associated floods (European Commission and Joint Research Centre 2011). Many of the water quality impacts are the same as those encountered during other sources of heavy rainfall and flood events, but with the addition of physical wind damage to infrastructure.

In August 2011, Tropical Storm Irene hit the eastern part of New York and surrounding US states, causing great damage to public drinking water systems. Several water suppliers issued boil water advisories, most commonly as a consequence of physical damage to water distribution systems (Vedachalam et al. 2014). Subsequent investigations revealed that the probability of a boil water advisory being issued in any particular municipality was enhanced by several factors including higher precipitation during the storm, a high density of septic systems, lack of recent maintenance and low population density (Vedachalam et al. 2014).

In addition to direct impacts to water infrastructure, superstorms and high winds can damage electrical supplies and transmission infrastructure, thus impeding the ability to produce and supply safe drinking water (Liu et al. 2008). During 2008, Hurricane Ike caused electrical failure to some 2 million customers (homes and businesses) in the USA (Schmidlin 2011). Many public water supply systems lost power, but continued to operate on backup generators. For other suppliers, water production, pumping and monitoring systems failed. Nine days after the hurricane hit, 25 public water systems still had boil water advisories in place and 13 were using electrical generators (Schmidlin 2011). Without electricity, sewage treatment plants and sewage pumping stations failed in some communities, resulting in overflows and bypasses of untreated or under-treated sewage to streams. Similarly, following Hurricane Sandy in 2012, some areas of New York were without running water for up to 11 days (Schmeltz et al., 2013). During this time, residents had to leave their homes for drinking water and could not flush their toilets.

A waterborne cholera outbreak was reported following Cyclone Aila in India, 2009 (Bhunia and Ghosh 2011). Faecal contamination of drinking water supplies was implicated as a major contributing factor in this outbreak (Palit and Batabyal 2010). On the other hand, a similar outbreak was anticipated following Cyclone Sidr in Bangladesh during 2007, but did not occur, which was attributed to the careful distribution of food and safe drinking water, as well as the timely implementation of health care intervention measures (Paul et al. 2011).

2.3. Drought

The impacts of drought on water quality may be highly variable and will depend on the raw water reservoir type, geographic location, type of climate, and the combination of events that precede, co-occur with, or follow, a given drought (Mosley 2015).

The lack of rainfall decreases runoff and impacts the mobilisation and accumulation of material from water catchments (Mosley 2015). Consequently, rainfall following prolonged periods of drought can mobilise accumulated sediment and nutrients in a water catchment, leading to sudden influxes to streams and reservoirs (Wright et al. 2014). Reservoirs that have been drawn-down over prolonged drought periods may be particularly susceptible to sudden concentration changes from inflows when they occur (Wright et al. 2014). During droughts an initial decrease in the organic carbon concentration in reservoirs is often followed by a large ‘flush’ once rainfall occurs and organic carbon concentrations may remain elevated for a considerable period of time (Ritson et al. 2014).

As drought leads to decreased natural runoff to rivers and streams, relative flow contributions from other point sources, such as mine drainage and wastewater discharge will be increased (Wright et al. 2014). Consequently, the ambient concentrations of contaminants that are derived from those sources will also increase (Mosley 2015). For example, increased lake water concentrations of total dissolved solids, as measured by increasing conductivity, nitrate, pharmaceuticals and endocrine disrupting compounds have been associated with severe drought conditions (Benotti et al. 2010). The cause of these elevations was shown to be an increased wastewater fraction to the relative contributions of lake inflows during prolonged periods of low natural runoff.

Droughts can fundamentally alter nutrient cycling and biota within both watersheds and reservoirs that influence water quality for months or years after the event (Wright et al. 2014). Elevated nutrient concentrations, combined with warm temperatures are conducive to the development of algal and cyanobacterial blooms (Heisler et al. 2008). Such blooms are associated with water quality impacts, including taste and odour problems, possible toxin production and increased disinfection by-product formation potential (Wert et al. 2014, Zamyadi et al. 2012).

Recent droughts in Australia and the USA have led to water quality implications for drinking water treatment processes, including turbidity, taste and odour compounds (2-methylisoborneol and geosmin), colour, pathogen concerns, and challenges in managing disinfection by-products (Mosley 2015, Wright et al. 2014). Under drought conditions the ratio of hydrophilic to hydrophobic components of DOC has been reported to increase, while the relative abundance of aromatic (UV-absorbing) species decrease (Ritson et al. 2014). Laboratory studies of soil and litter leaching have also confirmed this, revealing that DOC produced during simulated droughts is more hydrophilic and harder to remove by coagulation (Tang et al. 2013).

Groundwater levels may be lowered during extended drought due to increased pumping or lower recharge rates, which may allow for the intrusion of poor quality groundwater or seawater in coastal areas (Bouzourra et al. 2015, Vallejos et al. 2015). Intrusion of seawater increases bromide levels, which may increase the production of more toxic brominated disinfection by-products (McTigue et al. 2014, Watson et al. 2012). Where ozonation is used to treat drinking water, elevated bromide from seawater intrusion can also cause the formation of high bromate concentrations (von Gunten 2003). In some cases, contaminant sources normally outside the wellhead protection zone can be transported to within the new pumping zone of the wells through changes in groundwater flow regimes (Swartz et al. 2006).

Prolonged drought can result in a cascading series of consequences resulting from remedial action taken to maintain community water supply. For example, water conservation measures can increase water age in distribution systems, leading to a loss of disinfectant residuals and increased concentrations of disinfection by-products or the development of nitrification in chloraminated systems (Stanford et al. 2014). Furthermore, communities that blend multiple water sources (*e.g.*, surface water and groundwater) to manage water quality may find that the flexibility to do so is reduced, as access to some sources is diminished (Stanford et al. 2014).

2.4. Extreme heat

Higher temperatures can facilitate the growth of algae and toxic cyanobacteria, which flourish in quiescent, nutrient rich waters (Paerl and Paul 2012). It was reported that the European summer heatwave of 2003 was a key cause of a four-fold increase in the concentration of cyanobacteria in a northern European lake (Jöhnk et al. 2008). In this case, it was shown that in addition to the heatwave temperatures favouring cyanobacteria directly, a number of indirect mechanisms further contributed to growth. In particular, high temperatures also increased the stability of the water column, thereby reducing vertical turbulent mixing, which shifted the competitive balance in favour of buoyant cyanobacteria. The consequences of extreme air temperatures on cyanobacteria abundance appear to depend on the time of year in which the extreme temperatures occur, with a warm winter more clearly associated with high abundance than an extreme warm summer (Anneville et al. 2015).

Higher temperatures generally decrease survival of enteric pathogens in the aquatic environment (Azevedo et al. 2008, Carratala et al. 2013, John and Rose 2005). However, there are some for which survival and growth may be promoted during warm temperature events. The bacterial genus *Vibrio*, including *V cholorae* are important examples. High water temperature is a strong predictor for the presence of *Vibrio spp.* and they are mainly detected in warmer waters (above 15℃) (Lutz et al. 2013, Vezzulli et al. 2013). Many studies have demonstrated that the abundance of *Vibrio spp.* follows a seasonal pattern, largely dictated by temperature (Lutz et al. 2013, Rashid et al. 2013). It is believed that warmer temperatures enhance the persistence of *Vibrio spp.* by promoting biofilm formation and colonisation of environmental surfaces such as chitin (Stauder et al. 2010). The effect of increased sea surface temperature in promoting spread of *Vibrio spp.* in coastal and brackish waters has been considered as a possible causal factor explaining observed increases in *Vibrio* illnesses in many parts of the world (Vezzulli et al. 2013). It is equally conceivable that increased freshwater temperatures may increase the risk of *Vibrio spp.* exposure in some cases. Indeed, a survey of water sources for environmental reservoirs of a pathogenic *V. cholerae* strain during a recent cholera epidemic in Haiti resulted in environmental detections only when water temperatures were ≥ 31 ^{o}C (Alam et al. 2014).

Another pathogen known to thrive at elevated water temperatures is the free-living amoeba, *Naegleria fowleri* (*N. fowleri*), which causes primary amoebic meningoencephalitis, a rare, but lethal, disease. *N. fowleri* commonly occurs in soil and fresh water, but may proliferate to high numbers in warmer waters of 30 to 40 ^{o}C (Bartrand et al. 2014, Ji et al. 2014). *N. fowleri* have been reported in drinking water sources in warm climates of Western Australia, Arizona, Louisiana and Taiwan (Bartrand et al. 2014, Ji et al. 2014, Kao et al. 2012).

Furthermore, some pathogenic bacteria, including *Legionella* spp. and *Mycobacterium* spp., can invade and replicate inside free-living amoebae including *N. fowleri* and other related amoebae (Buse and Ashbolt 2011). Consequently, the amoeba may serve as a reservoir for these pathogenic bacteria, as well as provide protection from normally adverse conditions, such as drinking water disinfection (Greub and Raoult 2004, Loret et al. 2008, Thomas et al. 2010). As warm temperatures promote the growth of some free-living amoebae, warm temperatures are also conducive to the proliferation of some of the pathogenic bacteria strains that colonise them (Buse and Ashbolt 2011).

Warm temperatures may lead to an accelerated loss of disinfectant residuals in water supply distribution systems (Fisher et al. 2012, Fisher et al. 2011, Kohpaei et al. 2011). As a general rule, chlorine decay rates typically double for every 5 ^{o}C increase (Fisher et al. 2011). This could have numerous water quality implications, including increased pathogen risk, increased disinfection by-product formation and increased biofilm growth. Furthermore, high temperatures may promote the onset of nitrification in chloraminated systems (Sarker and Sathasivan 2011). Optimum temperatures for the growth of the responsible nitrifying bacteria in drinking water systems is between 25 and 30℃ (Skadsen 1993, Wolfe et al. 1990).

Free-living amoebae have been detected in a large number of man-made water systems, including drinking water distribution systems (Loret et al. 2008). *N. fowleri* in drinking water distribution systems can be managed using residual chlorine or chloramine disinfectants, however nitrification does pose control challenges (Thomas and Ashbolt 2011). The greatest challenges for controlling *N. fowleri* are believed to be in premise plumbing systems, in which residuals might be low and warm water temperatures could support rapid growth (Thomas and Ashbolt 2011).

2.5. Extreme cold

Ambient air temperature, in general, plays a significant role in establishing and maintaining thermoclines and stratification in drinking water reservoirs (Butcher et al. 2015). Sudden switches from warm to cold air temperatures can rapidly disrupt thermoclines, leading to the mixing of surface waters with water stored at deeper depths (Xing et al. 2014). Similarly, an influx of very cold water into a weakly-stratified reservoir can cause destratification (Brookes et al. 2005). In such circumstances, dormant water quality factors such as iron, manganese, or nutrient accumulation at depth may then impact surface water quality. An event of this type occurred in Sydney, Australia during the southern hemisphere winter of 2007 and led to a cyanobacterial bloom in a major water supply reservoir (Stanford et al. 2014).

In more extreme cold circumstances, ice and snow can impact water quality and water supply (Stanford et al. 2014). Raw water intake systems from surface water reservoirs can become blocked by ice when water temperatures are at, or below, freezing (Daly and Ettema 2006). Such blockages can limit the rate of drinking water production or require the increased use of alternative sources. In some regions, freezing temperatures are also associated with an increased rate of failures in water supply distribution systems (Fuchs-Hanusch et al. 2013).

In some cold regions, salt mixtures, known as ‘road salts’, primarily composed of sodium chloride, are applied to road surfaces for the removal of ice (Fay and Shi 2012). Run-off from surfaces which have been ‘de-iced’ in this way can lead to considerable salinisation of surface water catchments and groundwater systems (Daley et al. 2009, Ostendorf 2013, Perera et al. 2013). Runoff containing road salts can form a saline water layer at the bottom of reservoirs, hindering vertical mixing and thereby affect lake water quality and ecology (Novotny and Stefan 2012). Depending on the salt composition, this may also lead to increased bromide and iodide concentrations, with associated effects on disinfection by-product speciation (McTigue et al. 2014).

The kinetics of most physical, chemical and biological water treatment processes are temperature-dependent. Consequently, important processes, such as coagulation/flocculation and chemical disinfection, may be significantly disrupted at reduced water temperatures (Corona-Vasquez et al. 2002, Li et al. 2001, Xiao et al. 2009). Although disinfection concentration-exposure time (CT) tables are widely understood to be temperature-specific, some water treatment plants may be unaccustomed to the operational conditions required to achieve high CT values for adequate disinfection at significantly reduced temperatures. Due to very slow disinfection kinetics, it has been suggested that monochloramine disinfection might not provide adequate control of adenoviruses in drinking water under some low temperature circumstances (Sirikanchana et al. 2008).

Like superstorms and high winds, ice storms commonly lead to power outages (Liu et al. 2008, Ruszczak and Tomaszewski 2015). Loss of power can disrupt water supplies by the loss of the ability to effectively treat and/or distribute water (Stanford et al. 2014). Ice and snow storms can further exacerbate the water quality impacts by impeding access to any impacted facilities until roads are cleared and safe access can be provided (Stanford et al. 2014).

2.6. Wildfires

Wildfires (commonly referred to as 'bushfires' in Australia) may severely impact the integrity of drinking water catchments. Forest biomass is composed of many elemental substances, including carbon, nitrogen, phosphorous and a diverse range of inorganic species. A major product of wildfires is ash, the particulate material deposited on the ground and consisting of minerals and oxidised organic substances (Bodi et al. 2014). Ash is highly mobile and may be redistributed or removed from a burned site within days or weeks by wind and water erosion to surface depressions, foot-slopes, streams, lakes and reservoirs (Bodi et al. 2014).

Ash composition and character is variable and dependent upon a range of factors, including combustion temperatures. For relatively low temperature fires (less than 450ºC), the combustion of organic substances is largely incomplete and the remaining ash is organic-rich, with organic carbon being the main component (Bodi et al. 2014). At higher temperatures (exceeding 450ºC), most organic carbon is volatilised, producing mineral ash, which has an elevated pH when in solution. It is composed primarily of inorganic carbonates of calcium, magnesium, sodium, potassium, silicon and phosphorous, whereas at temperatures exceeding 580ºC the most common chemical forms are oxides (Bodi et al. 2014). Depending on burn severity, the organic carbon released from some types of wildfire ash can have significantly increased aromaticity, compared to non-burned forest floor detritus (Wang et al. 2015).

The potential mobilisation of ash components to water supplies is also variable depending upon the nature of the burnt material. For example, leaching experiments, using ash and other burnt vegetation fragments, have revealed substantial differences in dissolved organic carbon size distribution and other physical-chemical characteristics (Revchuk and Suffet 2014). Recently burnt ash had 10 times the organic carbon leaching potential, and was dominated by large size fragments, as compared to weathered, 2-year-old ash.

The major water quality impacts of wildfires are typically experienced after the fire, during subsequent heavy rainfall events (Stanford et al. 2014). Runoff from burnt areas carries considerable quantities of sediment (Emelko et al. 2011, Moody and Martin 2009, Silins et al. 2009, Smith et al. 2011), as well as soluble nutrients contained in the ash, which can lead to problems for potable water supplies (Bodi et al. 2014). For example, following a catchment wildfire, thunderstorms and spring snowmelt, increased dissolved organic carbon and disinfection by-product concentrations were reported in a Colorado drinking water supply (Writer et al. 2014).

Elevated concentrations of nutrients, most notably nitrogen and phosphorus, are the commonly reported wildfire-derived water quality contaminants (Emelko et al. 2011, Smith et al. 2011). Wildfires in Australia have been shown to increase catchment nitrogen and phosphorus exports by around 5 to 6-fold, peaking at 15 kg ha^{-1} of total combined nitrogen and 2 kg ha^{-1} of phosphorous (Lane et al. 2008). Nutrients transported as particulate matter dominated the first post-fire year, with the particulates transporting 69% of the total combined nitrogen and 94% of the phosphorus. Although dissolved forms increased in importance in subsequent years, particulates contained 68% of the nitrogen load, and 86% of the phosphorous load, over the first three post-fire years.

Forest biomass may also act as a sink for regional urban pollutants, including metallic components of air pollutants. Consequently, forest fires may liberate large quantities of gradually-accumulated contaminants, leading to elevated concentrations of substances, including arsenic, aluminium, cadmium, chromium, iron, lead, mercury, sulphate, chloride, calcium, magnesium, manganese, barium, sodium, and potassium in sediment and local stream flows (Bladon et al. 2014, Costa et al. 2014, Emelko et al. 2011, Smith et al. 2011). In one case, it was calculated that approximately 350g manganese were released to waterways per hectare of burnt forest (Costa et al. 2014). Following the burning of a catchment adjacent to Los Angeles, CA, USA, concentrations and loads of many trace metals, including lead and cadmium, were up to three orders of magnitude greater than pre-fire values (Burke et al. 2013). The maximum suspended sediment, trace metal, and cation concentrations coincided with, rather than preceded, peak discharge in post-fire runoff, amplifying the fire's impacts on mass loading.

The organic carbon leached from wildfire ash may possess very different potential for the formation of drinking water disinfection byproducts, compared to unburned forest floor detritus. For example, it was reported that organic matter leached from wildfire ash led to reduced production of trihalomethanes and haloacetic acids, but elevated formation of haloacetonitrile following chlorination and N-nitrosodimethylamine following chloramination (Wang et al. 2015).

Wildfires can also affect the hydrological processes that influence the timing and magnitude of streamflows in a variety of ways (Bladon et al. 2014). For example, the destruction of forest vegetation reduces evaporative losses from forests through precipitation interception and evapotranspiration, thereby increasing the rain and snow that reaches the ground and therefore increasing runoff. Changes in soil properties from fire also contribute to an increased magnitude of storm runoff (Burke et al. 2013).

Collectively, the impacts of wildfire on hydrologic processes can increase both peak flows and a susceptibility to flash flooding events (Bladon et al. 2014). On the other hand, anticipated increased streamflows following a major wildfire in Victoria, Australia, did not eventuate (Feikema et al. 2013). In this case, it was concluded that that under the conditions of low rainfall and low soil water content that are conducive to larger wildfires, a substantial soil water deficit must first be overcome before appreciable changes in streamflow will occur. Furthermore, it has been reported that wildfires within the Sydney Basin (NSW, Australia) do not have a significant medium-term impact on water yield due to the rapid regeneration of fire resistant buds that are found on native obligate resprouter communities (Heath et al. 2014). Nonetheless, the hydrological effects and recoveries of wildfire disturbances on eucalypt forests may be highly variable, depending on species concentration and diversity (Webb and Jarrett 2013).

Following wildfires, catchment soils remain exposed to sunlight, which may lead to higher soil temperatures than in tree-shaded catchments. In one reported case, summer stream water temperatures were, on average, 4ºC higher in burnt catchments, compared with unburnt catchments (Rhoades et al. 2011). Such temperature changes could lead to changes in microbial activity and DOC transformation (Ritson et al. 2014).

These impacts may recover within a few years or last for numerous decades (Emelko et al. 2011, Moody and Martin 2009, Silins et al. 2014). Following major wildfires in Colorado, USA, stream water turbidity and nitrate levels remained elevated for at least five years (Rhoades et al. 2011). Stream nutrient concentrations and loads following Australian wildfires recovered to unburnt levels during the second post-fire year. In particular, particulate-bound nutrient export declined sharply through a reduction in sediment delivery (Lane et al. 2008).

Observations taken following wildfires in the Australian Capital Territory suggest that the time taken for turbidity levels to recover following wildfire is dependent upon the preceding land-use in the burnt catchment (Harrison et al. 2014). In this case, water quality from areas previously covered with native vegetation recovered considerably faster than areas that had previously been used for pine plantation forestry. This was partially explained by a higher proportion of bare soil areas for a longer period of time in the ex-pine forest estate compared to the native vegetation area.

In addition to water, fire suppressant and retardant chemicals are commonly used to fight large wildfires (Plucinski and Pastor 2013, Song et al. 2014). Fire retardant formulations may contain a variety of chemical constituents, including ammonia, phosphorus, and cyanide. While these are all naturally-occurring in ash, and detectable in streams from recently-burnt catchments, a relatively minor contribution of these chemicals in streams may also originate from fire retardant use (Blake et al. 2012, Crouch et al. 2006).

3. Opportunities for Drinking Water Management Adaptation

The challenges presented to drinking water managers from extreme weather events are diverse, and often complicated, but not entirely unpredictable. Indeed, there are many lessons to be learned from previous experience in managing extreme weather events, and from the more fundamental investigations of water quality impacts. From those lessons come opportunities to improve planning and preparation, and to gain a more thorough understanding of the water quality and quantity consequences of extreme weather events which may help water utilities adopt effective mitigation strategies immediately prior to, and during, extreme situations. A summary of identified adverse water supply impacts from extreme weather events identified in this review is presented, along with effective mitigation strategies in Table 1. Such strategies may include further developments in the risk assessment and risk management activities already embedded in Water Safety Plans (WHO 2011) and the Framework for the Management of Drinking Water Quality (NHMRC & NRMMC 2011). In some instances, there is good evidence that adequate anticipation of negative impacts of extreme weather events can limit the human health consequences of the degradation of water supplies (Paul et al. 2011).

Table 1. Water quality and quantity consequences of extreme weather events and possible mitigation strategies.

Extreme event	**Duration of effect after the event[1]**	**Adverse supply impact**	**Effective mitigation strategies**
Heavy rainfall and floods	Short	• Elevated turbidity due to increased particulate and soluble substances in storm runoff • Overflow of combined sewer systems • Increased pathogen and contaminant concentrations • Decreased disinfection efficacy • Damage to infrastructure, including electrical supply • Very short retention times in reservoirs due to short-circuiting	• Diversifying water sourcing options • Pre-filtration of surface waters prior to intake in drinking water plants • Additional or increased disinfection processes • Supply of point-of-use filtration devices and personal water quality testing kits • Alternate delivery of potable water (*e.g.*, tankers) • Issuing of boil water advisories • Implementation of enhanced treatment options prior to a forecast event
Superstorms and high winds	Short	• Similar to "heavy rainfall and floods" above. • Loss of key staff due to transport difficulties or damage to their own property.	• Similar to "heavy rainfall and floods" above, plus: • Building redundancy into water supply systems, including back-up power generators • Plan to have alternate staff available on call or accessible electronically • Availability of alternate water sources
Drought	Moderate	• Increased nutrient loads after extended period of drought • Large "flushes" of organic carbon once rainfall occurs • Elevated risks of algal and cyanobacterial blooms • Intrusion of saltwater in coastal area groundwater, which can lead to increased brominated disinfection by-products	• Diversifying water sourcing options • Additional filtration in early stages of drinking water production • Increased monitoring of surface water reservoirs for signs of algal or cyanobacterial blooms
Extreme heat	Moderate	• Elevated risks of algal and cyanobacterial blooms • Accelerated loss of disinfectant residual in distribution system • Early onset of nitrification in chloraminated systems	• Diversifying water sourcing options • Careful monitoring and application of disinfectant • Vertical mixing of water supply reservoir • Stricter nutrient management in the catchment
Extreme cold	Moderate to Long	• Salinisation from de-icing salts • Lake destratification and mixing • Intake ice blockages and distribution system failures	• Careful control of road surface runoff • Enhanced distribution system monitoring and maintenance
Wildfires	Long	• Increased magnitude of storm runoff • Increased nutrient and contaminant loads • Increased organic carbon • Elevated risks of algal and cyanobacterial blooms • Elevated microbial activity and DOC transformation • Presence of fire-fighting chemicals	• Diversifying water sourcing options • Additional filtration in early stages of drinking water production • Careful monitoring and application of disinfectant • Additional monitoring of contaminants • Prevention of particulate matter entering water-courses (eg straw bales, construction of swales)

[1]short = days to weeks, moderate = weeks to months, long = years.

Among current projections regarding future extreme weather events, important knowledge gaps have been identified with respect to compound or combined extreme events (such as a storm surge associated with river flooding) and the sequences of events (such as successive flooding/drought) that may be most significant in terms of water supply impacts (Goodess 2013). Similarly, it may be expected that combinations of extreme events, or specific sequences of extreme events, may present particular challenges for water quality management. For example, it has been reported that the likelihood of cyanobacterial blooms may be altered in response to contemporaneous changes in both temperature and hydrologic conditions (Jöhnk et al. 2008, Paerl and Paul 2012). It is likely that particular combinations of such changes could be considered to be 'extreme', even if the individual conditions, when considered alone, are not especially extreme.

To manage the impacts of extreme weather events, the WHO Guidelines suggest that the use of more climate-resilient technologies and processes may be required. They propose that water storage systems may need to be upgraded to obtain greater storage capacity to be able to cope with greater microbial, turbidity and chemical loadings affecting treatment capacity (WHO 2011). However, there is potentially significantly more detail with which this advice could be supplemented, including broad scale principles for risk management under extreme challenges and more specific recommendations for improving the resilience of water supply systems to changes in source water quality.

For example, long standing approaches to catchment protection tend to be focused on minimising agricultural and other anthropogenic impacts, and thus enhancing the stability of raw water quality. However, this approach does not acknowledge the risk of extreme weather-associated catastrophic land disturbance that is particularly evident in forested regions (Emelko et al. 2011). It has been proposed that wildfire simulation modelling and geospatial risk assessment methods may be adopted to predict water quality impacts (Chang et al. 2014), and identify and prioritise at-risk water catchments for additional risk mitigation treatments (Thompson et al. 2013). Risk assessment results may be particularly useful for prioritising the management of hazardous fuels to lessen the severity and likely impacts of future wildfires, where budgetary and other constraints limit the amount of area that can be treated. Tools that predict the effect of climate change may also be useful to drinking water management by providing insights to changing catchment conditions and changing assumptions underlying existing risk assessments.

In response to growing water demands, some cities have begun diversifying water sourcing and management, using underground storage, water transfers, conservation, recycling, and desalination. These same tools are promising options for responding to a wide range of climate change impacts, including some extreme weather events (Hanak and Lund 2012). Similarly, many existing strategies for managing extreme weather are available to at least partially meet the challenges of increased frequency and severity of such events, including reservoir operations, levees, bypasses, insurance, and land-use regulation (Hanak and Lund 2012).

Careful management of reservoir storages, preceding and during large flooding events, can be used to control suspended matter and turbidity levels in the withdrawn water (Wang et al. 2013). Similarly, a variety of management options may be considered to better control water quality risks associated with cyanobacterial growth in water supply reservoirs. For example, hydrologic modifications, including enhanced vertical mixing and, if water supplies permit, increased flushing (reducing residence time) may be effective in some systems (Paerl and Paul 2012). However, stricter nutrient management will likely be the most feasible and practical approach to long-term cyanobacterial control in a warmer, stormier and more extreme world (Paerl and Paul 2012).

Extreme weather events can produce a series of physical, chemical, and biological impacts on water catchments that may have important design, operating, and cost implications for future drinking water treatment processes (Emelko et al. 2011). Most notably, a potential increased dependence on solids and DOC removal processes may be anticipated for catchments disturbed by events such as wildfires (Emelko et al. 2011). Changes in the character of DOC may lead to changes in the treatability of raw waters, which may lead to the need for optimised or additional treatment processes and/or lead to increased concentrations of disinfection by-products in the finished water (Ritson et al. 2014).

Traditional management practices that focus on treating only the early portion of storm runoff may be less effective following wildfire since peak contaminant loads tend to coincide with peak run-off flows (Burke et al. 2013). Common water treatment processes, such as sand filtration and conventional coagulation, may struggle to produce optimum water quality when challenged with high levels of natural organic matter and turbidity (Braun et al. 2014, Stanford et al. 2014). However, in circumstances where the additional costs can be met, the incorporation of processes such as GAC and membrane treatment can improve the overall removal of organics and bacteria (Braun et al.

2014). One drinking water treatment facility responded to a Colorado (USA) wildfire partially by the construction of a pre-sedimentation basin (Writer et al. 2014).

The increasing reliance of water supply systems on potentially vulnerable power and communications systems may increase the potential for cascading failures (Short et al. 2012). Experience with Tropical Storm Irene in the USA revealed that prior investments in infrastructure management can proactively address municipal water supply and quality issues (Vedachalam et al. 2014). As a first step, the identification of critical infrastructure that may be susceptible to impacts from extreme weather events should be undertaken (Short et al. 2012). The availability of back-up generator capacity may provide the capability to continue to treat and supply safe drinking water in some cases (Schmidlin 2011). Advanced modelling capabilities are increasingly available to assess resilience of current power supply systems to extreme weather events (Ouyang and Duenas-Osorio 2014), as well as forecast likelihoods and extensiveness of power outages (Liu et al. 2008, Quiring et al. 2014, Ruszczak and Tomaszewski 2015). Emerging modelling techniques may also be used to forecast the time to recovery from power outages (Castillo 2014, Nateghi et al. 2014).

Rates of gastrointestinal illness following extreme weather events are influenced by a number of factors, including the prevalence of specific pathogens in the affected region before the event, the type of weather event itself, the impact of the disaster on water and sanitation systems, and the availability of health care resources (Ivers and Ryan 2006, Watkins 2012). The geographic and social diversity inherent in the exposure to water quality risks from extreme weather will, therefore, require a high degree of adaptability in the planning and management strategies that are prepared.

Appropriate strategies for maintaining the uninterrupted supply of safe drinking water following a natural disaster by ensuring effective disinfection of available supplies may be highly effective to preventing outbreaks of illness in some circumstances (Watkins 2012). Following the 2004 tsunami in Indonesia, the chlorination of stored water, either in tankers or at the household level, was the only intervention associated with a decreased risk of bacterial contamination of drinking water (Gupta et al. 2007). Other factors, such as using a narrow-mouthed container, or even reported boiling, were not associated with a decreased risk of the contamination of stored drinking water. Following the 2004 flood in Bangladesh, a number of point-of-use drinking water disinfectants were shown to be potentially effective against waterborne diseases among flood-affected people (Islam et al. 2007).

These were alum potash, bleaching powder, Halotab and Zeoline((R))-200. Additional guidance on the use of such strategies could have significant public health benefits.

Guidance on the use of a simple, inexpensive test kit for a community-level assessment of the faecal contamination of drinking water sources would also be a potentially useful development. A simple 'hydrogen sulphide test' kit for faecal coliforms is commercially available (Gupta et al. 2008). However, its low sensitivity has raised concerns regarding its use as the sole indicator of faecal contamination in individual or community water sources (Weppelmann et al. 2014). Other portable detection systems are also available, including those that measure *E. coli* (Burnham et al. 2014, Wildeboer et al. 2010).

Alternate water supplies can be delivered to affected communities via a number of routes, including tankers (static or bowser) and/or packaged water. However, these supplies need to be carefully dispatched and monitored in order to protect public health. During one UK flooding event, vandalism of tankers endangered public health and reduced the available stock (Carmichael et al. 2013). Accordingly, guidance on dispatch and monitoring, under testing circumstances, would be valuable.

A pre-defined communication plan is an essential component of any emergency plan (Khan and Gerrard 2006). There is a substantial value in establishing a professional relationship between the water utility and the public health agency if one is not already well-established (Jalba et al. 2014). Ongoing communication, utilising all available channels, should underpin the response activities from water companies and health authorities (Carmichael et al. 2013). Many extreme weather events are also associated with a loss of, or congestion of, many traditional communication channels. In such cases, increased website and call centre traffic needs and a potential lack of electricity, must all be taken into account (Carmichael et al. 2013). In some circumstances, social media, which may be managed on hand-held devices from almost any location, can be an effective channel for disseminating public health and emergency warning messages (Sutton et al. 2015).

Desktop exercises (also known as 'hypothetical scenario exercises' and 'mock simulations') are widely used to identify weaknesses and improve emergency response plans for public health crisis situations (Araz and Jehn 2013, Banuls et al. 2013, Beaton et al. 2007, Lurie et al. 2008, Morris et al. 2012). Many water utilities also have experience with using desktop exercises for emergency planning (Mason and Verner 2008, Whitler and Stormont 2011). There is considerable guidance available for the design and conduct of such exercises for public health emergencies (Biddinger et al. 2010, Dausey et al. 2007). Some guidance has also been previously provided, specifically to aid in the preparation for water system incidents (Moyer 2005). Water management guidelines could similarly provide such advice regarding how these types of activities could be planned and executed. The use of focus groups may also achieve similar objectives in some cases (Becker and Middleton 2008, Burns et al. 2010). For some extreme scenarios, potentially involving mass casualties, desktop exercises may be inadequate and regular, full-scale regional exercises may be more appropriate (Klima et al. 2012).

Some potential contingency plans to assist communities withstand the impacts of extreme weather events will have significant associated costs, for which the full anticipated benefits may never be required or realised. A simple example is maintaining supplies of emergency packaged potable water and associated supply chains. The unpredictability of the need to use them, and their value in any particular circumstance, imply a level of risk associated with the cost of maintaining such supplies. Decision makers need to be able to assess this risk and the potential benefits, in comparison to other emergency preparedness alternatives, such as upgrading or reinforcing existing infrastructure. The use of multi-objective decision tree analysis has been demonstrated and promoted for this purpose (Crowther 2010). The result is the capability to quantify various logistical courses of action in terms of costs and supply shortfall. The general concepts described in this case study have potentially wide applicability to decision making in the face of uncertain extreme weather events.

Some consideration of drinking water quality and the ability to meet the health-based and aesthetic guideline values in relevant drinking water guideline documents is required. Chemical guideline values are generally (but not always) based on chronic risk and a level of exposure that is regarded as tolerable throughout a lifetime, while pathogen guideline values are based on acute risks. This means that short-term spikes in microbial pathogen concentrations can increase pathogen risks considerably and lead to outbreaks of waterborne disease, while limited short-term exceedance of chemical guidelines does not necessarily mean that the water is unsafe for consumption, provided the intake of the particular chemical(s) over longer periods of time does not exceed the acceptable daily intake (WHO 2011). This is particularly true for some disinfection by-products, for example, which may exceed conventional guideline values as a result of high-dose disinfection to maintain pathogen control in extreme weather event situations. However, consideration should also be given to any potential acute effects on a chemical-by-chemical basis.

Some guidance is already available on acceptable short term concentrations that are unlikely to result in adverse human health effects (US EPA 2012, WHO 2011). Where the data is available, short term guidelines could be based on short-term toxicity data, such as the Acute Reference Dose (Hamilton et al. 2004, Kimmel 2002). Where acute toxicity data is not available, allowing 100% of the tolerable daily intake to come from drinking water may be acceptable for a short period of time (WHO 2011).

In addition to water quality impacts, extreme events may also severely affect water quantity by impeding the ability for water treatment plants to produce sufficient quantities of potable water, or for distribution systems to deliver sufficient water to customers. For example, events, such as flooding and severe cold, have resulted in the significant loss of mains water supplies in a number of European countries over recent years (Carmichael et al. 2013). Resulting shortages have been documented to cause panic, despair, feelings of exposure, distress and helplessness among affected populations (Carmichael et al. 2013). These community responses pose additional challenges, which should be at least partially met by water supply utilities. Enhanced guidance on how to effectively meet such challenges would be of considerable value during and following extreme weather events.

4. Conclusions

Extreme weather events may impact drinking water supplies in a variety of ways, leading to water quality impacts, including increased concentrations of suspended material, organic matter, nutrients, inorganic substances and pathogenic microorganisms in source waters.

With some notable exceptions, the water quality impacts most commonly experienced by customers in developed countries have been primarily limited to aesthetic impacts (taste, odour, and colour) and elevated chemical constituents, such as disinfection by-products. However, impacts in less developed countries have been much more severe and have commonly included widespread outbreaks of gastrointestinal disease. Projected increases in the frequency and severity of events, such as heavy rainfall and floods, cyclones, droughts, heatwaves and wildfires, increase the significance of, and urgency for, improvements in the management of such events.

Water quality impacts of some types of weather events may not be realised until months after an event has occurred (*e.g.*, catchment accumulation of contaminants during a drought). Impacts may persist for months, or even years, after their initial onset (*e.g.* the impacts to catchments following wildfires). Water managers will need to be vigilant, not only at the onset of an extreme weather event, but they must also continue monitoring, planning, and preparing during the subsequent months to ensure they have the capability to respond to challenges to water quality potentially triggered by later events.

It is possible to design and operate systems to mitigate foreseeable extreme events. Many water quality impacts from extreme weather events may be successfully managed by water treatment plants and, therefore, do not lead to water quality impacts being experienced by customers, provided the treatment plants have been adequately designed and operated for the local circumstances. However, such impacts may impose additional burdens on treatment facilities, requiring additional power consumption, chemical use, maintenance or waste production. They may also represent an elevated level of risk and require additional risk management activities, including monitoring, by water utilities, regulators and others to protect customers. Consequently, guidance for managing extreme weather events should encompass a broad range of planning and operational activities to be undertaken by water utilities and other agencies.

There are numerous opportunities for improvements in the water quality management practices that are currently used to protect against impacts from extreme weather events. Guideline documents, such as the ADWG and the WHO Guidelines, have an important role to play in providing robust, scientifically-supported guidance, with the principal objective of protecting public health. Recently-experienced water quality impacts from extreme weather events have revealed the need for improvements in both developed and developing countries. Accordingly, it is recommended that future revisions of drinking water management guidelines pay particular attention to the management of water quality impacts associated with extreme weather events.

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- Extreme weather events are associated with diverse water quality impacts
- Projected increased event frequency and severity imply changing water quality risks
- Enhanced focus on extreme weather drinking water management is warranted
- Opportunities to adapt drinking water quality management systems are identified