Managing water quality impacts from drought on drinking water supplies

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ABSTRACT

Droughts, which are difficult to predict, are a natural feature of the hydrology in most regions. Climate change, however, has the potential to increase the frequency and magnitude of future droughts. While the lack of water availability during droughts is widely publicized, there are equally severe water quality impacts that occur during and after droughts as well. Recent droughts have led to water quality implications for drinking water supplies including turbidity, taste and odor, pathogen concerns, and challenges in managing disinfection byproducts (DBPs). This paper presents the results from a series of case studies prepared for a Water Research Foundation study on the effects of extreme weather on drinking water quality in order to help utilities prepare for vulnerabilities under future climate change. A key finding from the case studies is that droughts can fundamentally alter nutrient cycling and biota within both watersheds and reservoirs that influence water quality for months or years after the event. A few of the critical management actions for responding to degraded water quality related to droughts include awareness of potential impacts, increased monitoring during and after the event, and capacity to quickly adjust treatment processes.

Key words | algae, disinfection byproducts, drought, extreme weather, management, water quality

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INTRODUCTION

In the last few decades, there has been increasing evidence that extreme (i.e. low-probability) weather events (floods, droughts, heat waves, etc.) are recurring more frequently, and are affecting different regions than in the past (Peduzzi 2005; CSIRO 2008; CSNE 2010; NOAA 2010; Repetto & Easton 2010; Kunkel *et al.* 2013). It is believed that global climate change is, and will continue to be, a major driving factor for the increased number of extreme weather-related events, as supported by trends in global weather drivers such as atmospheric water vapor, arctic ice decline, and sea surface temperature increases (Perovich & Richter-Menge 2009; Deser *et al.* 2010). Droughts, in particular, are a major concern for utilities and water resource managers worldwide due to the far reaching impacts of constrained water supplies. However, while the lack of water availability during droughts is widely publicized, there are equally severe water quality impacts that occur during and after droughts. Numerous studies have been published that have assessed the affects of drought on ambient water quality, but not necessarily from the perspective of drinking water treatment (Bond *et al.* 2008; van Vliet & Zwolsman 2008; Wetz *et al.* 2011). In addition to the potential for future changes to water quality, the trend towards increasingly strict drinking water regulations is expected to continue (Figure 1). The combination of decreased water quality with lower maximum contaminant levels may result in vulnerabilities for many utilities, requiring substantial investment in updated treatment technology to maintain compliance.

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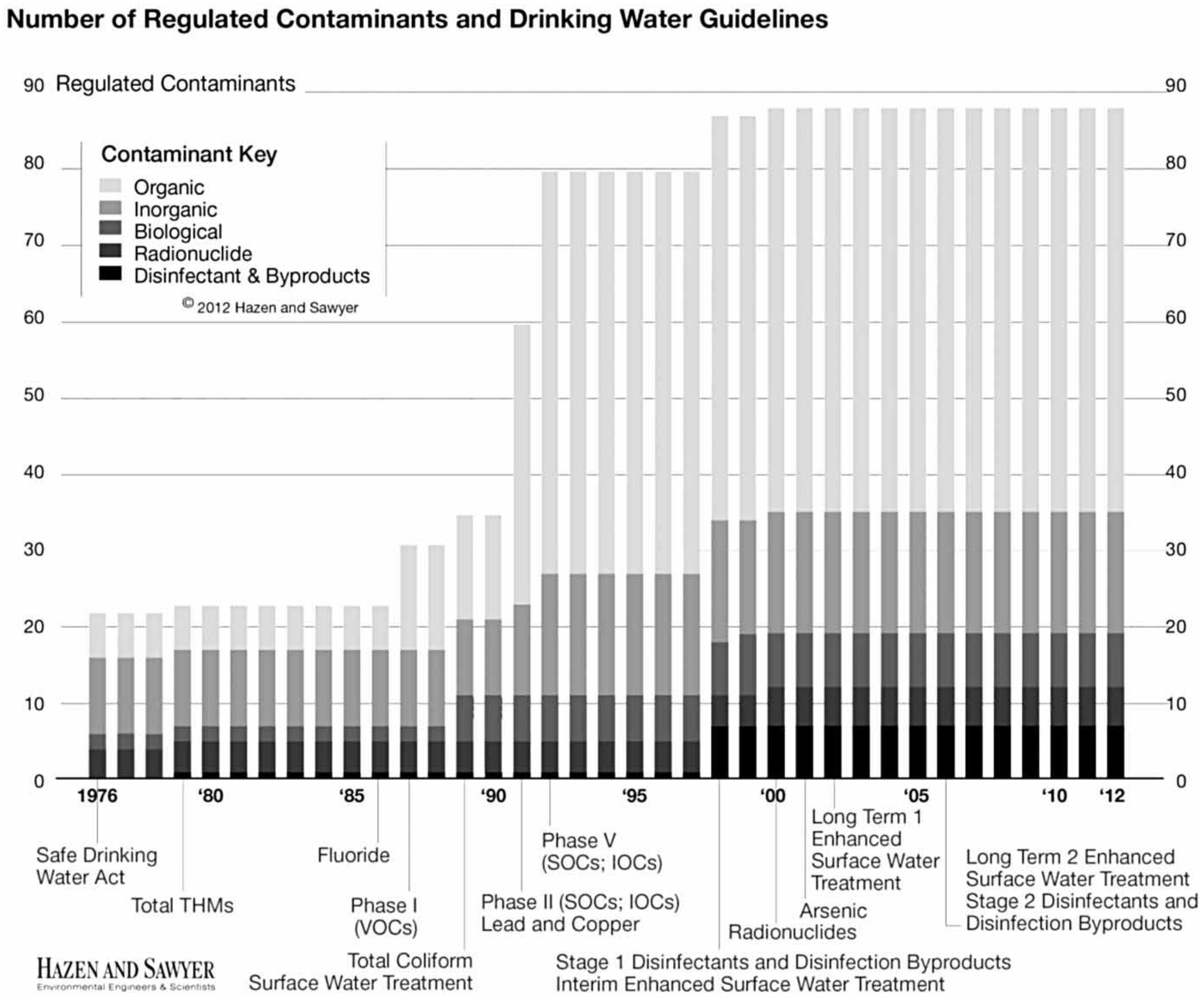

Figure 1 | Number of regulated contaminants and drinking water guidelines in the USA.

This manuscript aims to document many of the water quality, treatment and utility management challenges experienced by water utilities during drought conditions. The data presented in this study are based upon 46 case studies developed from drinking water utilities across the United States and Australia. Of the 46 case studies developed for the larger study ('Water Quality Impacts from Extreme Weather-Related Events', Water Research Foundation Project #4324, 2013), 18 of them were directly related to drought and are used to support the findings presented in the following sections. The manuscript first provides an overview of mechanisms for impacts to water quality during and resulting from drought conditions, then highlights eight case studies with their unique water quality and treatment impacts.

MECHANISMS FOR WATER QUALITY CHANGES FROM DROUGHT

Reduced rainfall levels have been demonstrated to result in multiple physical effects to watersheds, rivers, lakes, and reservoirs. The lack of rainfall decreases runoff and impacts the mobilization and accumulation of material from watersheds. Further, the character of natural organic matter (NOM) may change during droughts, impacting the chemistry and treatability of the NOM and affecting the removal efficiency at water treatment plants (WTP) (Tang *et al.* 2013). When streams and rivers experience reduced flow rates and flow velocities, a larger proportion of stream flow will come from groundwater baseflow and point discharges in the watershed. The elevations of reservoirs and lakes may drop as inflows are less than what leaves the water body from evaporation, diversions for irrigation and drinking water, downstream releases, or groundwater recharge (Bond *et al.* 2008). Each of these physical changes in hydrology will have specific effects on water quality depending on the surrounding land area, land use patterns, and stream inflows.

Watersheds

Poor water quality from watersheds typically originates from nonpoint sources; however, during droughts, inputs of runoff-related contaminants may decrease with decreased volume and velocity of watershed runoff. This change is only temporary as the sources of nonpoint pollution will tend to continue to build up in a watershed. This is particularly evident with agricultural areas, where nutrient inputs into waterways can decrease substantially during drought periods, only to spike following the end of droughts (Acker *et al.* 2005).

Rivers and streams

As natural runoff decreases in rivers and streams, water quality may change dramatically. Reduced flow translates into reduced dilution of point discharges, increasing the proportion of point source loading of contaminants. For example, mine drainage and wastewater discharges from natural gas drilling operations led to high total dissolved solids (TDS) in the Monongahela River, a tributary to the Ohio River during drought conditions in West Virginia and Pennsylvania in 2008. The elevated TDS could not be removed through conventional water treatment, leading to taste and odor problems as well as increased brominated disinfection byproduct (DBP) concentrations (Handke 2009). Reduced freshwater flows in coastal rivers during droughts can also result in the movement of high salinity water upstream, a primary concern for the City of Philadelphia on the Delaware River. In addition to increased pollutant concentrations, warmer, more stagnant waters can encourage harmful algal blooms (Paerl & Huisman 2008).

Lakes and reservoirs

Lakes and reservoirs are susceptible to drought impacts from the changing quality of river and stream inflow. Unlike the watershed catchment area which may retain contaminants during periods of droughts, reservoirs that receive inputs from wastewater and industrial sources may observe an increased concentration of source-derived contaminants during periods of drought as the available volume of water for dilution drops. A 2010 paper demonstrated the impact of increasing concentration of wastewater-derived nitrate and pharmaceutical compounds concurrent with the declining elevation of Lake Mead (Benotti *et al.* 2010). Internal reservoir processes will also impact water quality in terms of diffusion, mineralization, and vertical mixing of dissolved constituents throughout the water column. Low dissolved oxygen (DO) in reservoirs during drought can lead to dissolution of phosphorus from bottom sediments and encourage algal growth (Carlton & Wetzel 1988). Additionally, as water levels drop, bottom sediment may become resuspended in the water column.

Whether it is a reservoir, lake, or a slow moving stream, drought conditions can generally lead to environmental conditions that can encourage algal blooms by increasing nutrient concentrations, water temperatures, and residence times (Heisler *et al.* 2008; Paerl & Huisman 2008). Algae are major culprits of taste and odor problems and are also a source of NOM for DBPs. As previously stated, rainfall following drought can mobilize built-up nutrients in the watershed, further encouraging algal growth when nitrogen and phosphorus are components of the runoff. Blooms can also consist of harmful algae and/or cyanobacteria that produce toxins.

Case studies (impacts and responses)

In order to further illustrate the drivers for water quality changes due to drought, as well as some potential actions to counteract the negative effects of low rainfall conditions, several case study summaries have been provided below.

These case studies delve deeper into how different utilities from the USA and Australia have dealt with drought impacts from algae, DBPs, manganese, turbidity, and cyanotoxins resulting from drought conditions.

Southeastern Australia, Utility A – algal bloom

Water filtration plants (WFP) in Southeastern Australia experienced a multi-year drought from 2001 through early 2007. As such, nutrient accumulation occurred in the catchment lands that subsequently washed into the reservoir. This drought was followed by a cyanobacterial (blue-green algal) bloom in later winter/early spring of 2007. Turbidity levels increased from typical values of <3 NTU to nearly 30 NTU. Additionally, the drought conditions led to the presence of potentially toxic *Microcystis* and *Anabaena* species (which reached a maximum density of 700,000 cells per mL), and the presence of non-toxic algal byproducts 2-Methylisoborneol (MIB) and geosmin (Whiffin & Vigneswaran 2009). With severely degraded influent water quality, the WFPs were charged with handling increased complaints about taste and odor in the water while working diligently to minimize the presence of possible pathogens and toxins to produce a safe finished water product. The ability to provide high-quality finished water was maintained by the ability to quickly adjust reservoir intake levels to reduce turbidity, and increased source monitoring for cyanobacteria, MIB, and geosmin. Unfortunately, even with quick operation changes and increased monitoring, a sharp rise in taste and odor complaints occurred for finished water which persisted for a period of time following the drought.

Southeastern Australia, Utility B – algal bloom

Utility B's reservoir is operated solely as a drinking water source that provides safe drinking water to over half a million residents in New South Wales, Australia. Reduced rainfall in early 1997 preceded the formation of an algal bloom in the upper catchment. Unlike extreme rainfall events that could flush contaminants from the catchment into the reservoir, in this case light, sporadic rainfall in September 1997 slowly pushed the bloom from stagnant upstream rivers into the main storage. The initial algae bloom altered the phytoplankton characteristics of the reservoir storage with potentially toxic *Anabaena* and *Microcystis* species dominating. The presence of potentially toxic species raised concerns over the safety of the water as well as the potential for increased taste and odor compounds (MIB and geosmin). The ability to provide high-quality treated water was maintained by a combination of selecting the appropriate intake levels from the dam as well as increased and focused attention on chlorination to inactivate any toxins present.

Taste and odor compounds were elevated during the initial event but did not contribute to additional consumer complaints. In response to this event, a national blue green algae alert level system was put into place. The protocols recommend actions based on a three level alert system, whereby level 1 occurs when blue-green algae is between 500 and 2,000 cells/mL, level 2 occurs between 2,000 and 15,000 cells/mL, and level 3 occurs above 15,000 cells/mL. The bloom experienced during this event was considered a moderate event as cell concentrations reached approximately 12,000 cells/mL. Typical raw water cyanobacteria cell concentrations are negligible.

The actions associated with levels 1, 2, and 3 include increased monitoring for algae, increased monitoring for algae with toxicity testing, and increased monitoring with toxicity testing and media notification, respectively. This tiered system allows for the utility to appropriately identify and handle blue-green algae concerns of increasing severity. In addition to the level framework, liaison links with New South Wales Department of Health were established, a temporary powdered activated carbon (PAC) system was built to handle taste and odor compounds, and increased focus placed on operational parameters to reduce conditions favorable for future cyanobacterial bloom development.

Mid-Atlantic United States, Utility C – DBPs

Utility C owns and operates a WTP located in North Carolina and supplies drinking water to approximately 80,000 people. The three reservoirs that service the utility's WTP experienced a major drought in 2002 and 2007. Following the drought, the reservoirs refilled and normal hydrology resumed, but the utility experienced distinct increases in DBPs (trihalomethanes (THM) and haloacetic acids (HAA)). THM/HAA test results were much higher than normal throughout the distribution system and in some cases were above the maximum contaminant level (Figures 2 and 3).

Interestingly, HAA measurements were also elevated (between 50 and 60 ppb) during the spring and fall, but not during the summer of the 2007 drought. Typical values for both THM and HAA are <50 ppb. Thus, the major impacts from DBPs were neither during the drought nor immediately after refill of the reservoir, but instead during the summer months in the year after the drought/refill event.

While the running annual average was still within the regulatory limits, several Special Notices of high observed contaminant concentrations were sent out to affected areas. The increased DBP formation was correlated with the presence of elevated levels of organic carbon interacting with the current disinfectants in the treatment regime. It was believed one of the primary contributing sources of organic carbon was decaying vegetation along the reservoir shoreline (Figure 4), a hypothesis consistent with the delay between refilling of the reservoir and onset of the higher DBPs. In order to reduce DBPs during the summers after the droughts,

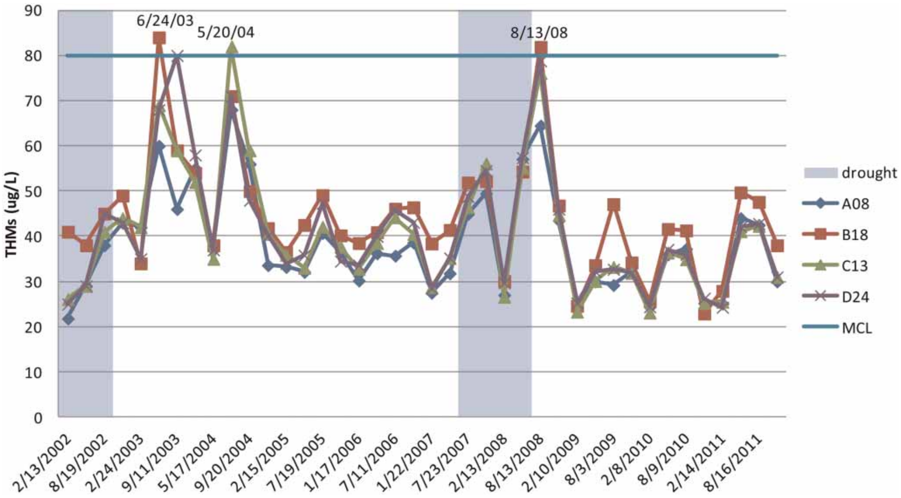

Figure 2 | Utility C quarterly sample results for THM at four locations.

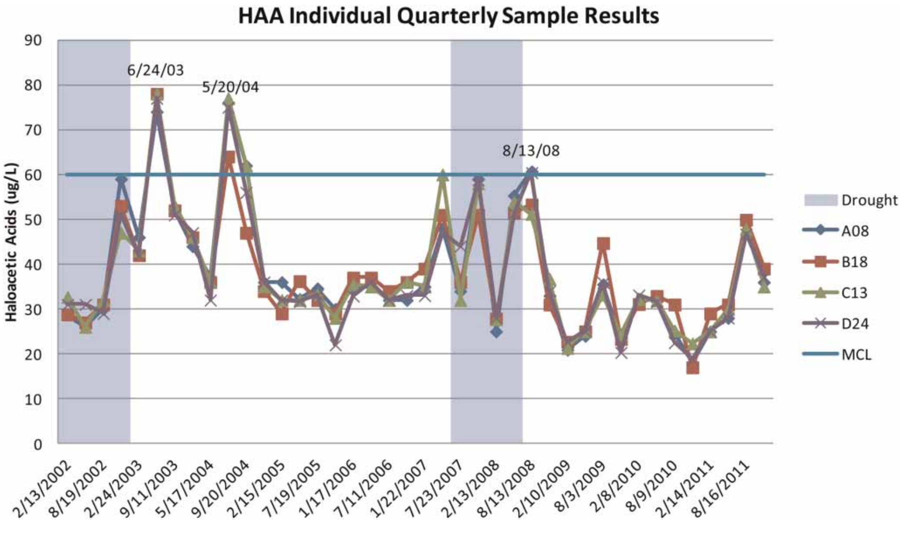

Figure 3 | Utility C quarterly sample results for HAA at four locations.

Figure 4 | Utility C water supply reservoir during 2002 drought.

the plant staff worked to optimize the treatment process by using wood-based PAC instead of the coal-based PAC that had been used to control for taste and odor control. Additionally, PAC doses were increased to remove more organic carbon, while chlorine doses prior to the filters were reduced. In response to this event, the WTP integrated the addition of wood-based PAC and a reduction of chlorine prior to the filters as part of the standard operating procedures (SOPs) for future drought events. Additionally, grasses and vegetation are routinely removed from the shoreline during periods of low water to prevent future occurrences.

Mid-Atlantic United States, Utility D – DBPs

Utility D's WTP provides water to over 450,000 customers throughout North Carolina. The area experienced a prolonged drought which lasted from 1998 through 2002, though the most severe impacts occurred in 2002 (Figure 5). The lake levels that feed the WTP were monitored closely throughout the drought, but the staff were not prepared for the rapid lake refill that occurred in just a few days following the end of the drought. The rapid lake refill caused alkalinity to decrease and total organic carbon (TOC) levels to increase. The normal TOC concentration of around 6.0 mg/L in the reservoir increased and the alkalinity average of 28 mg/L decreased after the heavy rainfall event with TOC reaching as high as 10 mg/L and the alkalinity dropping to 14 mg/L. This condition of altered water quality lasted for approximately 9 months after the refill event.

During the drought, water use restrictions led to increased water age and lower chlorine residuals in the distribution network. Additionally, DBP formation was higher once the lake refilled due to the increased TOC. Flushing programs were adopted to prevent nitrification as well as maintain the necessary chlorine residual in the distribution system and increased chemicals were applied to reduce TOC and maintain the settled and finished water quality. In response to this event, the WTP staff developed a water conservation plan, tiered water rates to assist with water conservation, and evaluated future alternative water source options.

Mid-Atlantic United States, Utility E – manganese

This utility experiences seasonally high manganese levels in the summer months in its eight billion gallon water supply

Figure 5 | Utility D reservoir during 2002 drought.

reservoir. The elevated manganese levels are associated with reservoir stratification and the loss of DO in the lower stratum of the reservoir. Due to low DO, manganese dissolves out of the bottom sediments and is introduced into the water column. In late May to late June 2006, a strong stratification of the reservoir was initiated by a moderately dry period with warmer than normal temperatures. Following the dry period, steady rain occurred throughout the watershed which resulted in an extended period of high flows. The major consequence of the rapid refill was the elevated manganese concentrations in the reservoir, which varied between 100 and 1,000 μg/L depending on depth. The utility evaluated whether selective withdrawal could be used to limit raw water manganese concentrations. Additionally, testing was conducted to establish the most appropriate dose of potassium permanganate under the varying water quality conditions to control the manganese levels in the finished water. In response to this event, utility staff increased sampling and analysis of both total and dissolved manganese in the reservoir at various depths, the utility installed solar powered reservoir circulators to promote DO levels in the bottom water zone. Following this event, the utility has taken several steps to mitigate the impact of future events on the quality of the raw water entering the water supply intake including: new intake structures with slide gates and a double leaf configuration to better control the raw water intake level, and installation of an advanced hypolimnetic oxygenation system to enhance DO levels at lower reservoir elevations.

Southern Australia, Utility F – turbidity

Utility F provides water and sewer services to approximately four million customers. The utility is serviced by several rivers, catchments, and reservoirs. A storm event in June 2007, following an extended drought and extensive bushfires, affected five of the catchment areas. The combination of drought, bushfires, and the storm event resulted in high turbidity levels, which peaked at 50–100 NTU, significantly above the typical value of <2 NTU. Because turbidity was elevated above the national drinking water guidelines, the reservoirs fed by the catchments had to be taken offline and alternate supplies provided. Some boil water notices were sent out and bottled water was also supplied to customers. In response to this event, there was an increase in water quality monitoring, intake levels on the reservoir were adjusted, and testing of disinfection efficacy with high turbidity water was undertaken. In case of another similar event, alternate short-term supply options have been put in place for the future and a new media filtration plant has been installed in case of future high turbidity events. Additionally, the emergency response plans (ERPs) have been reviewed, particularly for the complexities of having a severe drought followed by a significant storm.

Southeastern Australia, Utility G – *Cryptosporidium* and *Giardia*

Eighty percent of Utility G's water supply comes from a single lake, which experienced approximately 5 years of drought resulting in a buildup of fecal matter and other debris in catchment areas. Following the drought, the lake experienced heavy rainfall, which increased the storage levels from 58 to 85% with the first rain event and then up to 100% capacity with the second rain event. Not only did the heavy rain wash the fecal matter from the catchment areas into the lake, but several wastewater treatment plants in the area became overloaded and resulted in poorly treated effluent being fed into the lake. *Cryptosporidium* and *Giardia* were detected in addition to higher turbidity and changes to pH, temperature and conductivity following the two heavy rainfall events. Subsequently, over a 10 week period, three boil water notices were sent out to cover the health risks associated with finished water containing *Cryptosporidium* and *Giardia*. Finished water *Cryptosporidium* measurements reached a maximum of 273/100 L and *Giardia* measurement reached a maximum of 109/100 L, though average values were much lower. In response to this event, the utility implemented a Drinking Water Quality Incident Management Plan, increasing water quality monitoring and reducing the turn-around time for processing samples by employing more analysts.

Southern Australia, Utility H – multiple impacts

Utility H provides water and wastewater services for the Australian Capital Territory. A prolonged drought across the system's major catchments resulted in decreased flows, increased erosion and leaf litter and debris buildup on catchment riparian areas. Drought-breaking rains then resulted in extensive flooding. Following the rapid refill of the catchment, various changes to the source water quality were detected including increases in color, dissolved and total iron, dissolved and total manganese, turbidity, and dissolved organic carbon. There was also a decrease in DO and alkalinity. The changes in source water quality resulted in operational challenges including reduced filtration rates, reduced clarifier upflow rates, increased jar testing, and changes to sludge handling. In response to this event, increased water quality monitoring was initiated and operational response measures were taken. In order to prepare for future events, Utility H documented the changes to the treatment processes as well as reviewed the Hazard Analysis and Critical Control Points management plan to revisit some of the critical limits of the system.

DISCUSSION

In some events described in the case studies, the impacts of extreme weather conditions were felt immediately at the WTP while other impacts may not have been observed until months after the event. Additionally, as in the case of Utilities B and E, an extreme event was not enough to bring on a water quality crisis, but minor perturbations that occurred during the larger extended extreme conditions (drought) were sufficient to trigger water quality impacts. Two important lessons can be gained from these observations. First, extreme weather poses many challenges to utilities but the ultimate impacts to water quality and treatment may be triggered by combinations of events rather than stand-alone conditions. Second, the impacts may not be realized until months after an event and, as a corollary, impacts may persist for months or even years after their initial onset. Therefore, the take-away message is that utilities must 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 capacity and capability to respond to challenges triggered by later events.

As with all extreme weather scenarios, utilities aim to minimize water quality impacts during drought events. By employing effective SOPs along with up to date ERPs, utilities are typically able to handle extreme weather impacts through preparedness, response and adaptation activities. Frequent updates and reviews of SOPs and ERPs, particularly for human resources, financial resources, water supplies, and local and regional influences/constraints/liaisons are suggested in order to maximize staff understanding and usability of the plans. Effective internal communication and interagency coordination are important both prior to and during a drought situation. It is critical that preparations are made beforehand to identify a clear chain of command, establish an understanding and agreement of authority, coordinate with mutual aid networks and prepare staffing and communication plans with sufficient contingencies.

Additionally, water quality monitoring, modeling, bench- or pilot-scale studies, and consultations to define water quality changes were often cited as a means to respond to drought and other extreme weather scenarios, and as such, improving technical knowledge and in-house expertise can be extremely beneficial to utilities faced with drought events. The following is a list of recommendations summarized from the case studies for preparing for and responding to the potential water quality challenges from droughts:

- include drought events in worst-case planning scenarios;
- consider the installation of reservoir circulators to improve oxygenation of reservoirs;
- examine the use of improved intake infrastructure to block (or use) deeper/shallower water; consider building multi-level intake structure;
- conduct extensive monitoring and water quality modeling campaign for large reservoirs;
- develop a three-dimensional model of the reservoir to better understand how extreme events may impact reservoir dynamics and water quality at the intake;
- promote year-round conservation to help improve ability to handle seasonal droughts;
- conduct system stress-testing to ensure all components could work together during an extreme event;
- harvest vegetation that grows along reservoir edge and stream banks during drought to minimize the impact on the reservoir after refill;
- evaluate the use of PAC to remove organic matter during high TOC periods:
  - this approach is highly dependent upon infrastructure constraints (e.g. contact time), PAC type, and water quality;
- include algal blooms in risk assessment activities:
  - develop a cyanotoxin monitoring and response plan;
  - consider the use of PAC or other strategies for taste and odor control;
  - test chemical and physical algal control strategies before the event occurs;
- document adaptation measures to historical events in order to prepare for future events.

CONCLUSIONS

The range of impacts to water quality from drought have been somewhat diverse, but common themes include increased turbidity, taste and odor complaints, increased pathogen concerns, and increased challenges in managing DBPs. Such changes to water quality necessitate operational and treatment adaptations in order to stay within compliance with regulations as well as provide a level of water quality that consumers expect. Additionally, it is important to prepare for water quality impacts that may manifest themselves long after the onset of extreme weather conditions and that may persists for months or even years after the events occur. With increasing regulatory drivers dictating treatment objectives, utilities must balance drought responses with short-term public health protection and long-term water quality and regulatory compliance. Given the likelihood that the intensity, duration, and spatial extent of droughts will increase in the future, careful planning, evaluation of alternative water supplies and effective planning for capital improvements, emergency responses and communication will be necessary.

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