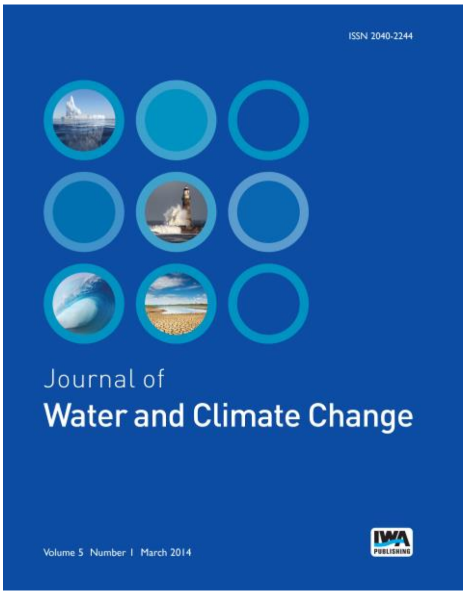

Enhancing climate adaptation capacity for drinking water treatment facilities

Audrey D. Levine, Y. Jeffrey Yang and James A. Goodrich

ABSTRACT

Conventional water treatment processes (e.g., coagulation, flocculation, sedimentation, and filtration) are widely used for producing drinking water from surface water sources. Transient, gradual, or abrupt changes in source water quality that could compromise treatment effectiveness can be triggered by climate and related meteorological events, accidental or intentional contamination, security breaches, or other disruptions. However, the design principles that underpin the majority of existing conventional treatment systems predate climate adaptation considerations. This paper considers the adaptation capacity of conventional water treatment systems. A modeling framework is used to illustrate climate adaptation mechanisms that could enable conventional treatment systems to accommodate water quality impairments. Treatment system resiliency is explored in response to generic climate-relevant water quality perturbations such as extreme temperature variations and changes in the quantity and characteristics of solids, particles, and organic constituents. Promising adaptation options include modifying chemical parameters (e.g., types of chemicals, dosages, sequence of chemical addition, mixing intensity and duration), filter operations, and microbiological augmentation of existing physical/chemical treatment systems. The capacity reserve concept provides an organizing principle that could be useful for prioritizing climate adaptation strategies such as major or minor treatment/infrastructure modifications, system-wide upgrades such as off-line storage, operational changes in distribution systems, or the use of supplemental water sources including reclaimed or recycled water.

Key words | climate adaptation, coagulation, conventional treatment, resilience, surface water, treatment system models

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INTRODUCTION

Water supplies are vulnerable to a host of climate-relevant stressors such as droughts, intense storms/flooding, snowpack depletion, storm surge, sea level changes, and consequences from fires, landslides, and excessive heat or cold spells (Intergovernmental Panel on Climate Change (IPCC) 2014). Given that there are over 150,000 public water systems in the USA (http://water.epa.gov/infrastructure/drinkingwater/pws/factoids.cfm) that deliver drinking water to over 300 million people every day, it is important to evaluate the adaptation capacity and resilience of these systems. Resilience can be defined as the ability to physically provide, repair, and recover its service functions following a disruption (McDaniels *et al.* 2008; Milman & Short 2008). In the context of water systems, resilience encompasses the source water and the infrastructure used to treat and convey water to and from end-users. According to the National Infrastructure Advisory Council (NIAC) (2009):

> '*Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruptive events. The*

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> *effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event*.'

Surface water resources (lakes, reservoirs, rivers, and streams) provide drinking water to approximately 70% of the US population, and are especially susceptible to extreme weather and climate-induced changes in water availability and water quality. Some climate and related meteorological events trigger abrupt water quality disturbances, such as erosion-induced increases in sediment and runoff following intense storms and flooding. Transient water quality impairments may also occur in the aftermath of spills, fires, accidental or intentional chemical releases, or security breaches (e.g., Ruhl *et al.* 2012; Bladon *et al.* 2014; Gallagher *et al.* 2015; Whelton *et al.* 2015). Climate-enhanced chronic droughts and their intensity can also directly or indirectly affect water quality due to changes in evaporation rates, temperature, salinity, aquatic habitats, and available surface area for gas exchange. Longer-term systemic impacts include changes in water availability, the frequency and intensity of algal blooms, gradual changes in the nature and concentration of dissolved organic matter, dissolved solids, and modulation of the microbiological population dynamics that can affect pathogen diversity, survival, and virulence (Zwolsman & van Bokhoven 2007; Thorne & Fenner 2008, 2011; Delpla *et al.* 2009; Emelko *et al.* 2011; Bogialli *et al.* 2013; Galway *et al.* 2015).

A changing climate is one of many drivers that affect the quality and availability of freshwater resources and can amplify, multiply, or temper threats imposed by concurrent other environmental stressors (National Research Council| (NRC) 2011; Intergovernmental Panel on Climate Change (IPCC) 2014). The capacity of conventional water treatment systems to respond or adapt to water quality perturbations depends on the inherent capacity of the treatment train to accommodate water quality changes that correspond to the intensity, frequency, and duration of each event in conjunction with watershed characteristics. From an adaptation perspective, it is important to understand the scope and magnitude of water quality changes that might affect the performance of drinking water treatment facilities. Quantification of performance impacts yields a basis to evaluate and, if necessary, increase the treatment capacity reserve in preparing for factors not originally considered in engineering. This paper explores the use of a generic model to assess the capacity of conventional water treatment processes (e.g., coagulation, sedimentation, and filtration) to adapt to climate-induced water quality changes. The types of location-specific data that are relevant for climate adaptation planning are illustrated using an example surface water treatment system.

CURRENT STATUS OF CONVENTIONAL WATER TREATMENT SYSTEMS

Traditionally, design of water treatment facilities has been predicated on the underlying assumption that ample source water is available to meet all water use requirements (domestic, municipal, commercial, industrial, and agricultural) within the design life of the facility and that the quality and quantity of water available from a given source are relatively predictable based on historical data. However, increasing evidence of the lack of climate stationarity (Milly *et al.* 2008) is raising questions about the validity of traditional design assumptions, particularly since the service life of many facilities can exceed 50 years, typically well beyond the design life. Conventional treatment, which involves sequential coagulation, flocculation, sedimentation, filtration, and disinfection, has been widely used since the early part of the 20th century (Howe *et al.* 2012) and continues to dominate treatment practices used by the majority of surface water treatment facilities currently operating throughout the world. Variations among the individual treatment facilities include the type of pretreatment, chemical use, sedimentation designs, filtration designs, post-filtration treatment, and operating practices (e.g., backwashing strategies, solids management, monitoring, maintenance, etc.). Other technologies that are becoming more prevalent include advanced oxidation, adsorption, membrane technologies, ion exchange, biological treatment, ultraviolet irradiation, and/or alternative disinfection. However, conventional treatment with chlorine as a primary disinfectant is likely to remain the cornerstone of surface water treatment for the foreseeable future due to the high costs of upgrading or rebuilding existing treatment facilities.

Design parameters for conventional treatment systems include system flow rates, reactor dimensions and hydraulic properties such as mixing efficiency, hydraulic retention time, flow patterns, and filter media characteristics. Precipitation events and resulting changes in surface water quality can impact coagulation and clarifier performance (Hurst *et al.* 2004). The effectiveness of rapid sand filtration can be influenced by inconsistent and variable hydraulic loading rates and changes in the quality and quantity of solids (Glasgow & Wheatley 1999; Harrington *et al.* 2003).

Chemical types and dosage are a key component of conventional treatment trains and are used to accomplish multiple objectives such as coagulation, flocculation, precipitation, oxidation, or disinfection. Water treatment chemicals include metallic salts, organic polyelectrolytes, oxidants, and corrosion and scale inhibitors; however, it is important to recognize that there are limitations on the types of chemicals that can be used in drinking water applications. All chemicals must undergo testing to ensure compliance with health effects criteria (http://www.nsf.org/services/by-industry/water-wastewater/water-treatment-chemicals/nsf-ansi-standard-60/). Additional registration requirements have been implemented for disinfectants (e.g., antimicrobial chemicals) (http://www.epa.gov/oppad001/chemregindex.htm).

Typically, chemical selection and optimization is tailored to the source water characteristics. Final decisions are based on regulatory requirements, performance, availability of chemicals, costs, and the quantity of residuals that are generated. In general, chemical effectiveness and reliability are influenced by multiple interdependent factors, some of which are relevant to climate adaptation. A summary of operational and water quality factors that influence chemical effectiveness in conventional treatment systems is given in Table 1. The effectiveness of climate adaptation strategies depends on the ability to modify operations or chemical use in conjunction with episodic, intermittent, or continuous changes in source water quality.

MODELING OF CONVENTIONAL DRINKING WATER TREATMENT FACILITIES

Mathematical modeling approaches for evaluating water treatment facilities include simple calculations, spreadsheet-based models, computational fluid dynamics, and dynamic models that are coupled to the physical dimensions and process data of existing treatment units. The primary application of models is to systematize process analysis, evaluate the impacts of chemical addition on pH, removal of particles, and removal of disinfection byproduct (DBP) precursors (Hsu & Huang 2002; Chowdhury *et al.* 2009; Uzun *et al.* 2015). The capacity to model physical treatment components, such as mixing, sedimentation, and filtration, is fairly well established from mass balance calculations and reactor hydrodynamics (Rietveld & Dudley 2006). However, mathematical models of flocculation are dependent on data and are often difficult to generalize or extrapolate to other treatment facilities (Rietveld & Dudley 2006). Modeling of disinfectant chemistry, degradation rates, and formation of DBPs is also fairly well studied and supported by a wealth of empirical and compliance monitoring data (Ged *et al.* 2015). Another limitation of modeling approaches is that there is often a misalignment between modeling data requirements and the availability of monitoring data, which tend to be designed to support regulatory requirements and provide operational oversight.

From a climate adaptation perspective, specific changes in water quality and quantity depend on the interplay among the key drivers and their assimilative capacity within a watershed and climatic zone. Modeling frameworks can be used to explore the efficacy of some types of adaptation measures, such as modifying hydraulic loading rates, modifying mixing and recirculation parameters, introducing alternative chemical approaches, adding supplemental storage capacity, or other safeguards to protect infrastructure from impacts of meteorological events. The inputs required for modeling climate adaptation potential include historic, current, and projected water quality data and details on the treatment system. While there are uncertainties associated with climate projections, models can provide insights into the impacts of water quality variability on treatment effectiveness and identify vulnerabilities and priorities. There are several quantitative models available to assess climate change impacts on water treatment plants. In this paper, we apply two mechanistic models, the WTP-CCAM (Li *et al.* 2012, 2014) and EauSim (Rietveld & Dudley 2006), using data from a conventional surface water treatment facility. While each model contains inherent uncertainties, the underlying equations were used to evaluate the resilience of existing treatment systems to source water

Table 1 | Summary of factors that affect chemical effectiveness in conventional treatment systems

Factors affecting chemical effectiveness	Coagulation/Flocculation	Sedimentation	Filtration	Disinfection	Distribution systems
Types of chemicals	Metal salts, organic polyelectrolytes	Metallic salts, organic polyelectrolytes	Metallic salts, organic polyelectrolytes	Oxidants	Corrosion and scale inhibitors
Operational factors	Mixing; sequence of chemical addition; reaction time	Loading rates, hydraulic detention time, hydrodynamics, residuals management	Loading rates, hydrodynamics, backwash practices, media characteristics, extent of microbial activity	Reactor hydrodynamics, contact time, sequence of chemical addition	System operation and flushing practices, system integrity, corrosion control, and ability to augment disinfection
Water quality parameters	Ionic strength, turbidity, alkalinity, pH, temperature TOC	pH, temperature, ionic strength	pH, temperature, turbidity, ionic strength, metals, organic carbon bioavailability	pH, temperature, turbidity, UV absorbance, oxidant demand	Temperature, ammonia, hardness, DBP formation, microbiological quality, scaling potential, and corrosivity
Particle characteristics	Particle size, surface properties, microbiological water quality (e.g., viruses, bacteria, protozoa, pathogens, cyanobacteria, algae, etc.)	Mass loading, particle size, particle density, settling properties	Particle size distribution, surface characteristics, potential for biological growth within filter	Microbiological water quality, DBP precursors	Biofouling
Organic characteristics	Molecular size, hydrophobicity, solubility, functional groups	Surface properties	Surface properties, biodegradability	Oxidant demand, UV absorbance, DBP precursors	Biofouling, DBP formation
Residuals management	No effect	Upstream chemical addition and solids characteristics	Backwash frequency; use of chemicals during backwash	No effect	Flushing frequency

variability induced by climate, weather, or other causes. In addition, initial assessments of the extent to which the individual components of the treatment facility have the capacity to adapt to a changing climate were conducted.

Modeling of climate-relevant water quality changes in an example watershed

To illustrate the concept of climate adaptation capacity, the Appalachian Plateau in the northeastern USA is used as an example watershed. A simplistic example of projected water quality changes in source water, shown in Table 2, provides a context for this analysis. In general, temperature, alkalinity, total organic carbon (TOC), and nutrient loading are expected to increase, while the hardness is expected to decrease (Li *et al.* 2012, 2014).

Modeling inputs

Data from a surface water treatment facility that is within this watershed, Greater Cincinnati Water Works Richard Miller Treatment Plant (GCWW) (http://www.cincinnati-oh.gov/water/about-greater-cincinnati-water-works/water-treatment/), were used to evaluate the efficacy of climate adaptation

Table 2 | Overview of projected surface water quality changes in the Appalachian Plateau of the USA (adapted from Li *et al.* 2012)

Parameter	Projected annual rate of change	Reference
Alkalinity	+0.036 mg/L as $CaCO_3$	Skjelkvåle *et al.* (2005)
Hardness	−0.022 mg/L as $CaCO_3$	Skjelkvåle *et al.* (2005)
TOC	+0.03 mg/L	Skjelkvåle *et al.* (2005)
Ammonia	+0.5%	Whitehead *et al.* (2009)
Temperature	+0.02 to 0.13 °C	Cromwell *et al.* (2007)

modeling. Available monitoring data were reviewed to identify a suite of source water quality data that could serve as proxies for climate-relevant data including alkalinity, hardness, total dissolved solids (TDS), turbidity, TOC, and pH. All data were supplied by the GCWW Miller Plant and had undergone internal quality assurance and data management protocols prior to being used in this case study.

Two models, WTP-CCAM (Li *et al.* 2012, 2014) and EauSim (Rietveld & Dudley 2006), were used to evaluate the consequences of five different water quality perturbations:

- temperature increase
- turbidity spike
- TOC spike
- alkalinity decrease
- TDS/ionic strength increase.

The responses of conventional treatment components (coagulation, flocculation, and sedimentation) were assessed using EauSim, while the downstream granular activated carbon (GAC) unit was analyzed using WTP-CCAM. The model inputs are summarized in Table 3 with information on the combination of treatment units that are relevant to the individual parameters. Process information (e.g., reactor dimensions, flowrates, reactor sequence) from the GCWW plant was used to model system performance. For the purposes of this analysis, a 5-year period was used to bracket the range of water quality and operational conditions. The extent to which the treatment system can accommodate deviations from these quasi-baseline conditions was modeled. Climate-relevant data can also be extrapolated from watersheds with similar land-use patterns.

RESULTS

A summary of the range of alkalinity, hardness, TDS, turbidity, TOC, and pH for the Ohio River water source over a 5-year period is shown in Figure 1. The extreme values reflect source water quality following a storm-event and also represent conditions where the effectiveness of conventional treatment may be compromised. Li *et al.* (2014) analyzed historic Ohio River data that were available through the EPA Information Collection Rule (ICR) (US EPA 2000) and found statistically significant correlations between TOC concentrations, ultraviolent light adsorption at 254 nm, and turbidity in the water (Li *et al.* 2014).

However, there are many cases where the extreme concentrations of individual parameters did not follow consistent trends. For example, high levels of TOC do not always correspond to high (or low) levels of turbidity, as shown in Figure 2. This degree of variability reflects the dynamics of hydrological and hydroclimatic processes in upstream watersheds and can impose significant challenges in optimizing chemical dosages to ensure concomitant removal of particles (turbidity), DBP precursors (TOC), and other waterborne contaminants (Winterdahl *et al.* 2014). The variable loading, coupled with temperature variability, also impacts filtration performance. It is important to note that future climate change scenarios emphasize the likelihood of intense precipitation events, drought, and related geochemical changes (Eikebrook *et al.* 2004; Monteith *et al.* 2007; Intergovernmental Panel on Climate Change (IPCC) 2014). Tong *et al.* (2012) showed such perturbations of water quality in surface stream induced by climate and land use changes in the Little Miami River watershed upstream of the GCWW's Miller plant intake. In addition, there are discrepancies between the types of parameters that are routinely monitored in water treatment systems and the parameters that might serve as sentinels or proxies for weather- and climate-induced water quality changes.

The impacts of each of the five water quality perturbations modeled using the GCWW as an example system are summarized in Table 4 along with adaptation options. While this example is somewhat general, it provides a systematic approach to identify potential adaptation options and their range of effectiveness. For the GCWW water plant, the

Table 3 | Summary of source water quality data used as model inputs

Source water data	Units	Comment	Combination of treatment units that use individual water quality parameters
Temperature	°C	Daily or monthly–5 yr summary	Coagulation–Flocculation–Sedimentation–Filtration–pH adjustment–Chlorination
pH	pH	Daily or monthly–5 yr summary	Coagulation–Flocculation–Sedimentation–Filtration–pH adjustment–Chlorination
Alkalinity	mg/L as $CaCO_3$	Daily or monthly–5 yr summary	Coagulation–Flocculation–Sedimentation–Filtration–pH adjustment–Chlorination
Aluminum (Al)	mg/L		Chlorination
Ammonium (NH_4)	mg/L	Seasonal variations	Chlorination
BDOC	mg/L		Chlorination
Bromate	μg/L		Chlorination
Bromide	mg/L		Chlorination
Calcium (Ca)	mg/L	Estimate from hardness	pH adjustment
Carbon dioxide (CO_2)	mg/L	Estimate from data	pH adjustment–Chlorination
Chloride (Cl)	mg/L		Chlorination
Free residual chlorine	mg/L		Chlorination
Instantaneous chlorine demand	mg/L	Estimate from data	Chlorination
Clostridium perfringens (incl. spores)	CFU/mL		Chlorination
Conductivity (EC)	mS/m	Estimate from TDS	Coagulation–Flocculation-Sedimentation–pH adjustment
Dissolved organic carbon (DOC)	mg/L	Estimate from TOC	Coagulation–Flocculation–Chlorination
Enterococci	CFU/mL		Chlorination
Escherichia coli	CFU/mL		Chlorination
Haloacetic acids	μg/L		Chlorination
Hydrogen carbonate (HCO_3)	mg/L	Calculate from alkalinity and pH	pH adjustment
Ionic strength	–		pH adjustment
Sulfate (SO_4)	mg/L		pH adjustment
Suspended solids	mg/L	Estimate from turbidity	Coagulation–Flocculation–Sedimentation–Filtration
THMs	mg/L		Chlorination
UV254	M^{-1}		Coagulation–Flocculation– Chlorination
Primary particles	mg/L	Estimate from turbidity	Coagulation–Flocculation–Sedimentation–Filtration

modeling and analysis described here show the potential to increase the treatment capacity of conventional processes. Other adaptation options for controlling specific disruptions such as changes in organic loading include upstream addition of powdered activated carbon (Carrière *et al.* 2009) or downstream use of granular activated carbon (Li *et al.* 2012, 2014). Modeling results can be used to streamline supplemental laboratory and pilot-testing of adaptation options.

While some general trends were observed through the modeled simulations, the results are limited by the lack of comprehensive chemical reaction information on the spectrum of chemicals that can be used for coagulation–flocculation and filtration aids. In addition, while the model provides a conservative estimate of the performance of sedimentation and filtration, it lacks the ability to fine-tune each treatment unit or the treatment system as a

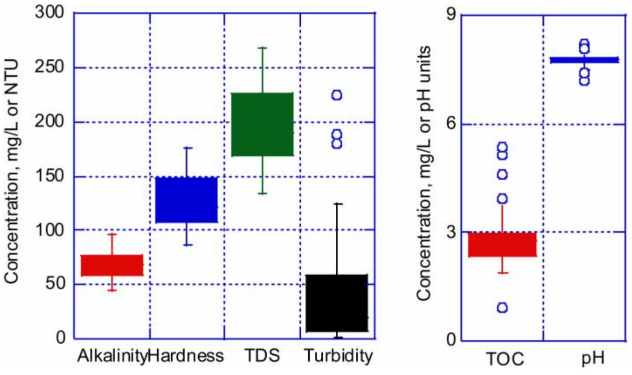

Figure 1 | Boxplots of alkalinity, hardness, TDS, turbidity, TOC, and pH from the Ohio River source water over a 5-year period.

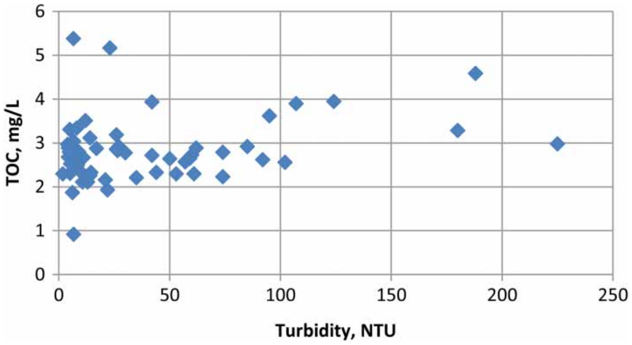

Figure 2 | Scatterplot of TOC and turbidity data from the Ohio River source water over a 5-year period.

whole. Nevertheless, the use of models to evaluate impacts from different climate-related water quality changes provides an opportunity to identify climate adaptation options within an existing treatment infrastructure. Models also enable identification of limits beyond which the adaptation of existing infrastructure becomes ineffective. Such examples can be found in coastal areas with severe salt water intrusion and prone to coastal storm surges.

DISCUSSION

Adaptation of existing or new water supply systems to new climate realities is central to sustainability and resilience. Climate or other disruptive events can impact water quality in multiple concurrent ways. Additionally, accidental or intentional disruptions to water supplies can also compromise treatment performance. While the modeling example presented in this paper focused on individual parameters, the net resiliency depends on climate adaptation options that can span a range of water quality challenges. The capacity reserve concept, derived from engineering practice (Tillman *et al.* 1998, 2005; Dominguez & Gujer 2006; Matos *et al.* 2013), provides an organizing principle that could be useful for prioritizing climate adaptation strategies.

Adaptation options

Water supply perturbations can result from multiple triggers. Adaptation options may range from major or minor modifications to existing treatment systems along with system-wide considerations such as off-line storage, operational changes in distribution systems, or the use of supplemental water sources including reclaimed or recycled water. The types of water supply challenges that can result from climate and weather-related events are summarized in Table 5. Climate adaptation options derived from the modeling framework are also summarized. In some cases, relatively available cost-effective solutions might be practicable, such as modifying chemical treatment approaches. In other cases, more comprehensive retrofits might be required.

Conventional treatment

Given the diverse nature of climate change impacts on surface water quality, conventional treatment processes are potentially economically viable adaptation candidates. To assure adequate capacity reserve, short-term climate adaptation options include chemical optimization, high-rate liquid–solid separation systems, and integration of biological filtration. Many of these adaptation options can be readily implemented with strategic modifications of chemical addition, mixing, and filter performance. While specific adaptation measures depend on watershed characteristics and treatment configurations, further analysis of several alternative approaches is warranted:

- targeted monitoring coupled with optimized chemical addition
- alternative coagulation/flocculation chemicals
- high rate liquid–solid separation systems
- integration of biological treatment.

Table 4 | Matrix of climate adaptation options that correspond to example water quality scenarios modeled using process data for the GCWW treatment facility

Scenario modeled	Impact on conventional treatment	Adaptation options	Data and modeling needs
Temperature increase	Improved efficiency of flocculation, sedimentation, filtration	Optimize chemical requirements	Coagulation/Flocculation chemical interactions
Turbidity spike	Could accommodate spike through optimization of coagulation/flocculation if chemical dosages modified	Real-time upstream monitoring to identify onset of turbidity spike; chemical optimization for coagulation/flocculation; incorporate high-rate sedimentation systems such as ballasted sedimentation, dissolved air flotation, or plate separators to expand the capacity of existing treatment units	Particle characterization: size, density, microbial loading (e.g., algae, cyanobacteria, protozoa, bacteria)
TOC spike	Impaired turbidity removal; higher chemical dosages required; increased loading on filters	Real-time upstream monitoring to identify onset of turbidity spike; chemical optimization for coagulation/flocculation; optimize biological filtration; use of upstream adsorption processes such as powdered activated carbon to remove the adsorbable fraction of the TOC	TOC characterization (hydrophilic, hydrophobic, molecular size, biodegradability, oxidizability, functional groups, DBP formation potential); evaluate effectiveness of upstream oxidation for improving TOC removal; evaluate toxicity of residual TOC; identify compounds of health concern
Alkalinity decrease	Impaired coagulant performance	Use alternative chemical amendments	Predictive tools for evaluating role of alkalinity in coagulant/flocculant effectiveness
TDS/Ionic strength increase	Improved coagulant performance; potential impacts on simultaneous compliance; potential increased formation of brominated DBPs; potential impacts on scale formation; potential impacts on lead and copper release	Optimize chemical requirements	Characterization of components of TDS; predictive tools for evaluating role of TDS in chemical effectiveness

Targeted monitoring coupled with optimized chemical addition

More detailed characterization of waterborne particulates and organics is needed to optimize chemical selection and dosing. While bulk parameters such as turbidity and TOC are useful for routine monitoring, there is a need for improved capacity to model the impacts of weather and climate on these parameters. For example, the increased proliferation of cyanobacterial and algal blooms and associated toxins has been widely observed in surface water impoundments. While these organisms contribute to turbidity and TOC, their surface properties, chemical reactivity, and treatability differ from other types of turbidity and TOC. For example, increased turbidity loading may warrant modification of the coagulation/flocculation chemical regime (Kastl *et al.* 2004). Changes in particle size distributions may also affect coagulation/flocculation decisions. Decreased alkalinity may also necessitate tailored modification of chemical addition. Contaminants associated with runoff or sewer overflows may require additional pre- and post-treatment. Integrating upstream monitoring with treatment system models can lead to more resilient decision-support systems and more effective climate adaptation strategies.

Alternative coagulation/flocculation chemicals

The water industry relies on polyelectrolytes for multiple purposes with the dominant formulations consisting of polyacrylamides or polyDADMACs (Uyak & Toroz 2007;

Table 5 | Summary of water supply adaptation options associated with climate- and weather-related drivers

Climate and/or weather driver	Impacts on water supply	Adaptation options
More frequent and/or longer droughts	Increases in mineral content, dissolved solids, and salinity due to evaporation; potential changes in temperature and microbial activity; altered characteristics of organic matter and DBP precursors. Secondary impacts associated with aquifer depletion and co-mingling of alternative source waters; distribution system impacts due to subsidence, biofilm proliferation, and compromised capacity to maintain disinfection residuals under elevated temperatures	Alternative chemicals, microbial treatment, removal of DBP precursors; increased vigilance of distribution systems; infrastructure monitoring
More intense storm events	Excessive runoff, flooding, landslides, and infrastructure failures increase loading of particulates, chemical, and microbiological contaminants. Secondary impacts from erosion. Volumetric loading affects water quality and aquatic habitats. Invasive species proliferation	Upstream controls, environmental buffers, alternative chemicals, multiple barriers. Stormwater management; infrastructure monitoring
Storm intensity and frequency	Seasonal changes in water availability and storage requirements, and impacts of extreme weather events (flooding, droughts) on water levels and water source vulnerability. Water quality impacts depend on watershed characteristics, local stormwater management practices, and infrastructure integrity	Off-line storage, alternative chemicals; infrastructure monitoring; alternative water sources (e.g., recovery of stormwater, water reclamation and reuse), additional treatment capacity
Snowpack depletion	Less storage, less spring runoff, less dilution, earlier and more pervasive algal and cyanobacterial blooms; altered characteristics of organic matter and DBP precursors	Alternative chemicals, microbial treatment; removal of DBP precursors; infrastructure monitoring
Proliferation of wildfires within watershed	Excessive erosion and runoff can introduce fine particulates and contaminants into surface water sources. Impacts on ecosystems and habitats can lead to water quality changes, algal growth, silting, and sedimentation	Upstream controls, environmental buffers, alternative chemicals, multiple barriers
Variability in air and water temperatures	Changes in evaporation rates (increase or decrease depending on temperature) impact mineral content, dissolved solids, mineral and gas solubility, microbial growth and die-off rates, microbial diversity, and biological activity	Off-line storage, environmental buffers, alternative chemicals, multiple barriers
Changing patterns of reservoir stratification and turnover	Less mixing, increased algal growth in upper layers, short-circuiting in reservoir, changes in oxygen content at intake	Upstream controls, alternative chemicals, multiple barriers
Population shifts to different climatic zones	Changes in water demand affect water age, impacts on microbial and chemical water quality in distribution systems; wastewater discharges into watershed	Alternative chemicals, modified hydraulics, infrastructure monitoring
Storm surge, coastal inundation, salt water intrusion	Physical damage to water intake and treatment facilities; inundation causing permanent structural damages; water quality changes; and salt water intrusion	Physical protection against flooding and wave impacts; elevation of critical processing equipment; management of salt water intrusion

Matilainen *et al.* 2010; Padhye *et al.* 2011). However, newer formulations are emerging based on using nanotechnology to design coagulants that target specific functional groups. For example, polymers containing quinone or pyrrole side chains have been reported as effective scavengers of radicals and inhibiting nitrosamine production (Bao & Loeppky 1991; Wang *et al.* 1994; Zeng *et al.* 2014). There has also been increasing interest in polyelectrolytes derived from natural products such as histidine, chitosan, and soy protein. These types of tailored polymers have the potential to substitute for polyDADMACs or other polyelectrolytes; however, it is important to ensure that alternative formulations meet National Sanitation Foundation (NSF) requirements and do not lead to other inadvertent reactions or DBP formation during treatment, storage, or distribution. Coagulation effectiveness can also be enhanced with strategic use of coagulants (Ma & Liu 2002; Jiang & Wang 2003) There are also concerns about DBP formation from alternative coagulants such as NDMA (Kinicannon *et al.* 2003).

High rate liquid–solid separation systems

There have been significant advances in high-rate sedimentation systems that can be retrofitted into existing facilities. For example, ballasted sedimentation, dissolved air flotation, or plate separators optimize sedimentation through increasing the settling velocity (ballasted sedimentation), decreasing the particle density (dissolved air flotation), or decreasing the rate of particle removal (plate separators). Integrated systems, such as the use of magnetically enhanced ion exchange, have been demonstrated to remove DBP precursors in conjunction with particle removal (Watson *et al.* 2015). There is a need to integrate these types of technologies into modeling frameworks to evaluate their potential roles in climate adaptation, costs, and capacity to respond to changing water quality.

Integration of biological treatment

Biological treatment systems have a long history in controlling biodegradable organics in wastewater and stormwater. Biological systems have also been used indirectly in water treatment as a result of biofilm development on surfaces and microbial colonization of filter media, adsorbents, and ion exchange resins. The augmentation of conventional treatment with microbial processes holds promise for climate adaptation. Microbial processes can be effective at mineralizing organics, nitrification and denitrification, and mediating oxidation-reduction reactions for removal of endocrine active compounds and other trace contaminants. From the perspective of climate adaptation, the elevated temperatures and organic content that are associated with a changing climate are well suited for biologically enhanced treatment systems. However, it is important that biological treatment systems do not harbor pathogenic organisms that could impair water quality. In addition, the microbial biomass can serve as precursor material for DBP formation including NDMA. Models and design data for biological filtration systems are continuing to develop.

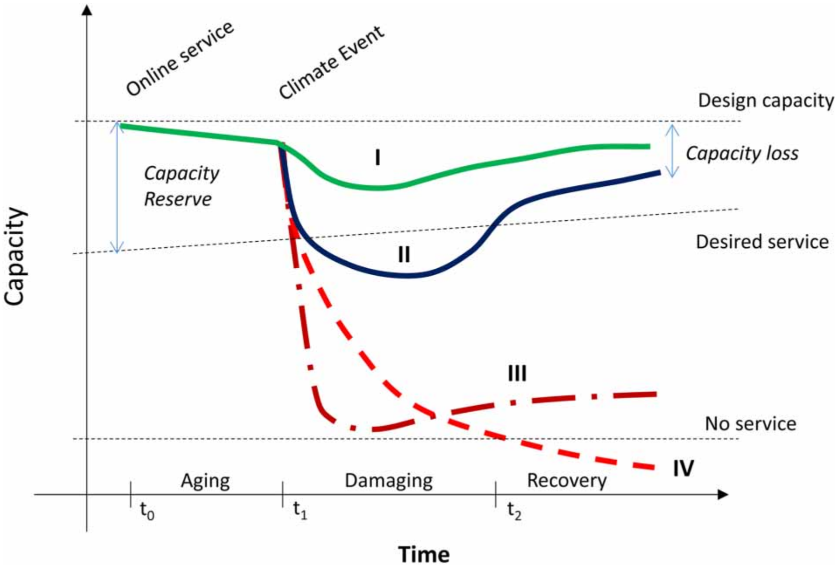

Figure 3 | Capacity reserve as a function of recovery time for different types of climate-relevant disruptions. Scenarios I and II are acute events that vary in intensity, Scenarios III and IV are longer-term disruptions that require adaptation capacity to avoid compromising the capacity to deliver safe drinking water.

Capacity reserve

The success of climate adaptation strategies can be considered in terms of the capacity reserve, which can be estimated as the difference between the water plant design capacity and the minimum treatment capacity required to meet the water quality and quantity requirements (Tillman *et al.* 1998, 2005; Dominguez & Gujer 2006). An appropriate degree of treatment capacity reserve is a common practice in managing unexpected risk. An illustration of the capacity reserve concept applied to infrastructure resilience is shown in Figure 3 in relationship to water system stressors that vary in intensity, duration, and severity.

Scenario I reflects an acute and temporary event such as a sewer overflow or chemical spill (Whelton *et al.* 2015) where there may be a lapse in the capacity to provide safe drinking water. Scenario II represents a lack of resilience to extreme weather events and their aftermaths, such as hurricanes, intense storms, flooding, or drought conditions (Pardue *et al.* 2005; Brozovic *et al.* 2007; Yoon & Raymond 2012; Dhillon & Inamdar 2013). Scenarios III and IV reflect long-term climate change impacts on source water quality that may result in a 'tipping point' being reached due to inadequate capacity to implement operational changes (increasing chemical feeds, extended pumping, additional finished water storage, etc.) or treatment plant upgrade. Recovery from Scenario IV may necessitate significant capital improvements such as additional treatment unit processes, source water storage, distributed network modifications, or paradigm shifting (direct/indirect reuse) to avoid future recurrence of the service disruptions.

CONCLUSIONS

Conventional water treatment processes (e.g., coagulation, sedimentation, and filtration) have a long history in producing drinking water from surface water supplies. As water quality changes in response to a changing climate, the adaptation capacity of the existing infrastructure should be considered. Case-specific analysis and process simulation may provide insightful information to develop engineering options for climate adaptation that incorporate watershed-specific conditions. Even though many models are based on steady-state assumptions and lack a direct way to accommodate water quality fluctuations, basic insights can be gained into capacity reserve. Harmonizing of monitoring data with modeling parameters is important for calibrating and validating models. Further insights can be gained through integrating upstream conditions. In addition, more robust data and models are needed to investigate the spectrum of chemical and microbiological reactions that are associated with the complete inventory of chemical amendments that can be used in water treatment practice. Integration of biological treatment models is also an important component of evaluating climate adaptation options and capacity reserve.

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