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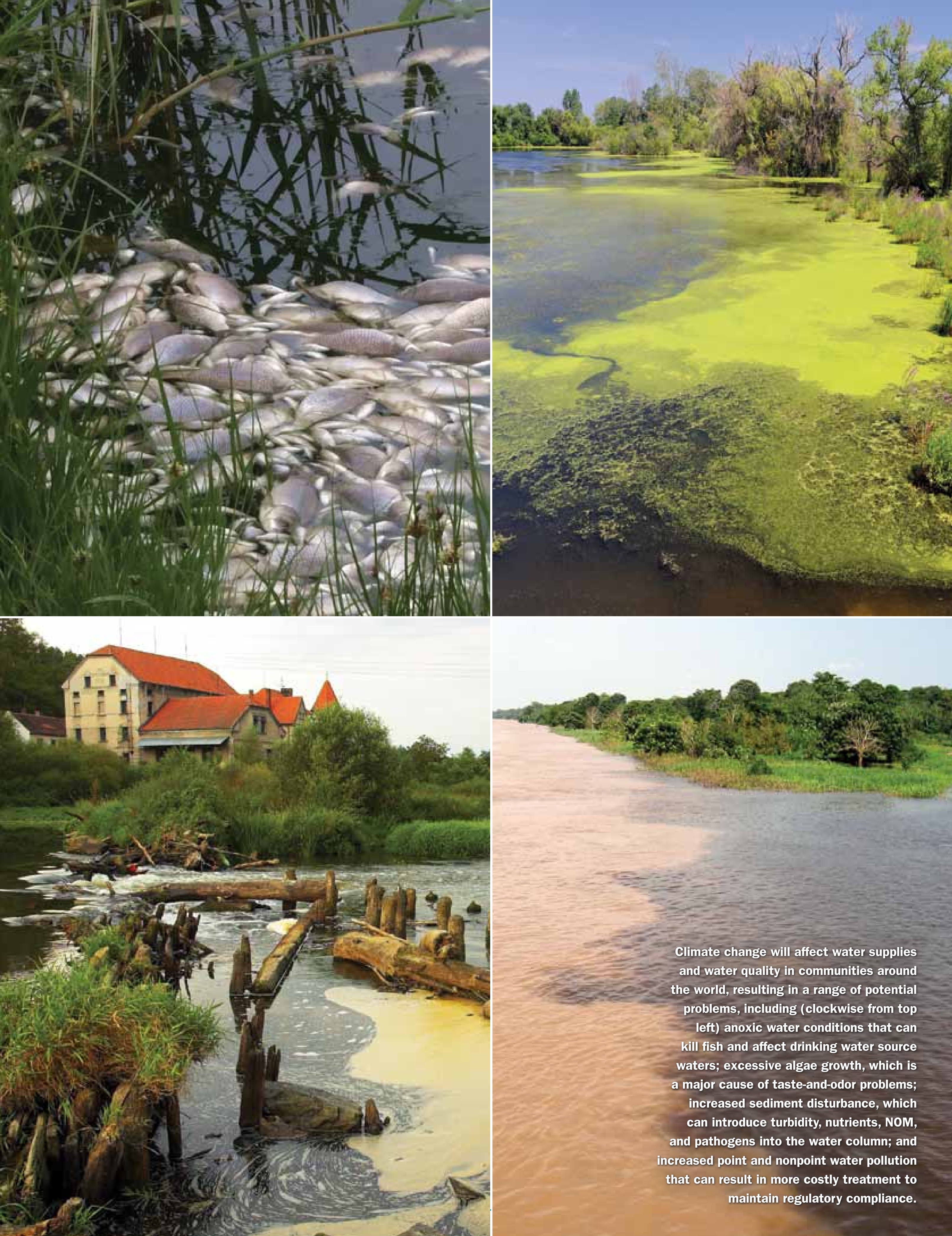
A better understanding of relationships among weather patterns and water quality will allow utilities to more effectively plan for the effects of climate change. Best practice requires understanding as much as possible about changes that can occur and their implications for utility operations and management. BY BEN WRIGHT, BEN STANFORD, JOSH WEISS, JEAN DEBROUX, JAN ROUTT, AND STUART KHAN

CLIMATE CHANGE
HOW DOES WEATHER AFFECT SURFACE WATER QUALITY?

WATER UTILITIES ACROSS the United States are seeking solutions to a broad range of possible climate change impacts and an uncertain future. The Water Research Foundation has identified a lack of specific information about how changing weather patterns affect drinking water quality. Numerous reports generically describe how climate change is expected to affect water quality, but utilities need a comprehensive resource that ties predicted weather changes to watershed processes that affect drinking water quality. This article provides information compiled from published literature on weather and water quality to help utilities develop a series of event–outcome relationships to describe specific changes to surface water quality relative to climate change (Figure 1, page 12).

Climate change is expected to affect water supplies in various ways, but the fundamental elements of climate and weather will remain the same. Of the fundamental components of weather—temperature, precipitation, wind, solar radiation, humidity, air pressure, and cloud cover—temperature, precipitation, and wind are the primary factors affecting surface water quality. These components are expected to vary substantially with climate change.



Climate change will affect water supplies and water quality in communities around the world, resulting in a range of potential problems, including (clockwise from top left) anoxic water conditions that can kill fish and affect drinking water source waters; excessive algae growth, which is a major cause of taste-and-odor problems; increased sediment disturbance, which can introduce turbidity, nutrients, NOM, and pathogens into the water column; and increased point and nonpoint water pollution that can result in more costly treatment to maintain regulatory compliance.

WEATHER EVENTS

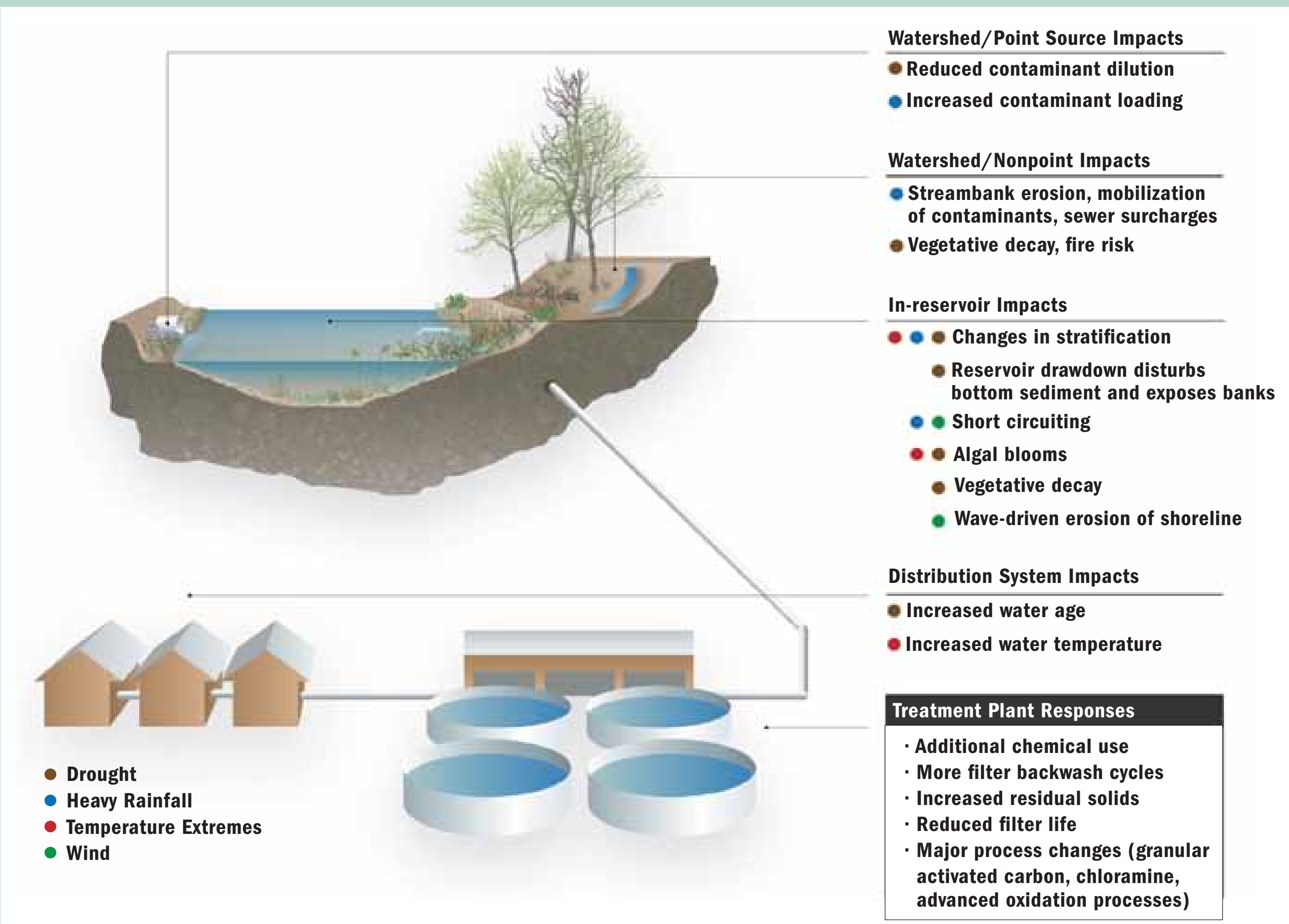
Weather events rarely consist of a single component, and the effect on water quality often results from a combination or a series of weather events that may occur rapidly or over a period of months to years. For example, multiple components may occur simultaneously: droughts coincide with high temperatures; storms, hurricanes, and tornadoes bring heavy rains and strong winds. Alternately, extended drought may be followed by heavy rains that negatively affect turbidity, contaminant concentrations, and organic matter in raw water supplies. One can use weather components to understand combined effects by looking at the aggregate effects of individual weather elements.

Drought. For water utilities, droughts can result in some of the most severe weather-related problems. Droughts affect water supplies as well as water quality. Decreased reservoir volumes and lake levels lead to increased inflow from point sources of pollution, including municipal and industrial sewer outfalls, mine discharges, and thermoelectric power plant return flows. A hypothetical reservoir that receives 5 percent of its recharge from upstream wastewater discharges would receive 10 percent from those sources if hydrologic conditions were 50 percent drier than normal, having potentially significant effects on source water quality. Although this situation may be manageable for infrequent drought events, more frequent or severe droughts could result in a need for changes to plant operations or system infrastructure.

As lake and reservoir levels decrease, algal growth can occur in warmer, stagnant waters; bottom sediments can become disturbed, resuspending material into the water column; and anoxic conditions or disruptions to seasonal stratification can change the oxidation–reduction

Figure 1. Relationship of Weather Events and Water Quality

Understanding event–outcome relationships can help water utilities predict and cope with weather-related changes to drinking water quality.



Changing seasonal patterns and increasing extreme weather events are likely to affect water quality for utilities in all parts of the United States.

state, releasing previously immobilized contaminants. Further exacerbating the situation, water-use conservation measures enforced during drought events can increase water age in a distribution system, leading to increased disinfection byproducts (DBPs) in chlorinated systems or nitrification in chloraminated systems.

Also, sea-level rise is expected to exacerbate the effects of drought by causing saltwater intrusion for drinking water diversions in tidally influenced sections of rivers. Under low-flow conditions, higher sea levels tend to push saltwater farther upstream, temporarily affecting the supply.

Heavy Rainfall. Heavy rainfall can mobilize contaminants from a watershed (i.e., nonpoint source pollution), disturb sediments in streams and reservoirs, and result in sewer overflows. The most significant pollutant loads are usually associated with the first flush of rainfall after long, dry periods. Beyond heavy rainfall, flooding has its own negative consequences, including infrastructure damage and groundwater well contamination.

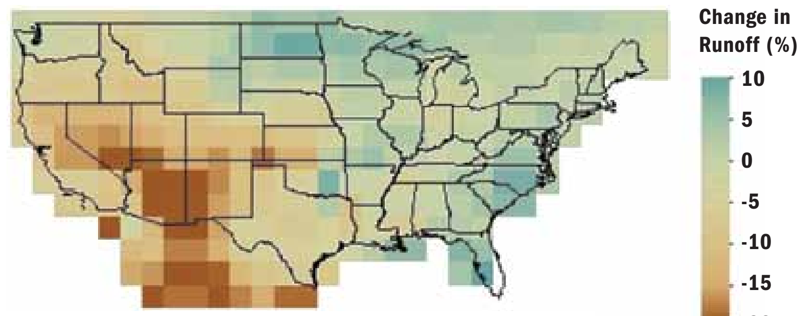
In addition, alkalinity, which influences treatment plant processes, tends to decrease under heavy rainfall because the percentage of streamflow originating as groundwater decreases.

Temperature Extremes. Temperature extremes are represented by very high or very low temperatures, which can result in significant challenges within a watershed and distribution system. Heat waves can encourage algal growth, particularly toxic cyanobacteria, which prefer higher temperatures. Extreme heat and cold also contribute to stratification–destratification within water supply reservoirs. High temperatures increase the potential for DBP formation in distribution systems and nitrification in chloraminated systems. Unusually warm winter temperatures, while not technically extreme, can result in earlier snowmelt, ice breakup, nutrient input, and subsequent algal growth in reservoirs.

Also, as air temperatures rise, water temperatures increase and dissolved oxygen in water decreases. Such conditions negatively affect aquatic habitat, which can affect a utility's releases and diversions from reservoirs.

Figure 2. US Annual Runoff Changes

Rising temperatures, less rainfall, and decreased snowpack are expected to seriously affect water supplies in the western United States.



Source: Chris Milly, National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory

Wind. Strong winds can affect source-water quality—particularly in large lakes and reservoirs susceptible to erosion from wind-wave action—and redirect inflows resulting in short-circuiting between inflow locations and water supply intakes. Wind can also force unexpected mixing in lakes and reservoirs. Together, wind, drought, and high temperatures can create an ideal situation for algal blooms and associated taste-and-odor problems, DBPs, and filter clogging.

Increased Frequency and Alternating Events. Climate change implies a predicted increase in the hydrologic cycle's speed and intensity. In other words, heavy rains, storms, droughts, and heat waves can occur more frequently. For example, if heavy rains that lead to turbidity occur too frequently, reservoirs may have little time to recover between events. Alternating events, such as drought and heavy rain, can negatively affect water quality, because organic material and nutrients build up in the watershed and are flushed into downstream reservoirs all at once.

Weather events can also cause indirect water quality problems. Changes in temperature and precipitation patterns can increase wildfire potential, encourage invasive species, or increase forest mortality, resulting in short-term water quality problems and long-term watershed complications. In addition, infrastructure damage from floods and power outages increase the difficulty in maintaining high-quality, reliable water supplies.

SYSTEM PROCESSES

Weather-related changes to source-water quality can occur in a watershed or within reservoirs; changes to finished water quality can occur in the distribution system. Watershed, reservoir, and distribution system processes influence water quality.

Point Sources. Constituents in point discharges usually include nutrients, total dissolved solids, metals, and DBP precursors but may also include organic chemicals or radionuclides, depending on the types of facilities located in the watershed. Higher concentrations of these contaminants result in more costly treatment to maintain regulatory compliance.

Watershed Mobilization/Nonpoint Sources. Depending on upstream vegetation conditions and land-use types, nonpoint-source pollution usually results in higher levels of nutrients, natural organic matter (NOM), pathogens, organic chemicals (e.g., pesticides and pharmaceuticals), and turbidity in watershed runoff.

Sediment Disturbance. Sediment mobilized from lake and stream beds and banks usually introduce turbidity, nutrients, NOM, and pathogens into the water column. Like other watershed processes, land uses strongly influence the types of material that accumulate in waterbody sediments.

Vegetative Decay. Recent utility experience following post-drought reservoir refill reveals sudden increases in DBP precursors resulting from die-off of terrestrial vegetation growing in the lake bed and increased flushing of NOM from the watershed.

Stratification–Destratification. Thermal stratification is an annual occurrence in most temperate-climate lakes and reservoirs. During summers, warmer water becomes physically differentiated from cooler water because of variations in density. The lower zone is usually anoxic because of the lack of mixing for reoxygenation and biological processes that consume oxygen. As temperatures cool during the fall, with the help of wind and higher inflows, lakes and reservoirs mix. For drinking water source waters, the hypolimnion (lower layer) or epilimnion (high layer) may be undesirable for diversions. For example, manganese can dissolve from bottom sediments into the anoxic hypolimnion, or the epilimnion may be warmer and have higher NOM. Therefore, most utilities selectively draw from the zone with the best water quality. However, lower reservoir levels limit selective withdrawal from a preferred zone. In addition, unseasonal mixing from droughts, storms, or temperature changes can degrade water quality throughout the reservoir.

Stratification is generally undesirable in finished water tanks. Unexpected destratification resulting from temperature fluctuations in tanks could result in older water with low disinfectant residual being delivered to customers.

Algal Growth. Algae is a major culprit in taste-and-odor problems and is a source of NOM for DBPs. Although weather can influence algal growth, nitrogen and phosphorous are necessary components. Therefore, watershed processes that can result in increased nutrients in a surface water supply can also encourage algal growth. This usually includes nutrients from point and nonpoint sources and dissolution of phosphorous from bottom sediments under anoxic conditions often associated with thermal stratification.

Increased Water Age and Temperature. The DBP and nitrification potential in chloraminated systems is closely correlated with increased water temperature and age.

WATER QUALITY OUTCOMES

To conveniently categorize the effects of the previously described processes on water quality, project researchers used the US Environmental Protection Agency's categorization of Maximum Contaminant Levels for the National Primary Drinking Water Regulations (organics, inorganics, DBPs, microorganisms, and radionuclides), along with a category for aesthetic water quality to capture the agency's Secondary Drinking Water Regulations. Reviewing watershed/distribution system processes reveals two primary patterns of water quality impacts.

- Point/nonpoint source pollution and sediment disturbance can result in increases to all water quality contaminant categories. Because these processes essentially reintroduce or concentrate material already in the watershed, the specific effects for a particular watershed depend greatly on existing land uses. For example,

LESSONS LEARNED

HURRICANE RESEARCH BOLSTERS EMERGENCY PREPAREDNESS

After Hurricane Irene struck the US East Coast in 2011, the Water Research Foundation (WaterRF) funded a survey of affected drinking water systems. The findings were compiled into a summary report to provide water systems with the most up-to-date information related to developing and managing an appropriate emergency-response plan. Now, in the wake of Hurricane Sandy, the information gleaned from the report will complement at least two additional research efforts conducted by WaterRF in partnership with other water-related organizations and US federal agencies during the next few months.

SURVEY RESULTS

Sixty-five affected water systems were surveyed about Hurricane Irene's operational and financial impacts. The WaterRF report highlights lessons learned for effective hurricane preparedness:

Regular Planning. Have a current emergency-response plan. A checklist offers a quick way to evaluate if preparations are adequate.

Power. Establish comprehensive emergency power plans that incorporate communication protocols for internal and external power sources to efficiently deal with power issues and avoid prolonged power outages. One of the biggest issues during Hurricane Sandy was difficulty getting fuel to power back-up generators.

Communication. Create communication channels with regulators, neighboring drinking water systems, other utilities, media outlets, and local emergency responders before a storm strikes. Phone/telemetry systems often present challenges.

Incident Command Structure (ICS). Set up an effective ICS to respond to severe storm events. Drinking water systems identified their ICSs as important resources for responding to storm events. Regularly updating the ICS, keeping staff well informed about the ICS, and ensuring that all roles are taken seriously are critical for being prepared for an emergency. In addition, locate the ICS so it isn't heavily affected by a storm.

Despite the uncertainty associated with climate change, there's no doubt it will become increasingly relevant to water resource managers in the 21st century.

these processes could increase radionuclides only if there's a current source of radionuclide material present. Many utilities may have access to watershed assessment information on facilities and land uses in their watersheds, thereby narrowing the list of potential contaminants.

- Stratification–destratification, algal growth, post-drought refill, and increased water age and temperature in a distribution system usually increase DBPs and microorganisms or reduce aesthetic water quality. The similarity among these processes is that it represents a conversion from one substance to another. Decay of chlorine residual, growth of microorganisms and algae, formation of DBPs, and dissolution of manganese are examples of these processes. Many utilities may already know if their supplies are susceptible to such occurrences, which may become more frequent under climate change. However, other utilities may face these problems for the first time as climate change significantly affects weather changes for some areas.

PLANNING FOR THE FUTURE

Based on general circulation models, climate change trends for most of the United States indicate temperatures will increase in most areas and rainfall will fluctuate seasonally. From a water supply perspective, except for the southern and mountain west, most areas aren't currently projected to experience reduced average annual runoff (Figure 2). However, changing seasonal patterns and increasing extreme weather events are likely to affect water quality for utilities in all parts of the United States. Recent research indicates increased global temperatures result in more moisture stored in the atmosphere, which leads to a more dynamic hydrologic cycle. Also, low Arctic sea-ice levels are expected to lead to more extreme weather across the United States throughout the year.

Drinking water utilities have successfully dealt with weather and climate variations over the past century, and most utilities are extremely resilient to hydrologic changes that affect water quality. Unfortunately, climate change may result in more frequent variations that lead to additional treatment costs. Climate variation—coupled with increasingly strict drinking water regulations—may require some utilities to implement costly process changes to maintain compliance.

Seasonal weather patterns and individual weather events can significantly affect the quality of source water from a watershed and in reservoirs and distribution systems. Climate change is expected to increase weather variability and increase the frequency and magnitude of extreme events. Despite the uncertainty associated with climate change, there's no doubt it will become increasingly relevant to water resource managers in the 21st century.

Authors' Note: *Hazen and Sawyer gratefully acknowledges the Water Research Foundation, the Water Environment Research Foundatiom, and the Water Services Association of Australia co-own technical information upon which this article is based. Hazen and Sawyer thanks these organizations for their financial, technical, and administrative assistance in funding the project through which this information was discovered. The comments and views herein may not reflect the views of the Water Research Foundation, its officers, directors, affiliates, or agents.*

Staffing. Remember that emergency situations often require additional staff; extra time from existing staff; and, in some cases, contract staff or vendors to respond to emergency situations. Consider preparing special schedules to ensure staff members can be rotated. Food and sleeping cots should be available in case roads are closed.

Road Blocks. Plan evacuation and alternate access routes to assist crews during emergency situations.

Infrastructure Maintenance. Prioritize infrastructure maintenance and replacement to maintain infrastructure resiliency and reduce damages during a major storm event.

Outside Resources. Seek assistance from neighboring water utilities. The Water/Wastewater Agency Response Network (WARN) helps utilities coordinate assistance across several states. Partnerships with utilities, public works, and public service providers in neighboring towns can help supplement local emergency assistance.

Documentation. Document lessons learned in an after-action report immediately following an emergency event to provide a record of damages, infrastructure capacity, response protocols, and recommendations for future emergencies and improvements.

Financial Assistance. Coordinate with appropriate entities to determine the primary Federal Emergency Management Agency (FEMA) contact and to establish clear lines of communication to keep all parties informed of the process. Drinking water systems reported that FEMA reimbursement may arrive several months after costs are incurred. To maintain drinking water services, utilities should anticipate this kind of delay in their business continuity plans.

Insurance. Consult with an insurance agent to ensure emergency-fund eligibility and to prepare financially for future emergency costs.

PLANNING AHEAD

Two hurricanes—Hurricane Irene and Hurricane Sandy—have hit the US East Coast in the last two years, causing widespread flooding and wind damage, resulting in infrastructure losses and power outages. Considering that such storms could become more frequent and severe, utilities can look to the past to plan for the future.

—Water Research Foundation