Addressing Changing Water Quality in Water Supply Reservoirs

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Using Decision Support Framework

For more than a century, surface water reservoirs have served as a critical source for public drinking water supplies. Conventional drinking water treatment processes have been employed to protect the public health from pathogenic microorganisms and other contaminants present in surface waters. In conventional treatment, the overall strategy is to chemically promote the aggregation of raw water particles and dissolved substances and remove the aggregates by physical means. Aggregation is accomplished by adding a chemical coagulant that neutralizes negative charge on the surfaces of raw water particles and converts dissolved natural organic matter (NOM) into a solid phase for subsequent removal. This is accomplished via processes known as coagulation and flocculation. The largest aggregates, known as flocs, can then be removed by clarification via sedimentation or flotation. The remaining finer particle aggregates are captured via granular media filtration. Accordingly, drinking water process selection and performance are largely driven by raw water concentrations of particles (as measured by turbidity), NOM, and other constituents (e.g., algae and cyanobacteria).

Key drivers of drinking water treatment process selection and performance

While most particles that comprise turbidity in natural waters are not a health hazard themselves, turbidity is used as an indicator or surrogate for pathogenic microorganisms and is a regulated parameter in the United States and Canada. Per the U.S. EPA's Surface Water Treatment Rule, utilities with conventional filtration plants must maintain finished water turbidity less than 1 NTU at all times and less than 0.3 NTU in 95 percent of samples each month. Elevated turbidity in raw or treated waters is often indicative of conditions under which microorganism transport is enhanced. Additionally, high particle concentrations in raw water can challenge overall treatment and result in high solids residuals production and treatment cost.

Natural organic matter is typically measured as total and dissolved organic carbon (TOC and DOC) and is comprised of precursors of disinfection by-products (DBPs). DBPs are a result of reactions of NOM with chlorine and other disinfectants and include compounds that are known or suspected carcinogens. NOM is also a source of negative particle charge that must be neutralized during the coagulation process and often drives the amount of coagulant required for treatment. In fact, for most waters, it is NOM that controls the optimum coagulant dose. NOM that remains in finished drinking water can impact corrosion processes in the water distribution system and is a source of carbon for the growth of biofilm on pipes.

Blooms of cyanobacteria are a source of taste and odor compounds in reservoirs, and in some cases can lead to the release of harmful cyanotoxins, which can be challenging to remove through conventional drinking water treatment processes. Because of their low density, cyanobacteria cells cannot be readily removed by settling processes and require a higher coagulation dose or alternative clarification process (e.g., dissolved air flotation) for effective removal. Cells are also a source of NOM and can therefore increase the production of disinfection by-products upon chlorination.

Because the design and performance of a drinking water treatment process train depends upon the raw water characteristics, particularly the concentrations of particles, NOM, and cyanobacteria, changing source water quality can present a serious challenge to drinking water treatment plant operations staff. Short term fluctuations due to extreme storm events can typically be managed, for example by optimizing coagulant dosage, adding powdered activated carbon (PAC), or making other temporary adjustments. However, more frequent occurrence of extreme events and long-term changes in source water quality can result in raw water conditions that are substantially different than those under which a treatment plant was meant to operate. Maintaining the desired level of treatment under such conditions often requires capital investments to upgrade existing treatment or add additional treatment processes.

Many utilities in northeastern North America and parts of Europe face a unique set of conditions in which successful efforts to reduce atmospheric pollution have led to the phenomenon of lake recovery, or "browning" (Anderson et al. 2017). This condition leads to increases in pH, NOM, and cyanobacterial blooms in surface water supplies. These long-term changes are problematic for treatment plants that were designed under fundamentally different water quality conditions, leading to increased treatment and residuals handling costs and reducing operational reliability and resilience. Changes in climate and the occurrence of extreme events likewise pose an acute challenge to water utilities. The critical questions utility managers must answer now are:

- What is the new normal for source water quality and how will we know when we are there?
- When is the right time to make capital investments?

To answer these questions, utilities need data and tools to help them better understand the nature of long-term changes due to lake recovery, climate, and other drivers to help them better initiate responses across the spectrum of planning horizons, from near-term operational responses to long-term capital planning decisions. Accordingly, the Water Research Foundation is funding the development of a Decision Support Framework (DSF) to support utility response to lake recovery, climate change, and other drivers of water quality change (Water Research Foundation Project #4920: Decision Support Framework for Drinking Water Treatment Plants Experiencing Lake Recovery). The DSF will aid utilities in identifying controls at the watershed, source water, and treatment plant to ensure reliable and cost-effective maintenance of water quality objectives.

Impacts of lake recovery and climate change on source water quality

Lake recovery is a leading factor in the long-term increase in DOC concentrations in surface waters in northeastern North America and parts of Europe. Evidence from several studies has indicated that leaching of terrestrial NOM due to decreasing soil acidity is a key mechanism driving the increased DOC levels observed in these lake systems, with important implications for treatability, process efficacy, and the formation of DBPs. Increasing DOC in surface waters can reduce water clarity, which can enhance thermal stratification, potentially further reducing water quality. Increased mobilization of N and P associated with soil organic matter (SOM) can help to stimulate cyanobacteria growth. Reduced acidity as surface waters recover has been linked to changes in phytoplankton community structure, with higher pH favoring cyanobacteria, some species of which produce chemical compounds that cause taste and odor problems.

Further influencing water quality of these sources are long-term changes in climate. It has been well established that temperature, precipitation, and hydrology are important factors in the production and transport of terrestrial NOM to surface waters. NOM concentrations have been known to increase with temperature, as NOM decomposition and solubilization rates are more rapid at higher temperatures. It is also well understood that extreme rainfall can correlate with increased contamination of surface water sources from releases of microbial contaminants, nutrients, and pesticides. Increases in temperature, precipitation, and atmospheric CO_2 have been linked to increasing primary productivity and biomass, which can affect both the amount and the character of SOM. Variability in runoff timing and patterns have likewise been found to be major influences on water quality parameters. Increasing temperatures and transport of nutrients can lead to eutrophic conditions and a rise in the frequency of algal blooms.

Case study: Halifax Water, Nova Scotia, Canada

Halifax Water is a regulated drinking water, wastewater and storm water utility, with 84,000 service connections, serving the Halifax Regional Municipality on the east coast of Canada. Halifax Water operates two large-scale surface water treatment plants, and several smaller scale surface and groundwater treatment plants. Halifax Water's two major water sources, Lake Major and Pockwock Lake, receive stream flows from largely forested, protected watersheds that receive no wastewater discharges. Historically, the lakes are low pH, low turbidity and low alkalinity sources, but, recent data indicate water quality changes consistent with lake recovery and climate change. Over the last 20 years, both lakes have seen a dramatic rise in pH, color, DOC, and taste and odor events which have resulted in increased treatment chemical usage, and decreased filter run times (Anderson et al. 2017, and Figure 1).

Of particular concern is the water treatment process at the JD Kline Water Supply Plant, which treats water from Pockwock Lake and employs a direct filtration process. In direct filtration, coagulation and flocculation are followed by filtration, without a clarification step. Direct filtration is appropriate for source waters with low concentrations of particles and organic matter. Under average conditions, direct filtration is recommended for sources with less than 5 NTU turbidity and less than 3 mg/L of TOC (Valade et al. 2009). Recent observations show Pockwock Lake water nearing or exceeding those recommendations at least part of the year. Meanwhile, climate change projections indicate increasing temperature and precipitation for Nova Scotia. These trends will further exacerbate water quality conditions through changes in forest ecology, primary production, and increasing occurrence of cyanobacteria blooms.

Improving source water quality management

The complex interplay between lake recovery, climate change, land cover, nutrient dynamics, and other drivers of water quality change call into question whether conditions will simply revert to the pre-industrial baseline or whether a new equilibrium will lead to conditions heretofore unseen. Increasing lines of evidence suggest the latter. The impacts of a specific combination of factors leading to water quality changes can be difficult, if not impossible, to fully understand. For waters experiencing lake recovery and climate change, studies have highlighted several observations that have important ramifications for developing a comprehensive response strategy:

- Long-term changes in surface water DOC for systems experiencing lake recovery appear to be most strongly related to changes in atmospheric deposition chemistry rather than climate change.
- Climate change impacts on temperature and precipitation patterns have a strong influence on seasonal variability in surface water DOC and other water quality parameters.
- Both lake recovery and climate change are factors in the increase in the occurrence of blooms of cyanobacteria, resulting in increased risk for issues with T&O compounds and toxins.

These complex interactions highlight the need for a better understanding of

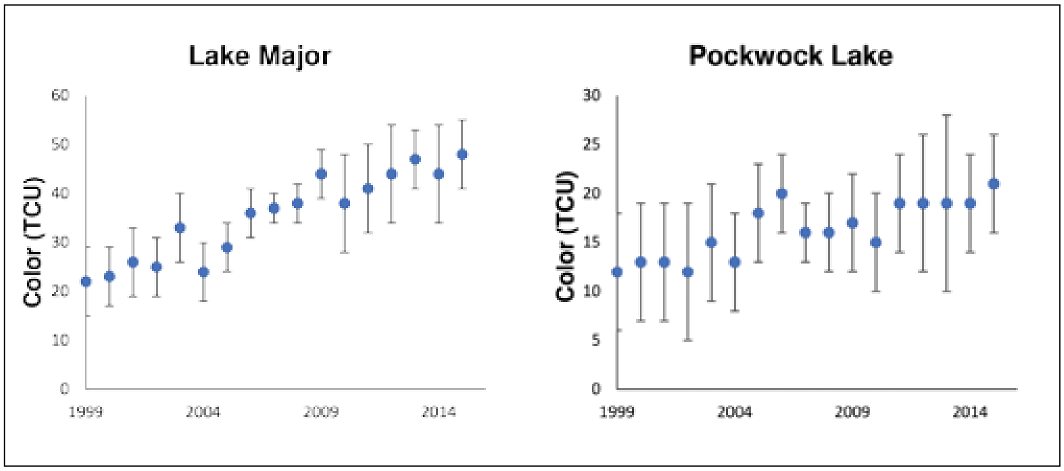

Figure 1. Example of water quality trends at Halifax Water's Lake Major and Pockwock Lake.

source water quality dynamics and better tools for identifying subtle temporal and spatial trends across a watershed. Traditional approaches to source water monitoring, which are typically limited to periodic sampling at a few key locations, and often ignore the greater watershed completely, are increasingly proving insufficient to support robust decision-making. Further, source water quality monitoring and treatment process performance monitoring are often siloed, with watershed managers and treatment plant operators making separate decisions with few opportunities for joint, holistic decision-making.

To address these challenges, the DSF under development is envisioned as a multi-platform watershed, source water, and treatment process monitoring tool with advanced data analytics and visualizations that will support holistic, data-driven decisions (Figure 2). Utilities like Halifax Water need a framework for developing a robust plan for responding to water quality changes due to lake recovery, climate change, and other critical drivers. They further require quantifiable metrics for ensuring achievement of plan objectives. The DSF will enable the development of triggers and thresholds that can be used to guide implementation of a system-wide water quality protection strategy both for the short term, operational, and longer capital planning horizons (Figure 2).

Though being developed and piloted for Halifax Water, the DSF is intended to be a widely applicable tool for managers and operators of reservoir drinking water supplies that are experiencing changes in water quality due to a variety of drivers. While the issue of lake recovery is unique to specific regions, long-term water quality changes and increasing frequency of extreme events due to climate change and other factors is universal. Utilities across North America and abroad recognize increasing uncertainty about what the future holds and the impacts that this uncertainty has on their capital planning efforts. While the DSF will be designed and tested for the specific case of lake recovery, the source-to-tap approach, analytical tools, and guidance materials will be widely applicable for the drinking water and lake management communities.

Acknowledgements

The authors acknowledge the financial support of the Water Research Foundation under Project #4920: Decision Support Framework for Drinking Water Treatment Plants Experiencing Lake Recovery.

References

Anderson, L.E., W.H. Krkosek, A.K. Stoddart, B.F. Trueman, and G.A. Gagnon. 2017. Lake recovery through reduced sulfate deposition: A new paradigm for drinking water treatment. *Environmental science & technology*, 51(3), 1414-1422.

Valade, M.T., W.C. Becker, and J.K. Edzwald. 2009. Treatment selection guidelines for particle and NOM removal. *Journal of Water Supply: Research and Technology-Aqua*, 58(6), 424-432.

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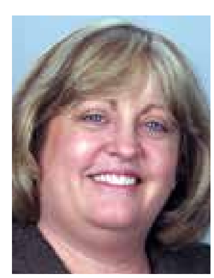

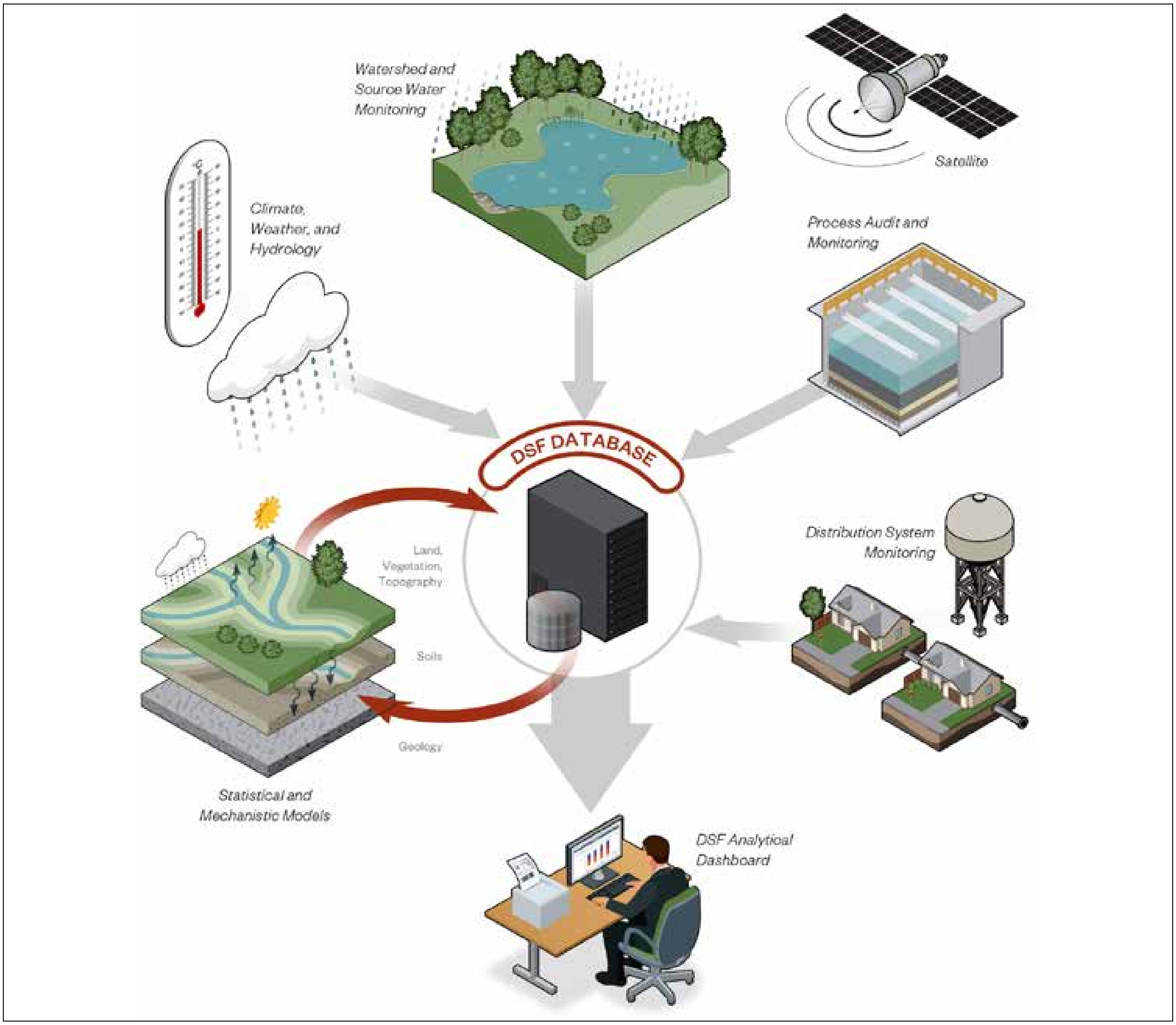

Figure 2. Illustration of the decision support framework.

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