Use of real-time sensors for compliance monitoring of nitrate in finished drinking water

Christopher S. Jones, Tianyi Li, Alex Sukalski, Darrin A. Thompson and David M. Cwiertny

ABSTRACT

Across the Midwestern United States, Public Water Systems (PWSs) struggle with high levels of nitrate in source waters from intense agricultural activity. Leveraging a sensor network deployed across Iowa surface waters, we evaluated the potential of the Hach Nitratax SC Plus, which uses UV-light absorption to quantify dissolved nitrate-nitrite (NO_x-N) down to 0.1 mg-N L^{-1}, for real-time monitoring of NO_x-N in drinking water. For six different PWSs over multiple years, we compare NO_x-N levels in source waters (surface and groundwater under surface influence) to those measured via traditional methods (e.g., ion chromatography (IC)) for US EPA compliance monitoring. At one large PWS, we also evaluated sensor performance when applied to near-finished drinking water (filter effluent). We find good agreement between traditional analytical methods and in situ sensors. For example, for 771 filter effluent samples from 2006–2011, IC analysis averaged NO_x-N of 5.8 mg L^{-1} while corresponding sensor measurements averaged 5.7 mg L^{-1} with a mean absolute error of 0.23 (5.6%). We identify several benefits of using real-time sensors in PWSs, including improved frequency to capture elevated NO_x-N levels and as decision-support tools for NO_x-N management.

Key words | compliance, drinking water, monitoring, nitrate, regulation, sensor

Christopher S. Jones
David M. Cwiertny (corresponding author)
IIHR Hydroscience and Engineering,
University of Iowa,
Iowa City, IA,
USA
E-mail: david-cwiertny@uiowa.edu

Tianyi Li
Alex Sukalski
Darrin A. Thompson
David M. Cwiertny
University of Iowa Center for Health Effects of
    Environmental Contamination,
Iowa City, IA,
USA

Tianyi Li
Department of Earth and Environmental Science,
University of Iowa,
Iowa City, IA,
USA

Alex Sukalski
David M. Cwiertny
Public Policy Center,
University of Iowa,
Iowa City, IA,
USA

Darrin A. Thompson
Department of Occupational and Environmental
    Health,
University of Iowa College of Public Health,
Iowa City, IA,
USA

David M. Cwiertny
Department of Civil and Environmental
    Engineering,
University of Iowa,
4105 Seamans Center for the Engineering Arts and
    Sciences,
Iowa City, IA,
USA

HIGHLIGHTS

- Monitoring of drinking water nitrate using in situ sensors at six community water systems is evaluated.
- Sensors placed in source and finished water agree well with more traditional nitrate analyses.
- Sensors provide accurate, high frequency monitoring data responsive to temporal dynamics in agricultural watersheds.
- Automated nitrate sensors can improve monitoring for better compliance with health-based regulations.
- Sensors can also be used as decision-support tools to guide nitrate management strategies.

INTRODUCTION

Nitrate (NO_3^-) is one of the original parameters identified by the 1974 Safe Drinking Water Act (SDWA) (Tiemann 2014) for regulation in US Public Water Systems (PWSs). A limit (maximum contaminant level (MCL)) of 10 mg L^{-1} (as nitrogen, e.g. NO_3-N) has been enforced by the states and the US Environmental Protection Agency (USEPA) since 1977. Likewise, the World Health Organization (WHO) set a drinking water guideline of 50 mg L^{-1} for NO_3^- (11 mg L^{-1} NO_3-N) in 1970 (WHO 1970). These limits were established to be protective against methemoglobinemia, a human infant (<6 months old) disease resulting from inadequate blood oxygen levels. Nitrate consumed by

the infant in water or infant formula prepared with high-nitrate water is converted to nitrite (NO_2^-) in the infant's digestive tract and is absorbed into the bloodstream. Nitrite reacts with hemoglobin to form methemoglobin, reducing the blood's ability to transport oxygen (Kross *et al.* 1992). This condition has been known in the USA since at least the 1940s (Comly 1945).

More recent research has suggested adverse health effects are possible for adults that consume high-nitrate water. Nitrite resulting from the reduction of nitrate consumed in drinking water can react with amides and amines in the bladder and the digestive system to form N-nitroso compounds with potent carcinogenity (Walker 1990; Bruning-Fann & Kaneene 1993). Weyer *et al.* (2001) found positive associations between drinking water nitrate levels and bladder and ovarian cancer in Iowa (USA) women for the period 1955–1988. An association between drinking water nitrate and female bladder cancer was also reported by Jones *et al.* (2016).

Other cancers have also been linked to drinking water nitrate. Schullehner *et al.* (2018) found statistically significant increased colorectal cancer risk for residents of Denmark consuming water with nitrate at levels above 0.9 mg/L (NO_3-N), less than one-tenth the US and WHO standards. A positive association between drinking water nitrate concentrations and non-Hodgkins lymphoma was reported by Gulis *et al.* (2002) for Slovakia over 1986–1995. Ward *et al.* (2018) reported that the most likely links between drinking water nitrate and negative health outcomes (not including methemoglobinemia) are increased risk of colorectal cancer, thyroid disease, and neural tube defects.

In the Midwestern-USA state of Iowa, PWSs face an ongoing struggle with nitrate contamination of surface and groundwater resources, an outcome of intense row crop and animal agriculture conducted on 80% of the state's land area (Hanson *et al.* 2016; Jones *et al.* 2018a, 2018b; Jones & Schilling 2019; McGill *et al.* 2019; Secchi & Cwiertny 2019). Approximately 60 of the state's drinking water utilities provide water to customers that exceeds 5 mg L^{-1} NO_3-N, and nearly 30% of the state's 880 PWSs have been deemed vulnerable to nitrate contamination (Eller 2015). Private wells are also affected, with about 12% containing NO_3-N concentrations greater than 10 mg L^{-1} (CHEEC 2009).

Enforcement of SDWA regulations in Iowa is a function of the Iowa Department of Natural Resources (IDNR). Regulations for nitrate, like those for most other regulated parameters, are enforced with compliance monitoring dictated by each utility's PWS permit. A utility's required monitoring frequency is dependent upon historical data for the utility, current source water nitrate concentrations, source water vulnerability, available treatment processes and source water blending capabilities. Sampling protocols call for grab sample collection of the finished (treated) water at the treatment plant, followed by delivery to a state-certified testing laboratory where analysis is conducted using Method 353.2, automated colorimetry (O'Dell 1993), or Method 300.0, ion chromatography (Pfaff 1993). A few PWSs have internal certified laboratories where results can be generated in minutes or hours; all others submit samples to the state laboratory or private entities where results may not be known for 48 h (or longer) following sample collection. Required sampling frequency ranges from daily to annually, depending upon the utility's permit.

Nitrate (and nitrate-nitrite in sum, NO_x-N) can be measured continuously *in situ* using devices that work on the principles of UV light absorption, as NO_x-N absorbs at 210 nm. Protocols for the deployment, operation, quality control and data management for these devices have matured rapidly over the past 15 years (Kirchner *et al.* 2004; Pellerin *et al.* 2016; Jones *et al.* 2018a), and data quality generated has been found to be accurate and dependable. Real-time monitoring has long been used by PWSs to track both turbidity and disinfectant levels as a barrier for microbiological contamination of drinking water, and the data has been deemed adequate and necessary for compliance with regulations. Utilities using surface water are required to continuously monitor filter effluent turbidity *in situ* and report exceedances of enforced limits; this data also informs treatment plant operators about impending needs for filter backwash or other maintenance processes (Pontius 1999). Similarly, continuous monitoring of residual chlorine is required in the USA to maintain the integrity of treated drinking water leaving the treatment plant and in the water distribution system (USEPA 1989). Real-time monitoring of parameters such as pH, specific conductance, oxidation-reduction potential and temperature has long helped the water supply industry optimize treatment processes and drinking water quality, protecting the public health. Continuous monitoring also provides an uninterrupted record to autopsy treatment plant upsets, and this information can be used to inform water customers about lapses in water quality.

In this study, we postulate that undetected violations of the drinking water standard (10 mg L^{-1} for NO_3-N) may be occurring in Iowa because sampling protocols, lab methods, and PWS permits are unable to account for episodically-high concentrations resulting from the dynamics associated

with Iowa's agricultural landscape, extreme weather and altered hydrology. To examine this question in detail, we compared high frequency (15 min) *in situ* nitrate data generated by sensors deployed in Iowa's streams as part of a statewide sensor network with data generated by nearby PWSs according to their operating permit protocols. Our research objectives also included examining how predictive the sensor data was of PWS permit data and assessing the suitability of real-time, continuous, *in situ* sensors to supplement or possibly replace grab sampling and lab monitoring for drinking water compliance for nitrate.

METHODS AND MATERIALS

Drinking water nitrate data

Our approach was to compare laboratory-generated NO_x-N data from six Iowa PWSs with data generated by real-time, continuous, *in situ* NO_x-N sensors deployed in nearby streams, or sensors deployed within the PWS itself. SDWA data for drinking water NO_x-N were obtained through a database maintained by the University of Iowa's Center for Health Effects of Environmental Contamination (CHEEC). CHEEC is a state-funded research center that maintains a database of all compliance data submitted by PWSs in Iowa under the SDWA. Queries to this database provided NO_x-N data used for SDWA compliance from PWSs near deployed in-stream sensors, allowing comparison of sensor data to NO_x-N levels in finished drinking water.

In identifying PWSs for analysis, a priority was placed on those systems that rely on surface water and groundwater under direct influence of surface water (GWUDI). The six utilities used in this studied are identified as PWS1–PWS6. They are described in detail below and summarized in Table 1, and their approximate locations are shown in Figure 1. These PWSs and all others in Iowa are granted water use permits from IDNR that allow them to withdraw stream and alluvial groundwater in amounts that maintain a set minimum flow downstream of the utilities' treatment facilities.

PWS1

This utility draws water from radial collector wells in the Iowa River alluvium. The utility has the capacity to use Iowa River water directly in an emergency and water from a former sand pit as low nitrate dilution water. Treatment processes include lime softening, granular activated carbon

Table 1 │ Iowa public water supplies (PWS) evaluated in this study

Utility	Population Served	Water source	Nitrate mitigation strategy
PWS1	63,265	GWUDI	Blending with emergency sources
PWS2	26,684	Surface	Reverse osmosis, blending
PWS3	133,499	GWUDI	Blending
PWS4	12,700	GWUDI	Blending
PWS5	523,098	Surface, GWUDI	Ion exchange, blending
PWS6	25,594	Surface	Blending with emergency sources

GWUDI = Groundwater under direct influence of surface water.

filtration, fluoridation, and disinfection with chlorine. No nitrate removal treatment is available.

PWS2

Relying solely on Iowa River water except during high nitrate episodes, this utility has just recently implemented nitrate removal capacity using reverse osmosis when river water nears or exceeds the nitrate MCL. The treatment plant also has the capacity to use water from a deep confined aquifer, and this has been used in the past as low-nitrate dilution water. Other treatment processes include lime softening, rapid sand filtration, fluoridation, and chlorination.

PWS3

This utility uses radial collector wells under the influence of the Cedar River. PWS3 also operates shallow vertical wells in the Cedar alluvium and has an emergency connection to the Cedar River. A total of 50 wells serve two treatment plants. Lime softening, rapid sand filtration, fluoridation and chlorination comprise the treatment train, but nitrate removal is not available. High nitrate episodes in the wells are managed by aggressive management of blending volumes, but the utility is vulnerable to MCL exceedances, although none have occurred to date.

PWS4

Shallow groundwater (15 m) from the Skunk River alluvium is treated using coagulation, sedimentation, lime softening,
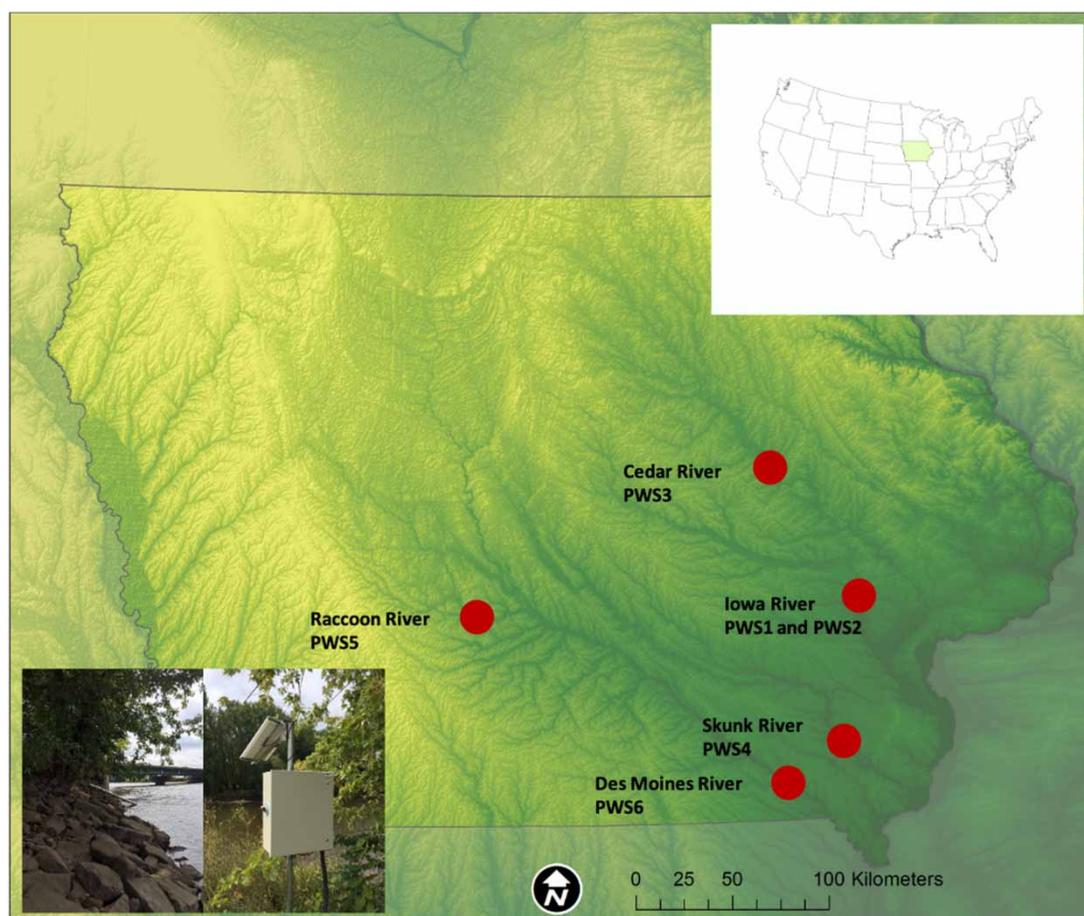
Figure 1 | Location of river sensors and PWSs in this study. In the upper right is the State of Iowa lying within the contiguous US; in the lower left is a typical sensor deployment in an Iowa river. Sensors are slid down the PVC housings into the moving current (left). The dry box on stream bank houses data logger, deep cycle batter, modem and other equipment (right).

filtration, chlorination and fluoridation. No nitrate removal capacity is available.

PWS5

This utility operates three treatment plants that process a diversity of water sources. Raccoon and Des Moines River water is used directly, along with GWUDI of both rivers. The largest treatment facility (pre-sedimentation, lime softening, rapid sand filtration) has ion exchange nitrate removal capacity. A second treatment plant (lime softening, rapid sand filtration) blends down high nitrate from radial collector wells with low nitrate lake water. The third facility (membrane treatment) has reverse osmosis treatment for both hardness and nitrate reduction. PWS5 monitors the filter effluent water from the first two plants using real time continuous nitrate sensors, with the data streamed onto the utility's SCADA system.

PWS6

Des Moines River water is used to provide the municipal supply. Treatment processes include coagulation/sedimentation, lime softening, sand filtration, chlorination and fluoridation.

Real time continuous nitrate measurement

Stream NO_x-N sensor data was aggregated from the University of Iowa's Water Quality Information System (IWQIS) (Jones *et al.* 2018a) and from US Geological Survey water quality stations (USGS 2019). At both the IWQIS and USGS sites, NO_x-N was quantified using the Hach Nitratax SC plus (Loveland, Colorado). Most of the sensors have a 5 mm optical cell path length that can accommodate NO_x-N in the range of 0.1–25 mg L^{-1}. Some of the devices have a 2 mm path length which can measure concentrations up to 50 mg L^{-1}. The Nitratax works on the principles of UV

light absorption. As the NO_x-N concentration increases, absorption of UV at 210 nm also increases. A built-in photometer measures the primary beam, while a reference beam corrects for interference caused by dissolved organic material and turbidity, facilitating measurement of unfiltered river water. The sensor's optic windows are automatically cleaned by a wiper mechanism just prior to each measurement.

For the IWQIS sensors, the UV cell was immersed into the stream extending outward several centimeters from a polyvinyl chloride housing, and data were collected streamside with a custom-designed data logger at each site, logging continuously at 15-min intervals. Sensors are retrieved for periodic maintenance and to prevent ice damage during winter and thus some data gaps are inevitable. Each station was powered by a deep cycle 12 V marine battery, continuously charged during daytime by one 20 W solar panel. Each sensor was serviced and calibrated to a known concentration solution by the Hach Service Department according to the manufacturer's specifications before field deployment. A typical IWQIS deployment is shown in Figure 1.

Data generated by the USGS sensors were harvested by IWQIS from the USGS website (USGS 2019). Deployment of USGS sensors and data handling were somewhat different from IWQIS protocols (Pellerin *et al.* 2013). USGS sensors were designated as such within the IWQIS system. More details on the IWQIS and USGS monitoring systems, including data quality control protocols, can be found at Jones *et al.* 2018a.

The IWQIS design is based on the generalized water cyberinfrastructure developed at the University of Iowa (Demir & Krajewski 2013; Krajewski *et al.* 2017). It provides an integrated and scalable workflow environment to support end-to-end cyberinfrastructure for sharing scientific research and raw data (Duffy *et al.* 2012; Gil *et al.* 2016), in addition to scientific visualization and modeling results that support watershed management and research (Demir & Beck 2009; Demir *et al.* 2009, 2015).

Nitratax sensors were also deployed in the filter effluent water of PWS5. Plastic tubing transported water from the combined filter effluent pipe to the bottom of a PVC enclosure that housed the sensor. Water overflowed at the top of the enclosure and was sent to waste, with total water residence time in the housing of ~1 min. Grab samples were periodically collected from the overflow for laboratory analysis for the purpose of lab/sensor data comparison.

Assessing field deployed sensor performance

To assess the accuracy of the Nitratax sensors, additional water quality data were obtained through PWS1, the City of Iowa City Water Treatment Plant (CICWTP) and PWS5, the Des Moines Water Works (DMWW), for comparison to concentrations obtained by in-stream sensors. For PWS1, NO_x-N sensor data from the Iowa River (IWQIS) was compared to NO_x-N data generated by Iowa River grab samples collected by PWS1 staff and analyzed by spectrophotometry. Sensor data generated by continuous monitoring of PWS5 filter effluent water was compared to concentrations measured in grab samples collected by PWS5 staff and also analyzed by ion chromatography in the treatment plant laboratory. Both laboratories (PWS1 and PWS5) are certified by IDNR. This scheme provided the opportunity to assess how concentrations from field- and treatment plant-deployed sensors compared to more traditional forms of analysis for NO_x-N in source water samples.

RESULTS

Sensor versus lab data comparison of NO_x-N

We first intended to establish that the sensor data reliably and accurately reflected river- and drinking-water NO_x-N. Grab samples collected and analyzed by labs at PWS1 (using USEPA-approved Hach Company TNTplus 835/836 Nitrate Method 10206) and PWS5 (using ion chromatography and Method 300.0 (Pfaff 1993)) were compared with the instantaneous sensor measurement at the time of grab sample collection (DMWW-PWS5), or the daily average sensor measurement retrieved from the historical database (CICWTP-PWS1). In the case of PWS1, the grab samples were from the Iowa River just downstream from a Nitratax sensor site. These data are shown in Figure 2(a). Over a 7 year period (2012–2019), lab samples ($n = 346$) averaged 6.9 mg L^{-1} while daily average sensor measurements averaged 7.2 mg L^{-1}, with no temporal trends observed in the lab/sensor NO_x-N ratio. A linear regression line produced an R^2 value of 0.947, while the mean absolute error was 0.55 (16.5%). It should be noted that quality in the Iowa River is very dynamic with large daily and seasonal changes in turbidity, organic carbon, temperature and other physical and chemical parameters.

Figure 2(b) shows a similar comparison for the PWS5 Fleur Drive Treatment Plant. The measured water had undergone all treatment processes occurring in the plant except for NO_x-N removal, disinfection, and fluoridation. Thus it was very similar in character to the finished drinking water provided to the customers, and, unlike the Iowa River, of a very stable quality throughout the year with turbidity
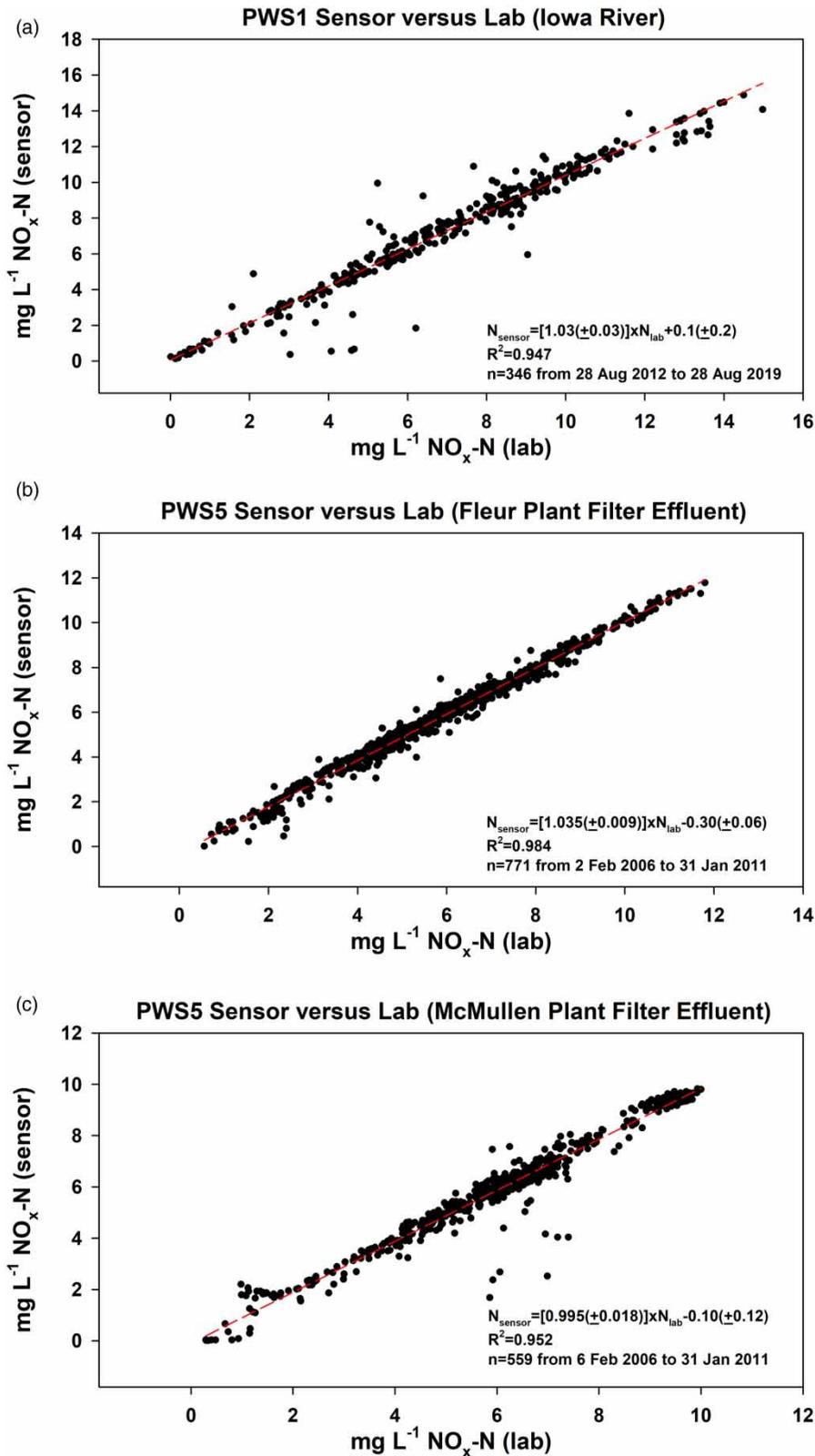
Figure 2 │ Comparison of sensor-generated NO_x-N concentrations and data generated by more traditional analysis of water samples collected as grab samples by PWS staff. Sensor data represent instantaneous measurements at the time of collection. A 1-to-1 line (dashed) is shown for comparison. Also provided is the output equation from a best-fit linear regression analysis of the data, where uncertainties in fit coefficients correspond to 95% confidence intervals.

characteristically low following sand filtration. The data period evaluated here was 2006–2011, with the number of grab samples totaling 771. Lab NO_x-N averaged 5.8 mg L^{-1} while instantaneous sensor measurements at the time of grab sample collection averaged 5.7 mg L^{-1}, again with no temporal trends observed in the lab/sensor NO_x-N ratio. A linear regression line produced an R^2 value of 0.984, while the mean absolute error was 0.23 (5.6%).

A third lab-sensor comparison (Figure 2(c)) was conducted on data (2006–2011) generated from the PWS5 McMullen Treatment Plant (filter effluent water). Lab NO_x-N averaged 6.3 mg L^{-1} whereas instantaneous sensor measurements at the time of grab sample collection averaged 6.1 mg L^{-1}. A linear regression line produced an R^2 value of 0.952, while the mean absolute error was 0.29 (7.3%). A few samples produced differences in NO_x-N concentration of >2 mg L^{-1} (Figure 2(c)) with the sensor measuring higher than the lab; these all occurred early in the period of record (2006–2007).

Stream sensors versus SDWA data

Time series stream sensor NO_x-N data were tracked along with finished drinking water data for the nearby PWS with the presumption that the two would trend in unison because the PWS source waters were either the stream itself or GWUDI. These time series data are shown in Figure 3(a)–3(e). In all cases the sensor data shown is the daily average for measurements collected at 15-min intervals, whereas the PWS data is lab-generated from grab samples. The sensor data is much denser since the PWS permits do not require daily monitoring in most cases. Stream sensor data is summarized in Table 2. Maximum sensor NO_x-N ranged from 14.5 mg L^{-1} (Skunk R.) to 20.5 mg L^{-1} (Raccoon R.). The percentage of days exceeding the drinking water standard of 10 mg L^{-1} is also shown in Table 2, with lowest and highest values again represented by the Skunk (8.5%) and Raccoon (31.1%). Stream NO_x-N concentrations were characteristically high in the Apr-Jun period correlating with farm field work and when precipitation is abundant. Concentrations decline in late summer as crop water and nutrient uptake is robust, and increase again in late fall and winter before declining again in late winter during snowmelt. Concentrations are especially elevated in post drought conditions such as spring 2013 and lower during periods of extended dryness such as 2014.

Figure 3(a) illustrates the time series NO_x-N of PWS1 and PWS2 finished drinking water (lab) and the nearby Iowa River (sensor). PWS1 finished drinking water should in theory be the same as the shallow alluvial water used to supply the plant, since there is no treatment capacity for NO_x-N removal (dilution with sand pit water is possible in rare circumstances). Drinking water NO_x-N concentrations are lower but trend in unison with the river. PWS2 finished water NO_x-N may reflect dilution with deep well water, or some reverse osmosis removal of NO_x-N later in the record. Since the primary PWS2 source is the river itself, finished water data should in theory be the same as the sensor, assuming no blending or NO_x-N removal. Figure 3(b) illustrates time series sensor data for the Cedar River and finished water treated at the two PWS3 treatment plants, which both use shallow alluvial water under direct influence of this river. Skunk River sensor and PWS4 drinking water data for finished water are shown Figure 3(c). PWS4 uses alluvial water under the influence of the Skunk River. Figure 3(d) illustrates Raccoon River sensor data and SDWA data for PWS5-McMullen Plant, which uses GWUDI of that river. Finally, Figure 3(e) shows NO_x-N sensor data for the Des Moines River and reported finished drinking water NO_x-N concentrations for PWS6, which uses this river for its source supply.

DISCUSSION

Each of the utilities is vulnerable to high NO_x-N episodes in its source water, and while each has a strategy to keep finished water below the MCL, some are more vulnerable than others. PWS5, for example, has ion exchange NO_x-N removal capacity at its Fleur treatment plant and has not had a violation of the drinking water standard since this capacity was implemented in 1992, even though source water NO_x-N has been as high as 24 mg L^{-1} NO_x-N (Corrigan 2020). PWS2 recently installed reverse osmosis for the purposes of NO_x-N removal after struggling with the contaminant for many years and diluting high NO_x-N river water with water from a low quality deep well. The other four PWSs use a combination of well management and blending with emergency sources to stay in compliance with regulations. An effect of this can be increased treatment and energy costs and lower quality finished water for parameters such as hardness, taste and odor as the sources used for dilution are usually inferior from a treatment perspective. Further, consumer water demand can overwhelm the water yield needed from a blended source to dilute finished water NO_x-N below the MCL.

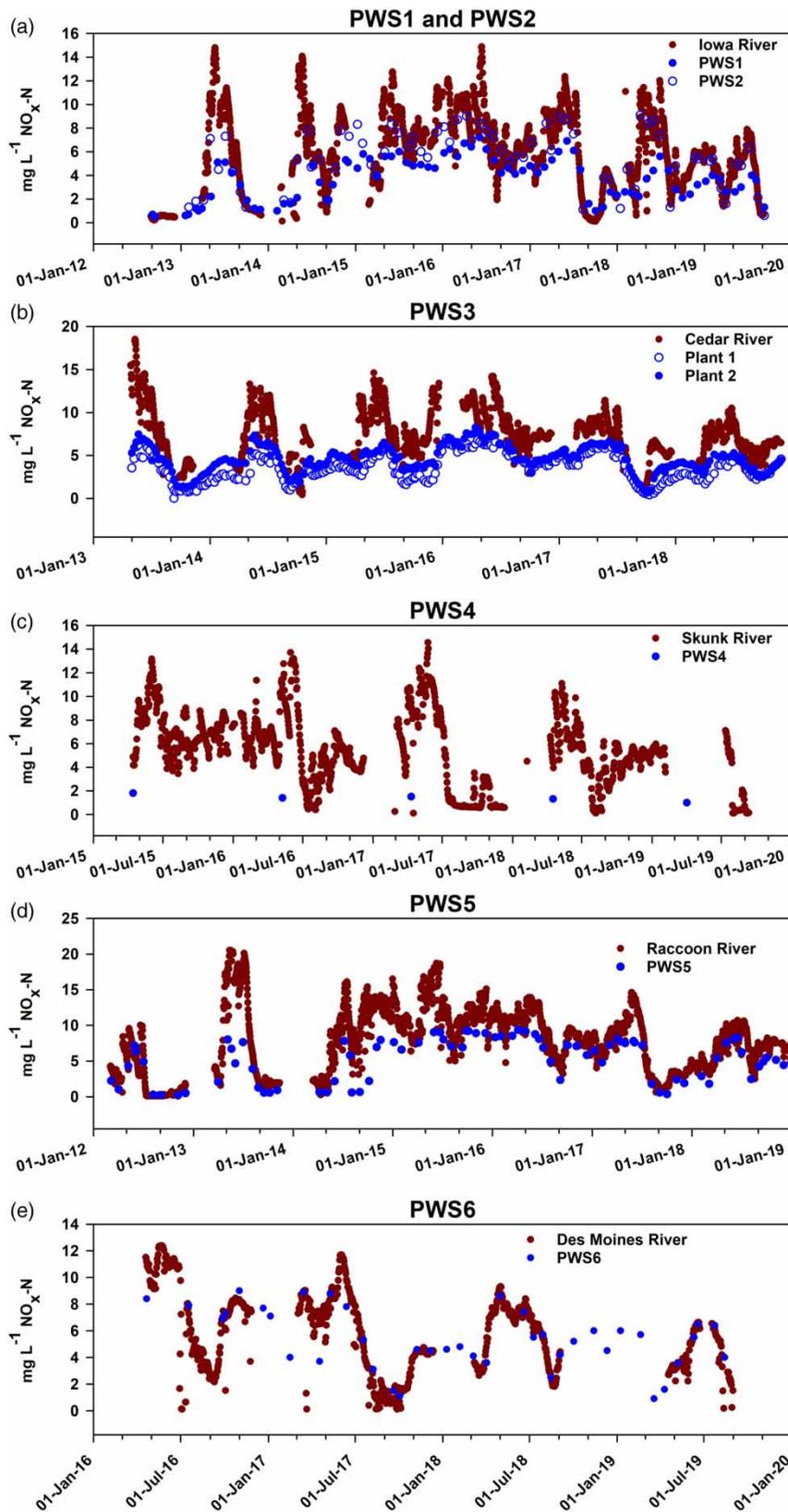It has been previously demonstrated that continuous NO_x-N sensors can inform plant operations (Jones *et al.*

Figure 3 │ Time series NO_x-N data for the finished water produced by PWSs in this study (blue), along with continuous data generated by sensors in nearby streams (brown). PWS5 finished water data is from the McMullen treatment plant.

Table 2 | Summary of NOx-N sensor data for the rivers evaluated in this study

River	n (days)	Average NO$_x$-N (mg L^{-1})	Maximum NO$_x$-N (mg L^{-1})	% of days >10 mg L^{-1}
Iowa	2,106	5.9	14.9	11.4
Raccoon	2,426	7.7	20.5	31.1
Cedar	1,607	7.3	18.5	17.1
Skunk	1,227	5.4	14.5	8.5

Data reflect daily averages, n = days.

2007) by providing utility staff with real-time data that can be used to manage diverse sources and implement removal treatment, and Figure 2 illustrates the accuracy of and reliability of the sensor data. Comparing the stream sensor data here with the SDWA data suggests continuous monitoring can also inform compliance and regulatory strategies. Few Iowa utilities are required to monitor for finished water NO$_x$-N more frequently than monthly, and only PWS5 here regularly reports compliance data on a daily basis, but only during known high source water NO$_x$-N episodes. The time series sensor data, shown within the backdrop of SDWA compliance monitoring of finished drinking water (Figure 3), shows that the frequency of required compliance monitoring may currently be insufficient to capture episodes where exceedances of the drinking water standard are possible. Using the data shown in Figure 3, we calculated the overall ratio of sensor NO$_x$-N to finished water NO$_x$-N (Table 3). From these ratios we estimated the sensor NO$_x$-N which conceivably could cause finished water NO$_x$-N at the treatment plant to exceed the MCL (10 mg L^{-1}), assuming no removal or blending (Table 3). Four of the treatment plants shown in Figure 3 had days of unreported SDWA data when their finished water could have exceeded 10 mg L^{-1}. Each of the PWSs here has strategies to cope with high NO$_x$-N episodes and so we do not assert that unreported violations are occurring at these utilities. Rather, we wish to point out that the frequency of required compliance monitoring may be insufficient to capture high NO$_x$-N episodes, and the resulting data may give the public an inaccurate picture of the threat the contaminant poses to safe drinking water in each of these communities.

Monitoring costs

It appears likely that widespread continuous, real-time *in situ* monitoring of both municipal source supply and treated water could help improve drinking water quality and reduce risks presented to the public health by high-NO$_x$-N water. Many of the Iowa PWSs coping with high NO$_x$-N water are small, rural communities that typically struggle to maintain adequate water and wastewater infrastructure (National Research Council 1997) and extra water monitoring costs could be financially burdensome. However, NO$_x$-N is regulated as an acute contaminant, and adequate and timely monitoring data is necessary for robust protection of public health. Fees for NO$_x$-N analysis at a certified lab are around $20, but many other costs are also associated with this traditional monitoring: labor for sample collection, bottles, and shipping or transporting the samples, to name a few. Total costs for one sample could easily double the lab cost, and by the time results are received, finished water NO$_x$-N concentrations may have exceeded or retreated below the MCL. At $40 total cost per sample, one year of daily monitoring would total $14,600. This compares favorably with the costs associated to deploy a Nitratax sensor ($20,000), which can generate data in real time for many years with minimal maintenance (Jones *et al.* 2007; Jones *et al.* 2018a).

It is worth emphasizing that in our study, even with the abundance of compliance data collected in the larger community water systems (i.e. PWS1, PWS3, PWS5), daily sensor data (Figure 3) are far more abundant over the time intervals considered. This provides higher temporal resolution for how water quality is changing at the treatment plants across seasons, which is particularly valuable during the high rates of NO$_x$-N increase (and decline) that coincide with weather and the start and stop of intense agricultural activity in Iowa. Thus, aside from their ability to provide insights into finished water quality when NO$_x$-N management systems are not being used, the real time data provided by the sensor should be valuable as a decision-support tool for such PWS regarding the vulnerability of their source water to nitrate contamination and

Table 3 | Ratio of NO$_x$-N in finished water to that measured by nearby river sensor, along with the sensor NO$_x$-N that would in theory produce finished water of 10 mg L^{-1}

Utility	PWS1	PWS2	PWS3 Plant 1	PWS3 Plant 2	PWS4	PWS5 McMullen	PWS6
Ratio of finished/sensor NO$_x$-N	0.66	0.97	0.51	0.62	0.26	0.68	0.93
Sensor NO$_x$-N that would generate 10 mg L^{-1} in finished water	15.1	10.3	19.7	16.1	38.5	14.8	10.8

when best to use nitrate control strategies to maintain SDWA compliance.

Finally, the time series data, like those illustrated in Figure 3, can help regulatory agencies design, implement and enforce compliance monitoring requirements for PWSs vulnerable to NO_x-N violations. Monthly compliance monitoring (e.g. PWS4, PWS6 and likely many others) or less may be inadequate to ensure the integrity of drinking water and protect the public health of the affected communities.

CONCLUSIONS

Our analysis shows good agreement between sensors and more traditional modes of NO_x-N analysis. Thus, when NO_x-N control strategies are not being employed, sensor measurements in source waters can be a good estimate for finished drinking water quality. We also anticipate that they would provide accurate data if deployed directly in a higher quality water source, such as finished drinking water prior to distribution.

Accordingly, we contend that ideal use of these sensors is via deployment at/near the intake (e.g. a PWS where there is no nitrate control) or directly in finished drinking water such as during clearwell storage. We would advocate for the use of these sensors for compliance monitoring as an alternative to more traditional laboratory measurements such as ion chromatography. For such applications, acquisition and use of sensors may be most practical and economically viable for large community water systems with sufficient resources to purchase, install and maintain this equipment. However, sensor deployment would reduce existing costs (e.g. personnel and analytical) associated with more traditional monitoring and reporting, and these savings may make their use more reasonable for smaller, more resource-constrained systems. Beyond compliance monitoring, these sensors would also be a useful decision support tool for PWSs with source water at risk from NO_x-N contamination. Real time quality data would be instructive on the timing of when best to activate NO_x-N management systems, as well as when source quality is acceptable and such systems are no longer necessary. This in turn would help to reduce treatment costs, as in some cases (e.g. ion exchange and reverse osmosis), NO_x-N treatment systems can be costly and ultimately result in higher water rates for consumers.

Broader use of these sensors in drinking water quality monitoring would also yield benefits for public health.

Greater frequency of data collection would be more likely to identify violations when seasonal and temporal dynamics result in spikes in NO_x-N concentration that may otherwise go undetected during gaps in the compliance sample collection schedule. Further benefit to the public health community would be derived from the improved knowledge regarding exposure to NO_x-N below the current USEPA MCL, especially amid growing concern about chronic NO_x-N health effects from exposure below 10 mg L^{-1} (Temkin *et al.* 2019). Sensor data would help to more accurately determine the extent and duration of NO_x-N exposure at levels where adverse chronic effects are now being suggested, and this information would help regulators in assessing the benefits and costs of lowering the NO_x-N MCL from its current value of 10 mg L^{-1}.

A final benefit of these sensors is that the real-time output of water quality data could be used to better inform consumers. Data from a sensor is easily exported and displayed (Jones *et al.* 2018a), allowing results to be shown in real time at the utility homepage. In moving toward 'smarter water systems', drinking water providers need to ensure that data relevant to the consumer and their public health is readily available and easily shared. These sensors would help to accomplish that goal.

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Bruning-Fann, C. S. & Kaneene, J. B. 1993 The effects of nitrate, nitrite and N-nitroso compounds on human health: a review. *Veterinary and Human Toxicology* **35**, 521–538.
CHEEC, Center for Health Effects of Environmental Contamination, University of Iowa 2009 *Iowa Statewide Rural Well Water Survey Phase 2 (SWRL2): Results and*

Analysis. Submitted to Iowa Department of Natural Resources Watershed Monitoring and Assessment Section. https://cheec.uiowa.edu/sites/cheec.uiowa.edu/files/SWRL2%20results.pdf.

Comly, H. H. 1945 Cyanosis in infants caused by nitrates in well water. *Journal of the American Medical Association* **129** (2), 112–116.

Corrigan, T. 2020 (4/1/20). Personal Communication (telephone call).

Demir, I. & Beck, M. B. 2009 GWIS: A prototype information system for Georgia watersheds. In *Georgia Water Resources Conference: Regional Water Management Opportunities*, UGA, Athens, GA, USA.

Demir, I. & Krajewski, W. F. 2013 Towards an integrated flood information system: centralized data access, analysis, and visualization. *Environmental Modelling & Software* **50**, 77–84.

Demir, I., Jiang, F., Walker, R. V., Parker, A. K. & Beck, M. B. 2009 Information systems and social legitimacy scientific visualization of water quality. In *2009 IEEE International Conference on Systems, Man and Cybernetics*. IEEE, pp. 1067–1072.

Demir, I., Conover, H., Krajewski, W. F., Seo, B. C., Goska, R., He, Y., McEniry, M. F., Graves, S. J. & Petersen, W. 2015 Data-enabled field experiment planning, management, and research using cyberinfrastructure. *Journal of Hydrometeorology* **16** (3), 1155–1170.

Duffy, C., Gil, Y., Deelman, E., Marru, S., Pierce, M., Demir, I. & Wiener, G. 2012 Designing a road map for geoscience workflows. *Eos, Transactions American Geophysical Union* **93** (24), 225–226.

Eller, D. 2015 60 Iowa cities see high nitrates. *Des Moines Register*, July 4, 2015. Available at: https://www.desmoinesregister.com/story/money/agriculture/2015/07/04/high-nitrates-iowa-cities/29720695/ (Accessed Feb. 1, 2020).

Gil, Y., David, C. H., Demir, I., Essawy, B. T., Fulweiler, R. W., Goodall, J. L., Karlstrom, L., Lee, H., Mills, H. J., Oh, J. H. & Pierce, S. A. 2016 Toward the geoscience paper of the future: best practices for documenting and sharing research from data to software to provenance. *Earth and Space Science* **3** (10), 388–415.

Gulis, G., Czompolyova, M. & Cerhan, J. R. 2002 An ecologic study of nitrate in municipal drinking water and cancer incidence in trnava district, Slovakia. *Environmental Research* **88** (3), 182–187.

Hanson, M. J., Keller, A., Boland, M. A. & Lazarus, W. F. 2016 The debate about farm nitrates and drinking water. *Choices* **31** (316-2016-7799), 1–7.

Jones, C. S. & Schilling, K. E. 2019 Iowa statewide stream nitrate loading: 2017–2018 update. *The Journal of the Iowa Academy of Science* **126**, 6–12.

Jones, C. S., Hill, D. & Brand, G. 2007 Use a multifaceted approach to manage high source-water nitrate. *Opflow* **33** (6), 20–22.

Jones, R. R., Weyer, P. J., DellaValle, C. T., Inoue-Choi, M., Anderson, K. E., Cantor, K. P., Krasner, S., Robien, K., Freeman, L. E. B., Silverman, D. T. & Ward, M. H. 2016 Nitrate from drinking water and diet and bladder cancer among postmenopausal women in Iowa. *Environmental Health Perspectives* **124** (11), 1751–1758.

Jones, C. S., Davis, C. A., Drake, C. W., Schilling, K. E., Debionne, S. H., Gilles, D. W., Demir, I. & Weber, L. J. 2018a Iowa statewide stream nitrate load calculated using in situ sensor network. *JAWRA Journal of the American Water Resources Association* **54**, 471–486.

Jones, C. S., Nielsen, J. K., Schilling, K. E. & Weber, L. J. 2018b Iowa stream nitrate and the Gulf of Mexico. *PloS one* **13** (4), e0195930. https://doi.org/10.1371/journal.pone.0195930.

Kirchner, J. W., Feng, X., Neal, C. & Robson, A. J. 2004 The fine structure of water-quality dynamics: the (high-frequency) wave of the future. *Hydrological Processes* **18**, 1353–1359.

Krajewski, W. F., Ceynar, D., Demir, I., Goska, R., Kruger, A., Langel, C., Mantilla, R., Niemeier, J., Quintero, F., Seo, B. C. & Small, S. J. 2017 Real-time flood forecasting and information system for the state of Iowa. *Bulletin of the American Meteorological Society* **98** (3), 539–554.

Kross, B. C., Ayebo, A. D. & Fuortes, L. J. 1992 Methemoglobinemia: nitrate toxicity in rural America. *American Family Physician* **46**, 183–188.

McGill, B. M., Burgin, A. J., Hively, W. D., Loecke, T., Dagnew, A. T. & Beeson, P. 2019 Farming for human health and a smaller dead zone: how agricultural conservation practices, climate change, and subsurface drainage intensification affect nitrate loads in Iowa. *AGUFM* **2019**, GC33D-03.

National Research Council 1997 *Safe Water From Every Tap: Improving Water Service to Small Communities*. The National Academies Press, Washington, DC. https://doi.org/10.17226/5291.

O'Dell, J. W. 1993 *Method 353.2: Determination of Nitrate-Nitrite Nitrogen by Automated Colorimetry*. Environmental Monitoring Systems Laboratory. US Environmental Protection Agency, Cincinnati, OH, USA.

Pellerin, B. A., Bergamaschi, B. A., Downing, B. D., Saraceno, J. F., Garrett, J. D. & Olsen, L. D. 2013 *Optical Techniques for the Determination of Nitrate in Environmental Waters: Guidelines for Instrument Selection, Operation, Deployment, Maintenance, Quality Assurance, and Data Reporting*. Techniques and Methods, 1-D5, United States Geological Survey, California Water Science Center, Sacramento, CA, USA.

Pellerin, B. A., Stauffer, B. A., Young, D. A., Sullivan, D. J., Bricker, S. B., Walbridge, M. R., Clyde Jr, G. A. & Shaw, D. M. 2016 Emerging tools for continuous nutrient monitoring networks: sensors advancing science and water resources protection. *JAWRA Journal of the American Water Resources Association* **52**, 993–1008.

Pfaff, J. D. 1993 *Method 300.0 Determination of Inorganic Anions by ion Chromatography*. US Environmental Protection Agency, Office of Research and Development, Environmental Monitoring Systems Laboratory, Cincinnati, OH, USA, pp. 28.

Pontius, F. W. 1999 Complying with the interim enhanced surface water treatment rule. *Journal-American Water Works Association* **91** (4), 28–188.

Schullehner, J., Hansen, B., Thygesen, M., Pedersen, C. B. & Sigsgaard, T. 2018 Nitrate in drinking water and colorectal cancer risk: a nationwide population-based cohort study. *International Journal of Cancer* **143**, 73–79.

Secchi, S. & Cwiertny, D. M. 2019 *Iowa's Grants to Counties Program: A Valuable but Underutilized Program for Protecting the Public Health of Private Well Users*. University of Iowa Institutional Repository. Available at: https://iro.uiowa.edu/view/delivery/01IOWA_INST/12716559630002771.

Temkin, A., Evans, S., Manidis, T., Campbell, C. & Naidenko, O. V. 2019 Exposure-based assessment and economic valuation of adverse birth outcomes and cancer risk due to nitrate in United States drinking water. *Environmental Research* **176**, 108442.

Tiemann, M. 2014 *Safe Drinking Water act (SDWA): A Summary of the act and its Major Requirements*. Congressional Research Service, Washington, DC, USA, pp. 7–5700.

USEPA, United States. Environmental Protection Agency. Office of Drinking Water. Science and Technology Branch 1989 *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources: Draft*. Science and Technology Branch, Criteria and Standards Division, Office of Drinking Water, US Environmental Protection Agency, Washington, DC, USA.

USGS 2019 *National Water Information System, Current Water Data for Iowa*. Available at: https://waterdata.usgs.gov/ia/nwis/rt.

Walker, R. 1990 Nitrates, nitrites and N-nitrosocompounds: a review of the occurrence in food and diet and the toxicological implications. *Food Additives & Contaminants* **7** (6), 717–768.

Ward, M. H., Jones, R. R., Brender, J. D., De Kok, T. M., Weyer, P. J., Nolan, B. T., Villanueva, C. M. & Van Breda, S. G. 2018 Drinking water nitrate and human health: an updated review. *International Journal of Environmental Research and Public Health* **15**, 1557.

Weyer, P. J., Cerhan, J. R., Kross, B. C., Hallberg, G. R., Kantamneni, J., Breuer, G., Jones, M. P., Zheng, W. & Lynch, C. F. 2001 Municipal drinking water nitrate level and cancer risk in older women: the Iowa Women's Health Study. *Epidemiology* **12** (3), 327–338.

WHO 1970 *European Standards for Drinking Water*, 2nd edn. World Health Organization, Geneva, Switzerland.