Inorganic contaminants in Canadian First Nation community water systems

Kaycie Lane, Benjamin F. Trueman, Javier Locsin and Graham A. Gagnon

ABSTRACT

While previous Canadian studies have examined microbiological water quality in First Nations, there is little published information on inorganic contaminants. In Atlantic Canada, the lead, manganese, and arsenic content of First Nations' drinking water has been measured for more than a decade, but the data have not been analyzed comprehensively. These contaminants are linked with health problems, and high levels in drinking water are a cause for concern. We examined 12 years of data from 47 First Nation community water systems to identify systems experiencing difficulties meeting sampling frequency or regulatory guidelines. While most contaminant concentrations were below guideline values, we identified elevated concentrations and issues with sampling frequency. No system met both sampling frequency requirements – a minimum of one sample per year per analyte – and regulatory guidelines. Exceedance rates for lead, manganese, and arsenic were high in some systems. Moreover, current sampling procedures for lead specify that taps be flushed prior to sampling, which is known to underestimate lead exposure. We find that a switch to random daytime sampling would at least sometimes yield higher estimates of lead at the tap. Our analysis demonstrates the need for increased monitoring and updated sampling procedures to better characterize inorganic contaminant occurrence in First Nations.

Key words | arsenic, drinking water quality, First Nations, lead, manganese, metals

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HIGHLIGHTS

- Most samples in most communities were below maximum concentration limits.
- We identified elevated Pb, As, and Mn in some communities.
- Sampling frequency was lower than expected in many communities.
- The fully flushed sampling protocol likely underestimated Pb concentrations.

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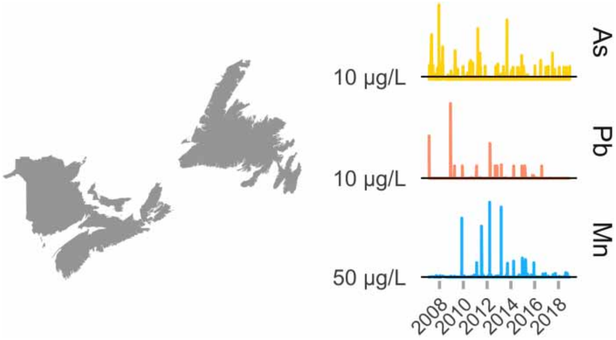
GRAPHICAL ABSTRACT



INTRODUCTION

First Nations across Canada have experienced more boil water advisories than municipal communities, due in part to low chlorine residuals, high turbidity, poor infrastructure, and positive coliform samples (Neegan Burnside 2011; Health Canada 2014a). The federal government has made a commitment to end long-term drinking water advisories by 2021 (Indigenous Services Canada 2019). Turbidity, chlorine residual, total coliforms, and *E. coli* counts have been prioritized because boil water advisories are commonly issued as a result of changes in these parameters. Lead, manganese, and arsenic sometimes also exceed the relevant maximum acceptable concentrations or aesthetic objectives specified by Health Canada's water quality guidelines (Health Canada 2006, 2019a, 2019b). But while compliance with microbiological guidelines (e.g., *E. coli* and total coliforms) and other basic water quality standards (e.g., chlorine residual and turbidity) has been evaluated in previous studies (Neegan Burnside 2011; Health Canada 2014a), inorganic contaminants have not been analyzed comprehensively; past government reports have provided some data but little analysis (Health Canada 2014a).

Elevated concentrations of arsenic, manganese, or lead may represent a significant public health hazard. Arsenic exposure via drinking water is associated with cardiovascular, reproductive, and neurological effects as well as tumorigenesis (Abdul *et al.* 2015). Chronic arsenic exposure through drinking water has been linked with elevated lung cancer mortality (Chiu *et al.* 2004). Arsenic may induce neurobehavioral changes (Tsai *et al.* 2003), increase fetal mortality, and increase the likelihood of a preterm birth (Hopenhayn *et al.* 2003). Health Canada's guidance specifies a maximum acceptable concentration for arsenic of 10 μg/L (Health Canada 2006).

In the past, manganese was viewed as an aesthetic concern; the guideline up until 2019 specified an aesthetic objective of 50 μg/L. However, manganese appears to be neurotoxic at environmental exposure levels (Kim *et al.* 2009; Bouchard *et al.* 2011), and Health Canada has recently released a health-based maximum acceptable concentration of 120 μg/L (Health Canada 2019b). Childhood exposure to manganese is associated with cognitive and attention deficits (Bouchard *et al.* 2011), and co-exposure to lead and manganese may be especially detrimental (Kim *et al.* 2009; Henn *et al.* 2012). High levels of manganese in water are also sometimes associated with high lead concentrations (Schock *et al.* 2014; Trueman *et al.* 2019).

Compared with manganese, the health effects of lead are better understood. Childhood lead exposure is strongly linked with behavior disorders (Nigg *et al.* 2008) and long-lasting cognitive deficits (Evens *et al.* 2015; Reuben *et al.* 2017). Low-level exposure in adults has been linked with hypertension (Navas-Acien *et al.* 2007), cardiovascular disease mortality (Lanphear *et al.* 2018), and renal dysfunction (Loghman-Adham 1997). Due to exposure concerns, Health Canada has recently released a new guideline for lead in drinking water with a maximum acceptable concentration of 5 μg/L (Health Canada 2019a). While the previous guideline specified that lead should not exceed 10 μg/L, this may not have been protective as an exposure threshold: for instance, Levallois *et al.* (2014) found that the odds of blood lead levels at or above the 75th percentile were 4.7 times greater when the mean water concentration was more than 3.3 μg/L.

Furthermore, monitoring strategies and regulations based on flushed sampling – such as the previous Health Canada guideline – systematically underestimate lead exposure (Riblet *et al.* 2019). This is because water is typically consumed after it has been stagnant in plumbing for some time (Riblet *et al.* 2019), during which lead is released. Health Canada's new guideline for lead specifies random daytime or 30 min stagnation sampling – instead of flushed sampling – to better estimate lead exposure via drinking water (Health Canada 2019a). Both methods have been shown to approximate actual exposure to lead via comparison with composite proportional sampling (the collection of an aliquot from each volume of water used for drinking or cooking) (Van de Hoven *et al.* 1999; Riblet *et al.* 2019). Random daytime sampling is less resource-intensive than 30 min stagnation sampling, but many samples are needed due to the increased variability compared with methods involving collection after a fixed stagnation period.

Here, we used a 47 community system dataset to analyze sampling frequency compliance (the number of samples per year) and regulatory compliance (the concentration of analytes) with Health Canada guidelines over a 12-year period from 2007 to 2018. We also compared historical flushed sample data with random daytime sample data collected in a subset of four First Nation community water systems.

MATERIALS AND METHODS

This research was conducted in partnership with the Atlantic Policy Congress of First Nation Chiefs (APC), which advocates a strong Indigenous voice supported by research and analysis and aimed at changing policies impacting First Nations. Staff from the APC were essential in explaining the project to communities, organizing information, and ensuring that community staff (e.g., water monitors and operators) were aware of the project. During manuscript preparation, the APC reviewed drafts and interim reports for accuracy. Consistent with the Ownership, Control, Access and Protection (OCAP) guidelines for First Nation research, the Dalhousie team was guided by the goals of the APC regarding information management and dissemination.

The authors of this paper represent the Centre for Water Resources Studies at Dalhousie University. Professor Gagnon led this project and has led previous water management research projects in partnership with the APC. Under Professor Gagnon's supervision, K. Lane worked with APC staff to collect samples and prepare reports for communities and the APC. B. Trueman and J. Locsin analyzed and interpreted the data.

The First Nations Community-based Water Monitor Program

Water quality monitoring in First Nations is performed by community-based monitors. Data – along with sampling locations, detection limits, and analytical methods – are reported via an online system (the WaterTrax system). The APC works in partnership with Mi'kmaq, Maliseet, Passamaquoddy, and Innu Chiefs and provided access to the bulk of the data used in this study. Names of Nations and community systems have not been shared in accordance with the non-disclosure policy of the APC, which is aligned with the First Nations OCAP guidelines (First Nations Information Governance Centre 2018). According to the manual distributed to monitors from each Nation, samples for the determination of arsenic, lead, and manganese are to be collected once a year (First Nations and Inuit Health Branch 2007; Health Canada 2013). This amounts to an expected total of 12 samples per community system per analyte from 2007 to 2018.

The Community-based Water Monitor Program is overseen by Health Canada and compensates community residents for the collection of water samples. Sampling frequency is specified by the water monitor manual (Health Canada 2013); sample locations are selected by the monitor and the Environmental Health Officer and must be representative of the water distribution system. The manual provides clear sampling procedures for free chlorine, biological parameters, and inorganics (the current inorganic sampling protocol specifies that flushing occurs prior to sampling). Monitors are responsible for submitting samples to an accredited laboratory and communicating adverse sample results to Chief and Council, the Environmental Health Officer, and Health Canada. Along with a manual, monitors are provided with reference materials and training workshops.

Random daytime sampling study – research approach

The random daytime sampling study described here was part of a larger project involving the APC and the Centre for Water Resources Studies. Six communities were chosen for the larger study based on source water type, population, location, and whether the system was part of a municipal transfer agreement. The four communities selected for random daytime sampling are described in Table 1. They agreed to collect random daytime samples, and we provided sampling instructions to each water monitor, explained the procedure, and offered the option to opt out of the study. After collection, samples were either shipped to Dalhousie University or retrieved by one of the study authors.

Compared with fully flushed sampling, the random daytime method provides a better estimate of drinking water lead exposure because it captures lead release to stagnant as well as flowing water. The method may also offer an advantage over 30 min stagnation sampling in that particulate lead is not flushed out of the system before collection (Deshommes *et al.* 2010). Random daytime sampling captures a range of consumer lead exposures provided that a sufficient number of samples are collected (Van de Hoven & Slaats 2006).

Table 1 | Characteristics of the four water systems where random daytime samples were collected

Community system	Source	Connections	Population	System type[a]
11	Groundwater	695	3,000	non-MTA
15	Surface water	35	60	MTA
21	Groundwater	Unknown	440	non-MTA
35	Surface water	174	600	non-MTA

[a] MTA: a municipal transfer agreement is a contract whereby a municipality provides water or wastewater services to a First Nation; non-MTA water systems are operated and owned by the First Nation.

Between January and August 2018, samples in each of the four community systems were collected from households for the determination of total manganese, lead, and arsenic. A water monitor visited each home during working hours, avoiding periods of high-water use and overnight stagnation. Samples were collected immediately after entry, without a fixed stagnation period or prior flushing (site and collection time were not, strictly speaking, randomly selected). The monitor collected a 1 L sample from a fully opened cold drinking water tap; typical flow rates under these conditions have been measured previously at 3–10 L/min (Clark *et al.* 2014). Upon receipt, we preserved samples to pH <2 with trace metal grade nitric acid and digested them at room temperature for a minimum of 24 h. We drew aliquots of 10 mL from each preserved sample and analyzed them by inductively coupled plasma mass spectrometry (ICP-MS) (X Series 2 ICP-MS, Thermo Fisher Scientific, MA, USA) according to Standard Method 3125 (APHA 2012) with reporting limits for lead, manganese, and arsenic of 0.4, 0.8, and 0.4 μg/L, respectively.

Data analysis

We compiled and analyzed total lead, manganese, and arsenic data collected over the period 2007–2018. Thirty-three First Nations in Atlantic Canada, representing 47 community water systems, have reported data over this period. Consistent with the Community-based Water Monitor manual (Health Canada 2013), results have been communicated by the community system instead of by First Nation.

We used a non-parametric statistic – Kendall's τ – to describe trends in compliance with sampling requirements and regulatory guidelines. We considered any sample with greater than 10 μg Pb/L (the Health Canada maximum acceptable concentration up until 2019), 10 μg As/L (the current Health Canada maximum acceptable concentration), or 50 μg Mn/L (the Health Canada aesthetic objective up until 2019) as a guideline exceedance.

Kendall's τ has been used extensively for trend testing (El-Shaarawi & Niculescu 1992). It measures the strength of association between two variables, one of which, in this case, is time. Kendall's τ ranges from -1 to 1, and in the present context, it can be interpreted as follows: given a date and a value, $\tau = 1/3$ indicates that a subsequent value is twice as likely to be greater as smaller. In general, $(1+\tau)/(1-\tau)$ is the odds ratio of concordant (values increase with time) to discordant (values decrease with time) pairs (Noether 1981).

We also compared random daytime samples with flushed samples from the dataset by the community system. Since data were positively skewed and included singly or multiply left-censored values (reported as below one or multiple reporting limits), we used the generalized Wilcoxon test for group comparisons (Helsel 2012; Lee 2017). Random daytime and flushed samples were also compared using the Wilcoxon rank-sum test (R Core Team 2019) after re-censoring at the highest reporting limit for each community system and element.

The latter (rank-sum) test is a non-parametric analog to the *t*-test. In its most general form, it is used to determine whether the values in one group, x, tend to be greater than the values in another, y. It is computed by ranking all of the data and then summing the ranks in each group. The sum corresponding to the smaller group (or either sum if the group sizes are equal) is compared against the probability distribution of sums under the null hypothesis ($\mathrm{Prob}(x_i > y_i) = 0.5$) (Helsel & Hirsch 2002). While the Wilcoxon rank-sum test is readily applied to left-censored data at one reporting limit (censored values are assigned the tied minimum rank), the generalized Wilcoxon test is necessary when there is more than one reporting limit.

For each rank-sum test, we estimated multiplicative differences between random daytime and flushed samples using a normal approximation to the Hodges–Lehmann estimator after natural log transformation, as detailed in our previous work (Trueman *et al.* 2016, 2018) and elsewhere (Helsel & Hirsch 2002; R Core Team 2019). All data analysis was carried out using R (Grolemund & Wickham 2011; Lee 2017; Wickham 2017; R Core Team 2019).

RESULTS AND DISCUSSION

Variation in lead, arsenic, and manganese concentrations

Most analyte concentrations in the dataset were below the relevant maximum acceptable concentration or aesthetic objective (Figure 1). Ninety three and 96% of lead levels were below 5 and 10 μg/L, respectively, and 93% of arsenic levels were less than 10 μg/L. Seventy seven and 84% of manganese levels were less than 50 and 120 μg/L, respectively. Median lead, arsenic, and manganese levels were also quite low: <0.5, <1, and 4 μg/L. However, elevated concentrations did occur: maximum lead, arsenic, and manganese levels were 3, 0.25, and 47 mg/L, and the corresponding 99th percentiles were 0.495, 0.046, and 10.64 mg/L.

Community sampling frequency

While all but 14 community systems *averaged* at least one sample per analyte per year over the study period, 45 missed a sample for at least one analyte in at least 1 year. For example, system 46 reported 30 concentrations for each analyte over the study period, but these data represent only 11 of the 12 years (Figure 2). Sampling in other systems

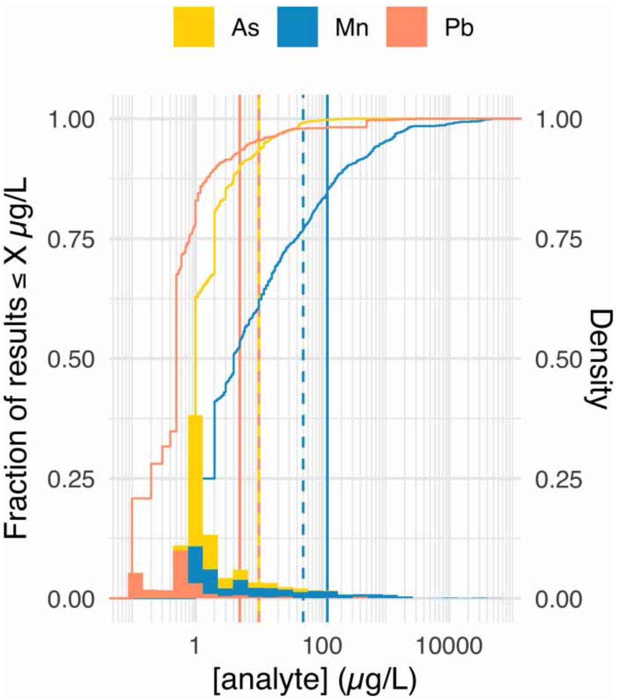


Figure 1 | Empirical cumulative distribution functions (lines, left *y*-axis) and stacked histograms (bars, right *y*-axis) representing data from all 47 community water systems. Solid lines indicate the current maximum acceptable concentrations for lead, manganese, and arsenic; dashed lines indicate the maximum acceptable concentration for lead and the aesthetic objective for manganese before 2019.

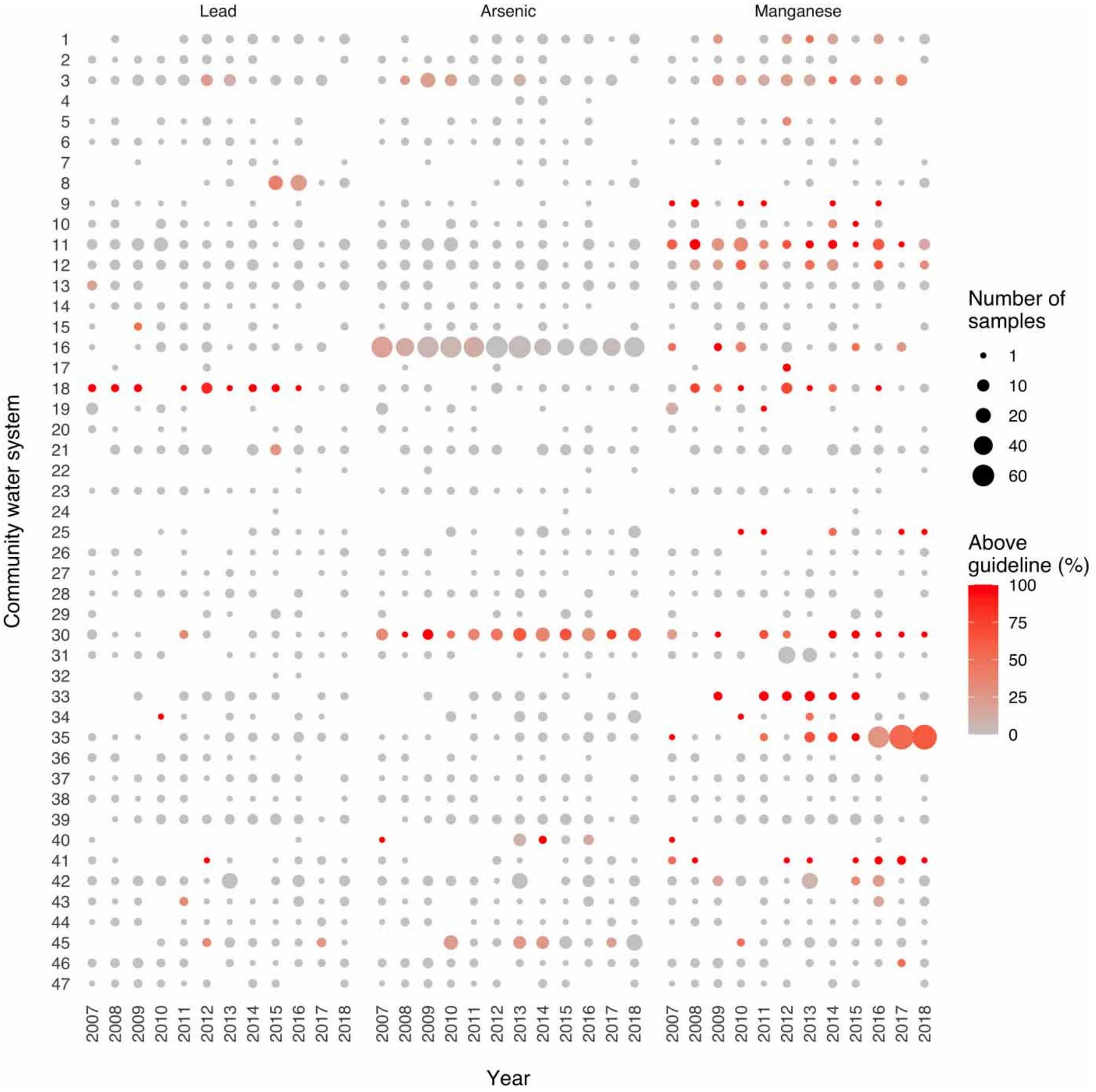


Figure 2 | Sampling frequency by the community water system over the study period. Point sizes are proportional to the number of samples collected, and the color scale represents the fraction exceeding the relevant guideline value (10, 10, and 50 μg/L for lead, arsenic, and manganese, respectively). The smallest point size represents one sample; these points are either gray or red, indicating either 0 or 100% compliance. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wh.2020.185.

was more sparse: system 4 reported arsenic only, and only in 3 of the 12 years (Figure 2). Systems 32, 22, and 17 have all collected samples in just 2–3 of the 12 years, while system 24 collected samples only in 2015. None of these four communities averaged one sample per analyte per year.

The water monitor guidelines suggest that guideline exceedances be followed by resampling (Health Canada 2013). Of the three parameters, arsenic was sampled most frequently, particularly in systems 3, 16, 30, and 45. System 16 collected 29 or more samples for arsenic every year over the study period. Manganese was sampled, on average, 20 times more frequently than recommended in system 35. Lead was sampled more frequently, on average, than the guideline requirements in 33 systems. System 8 is

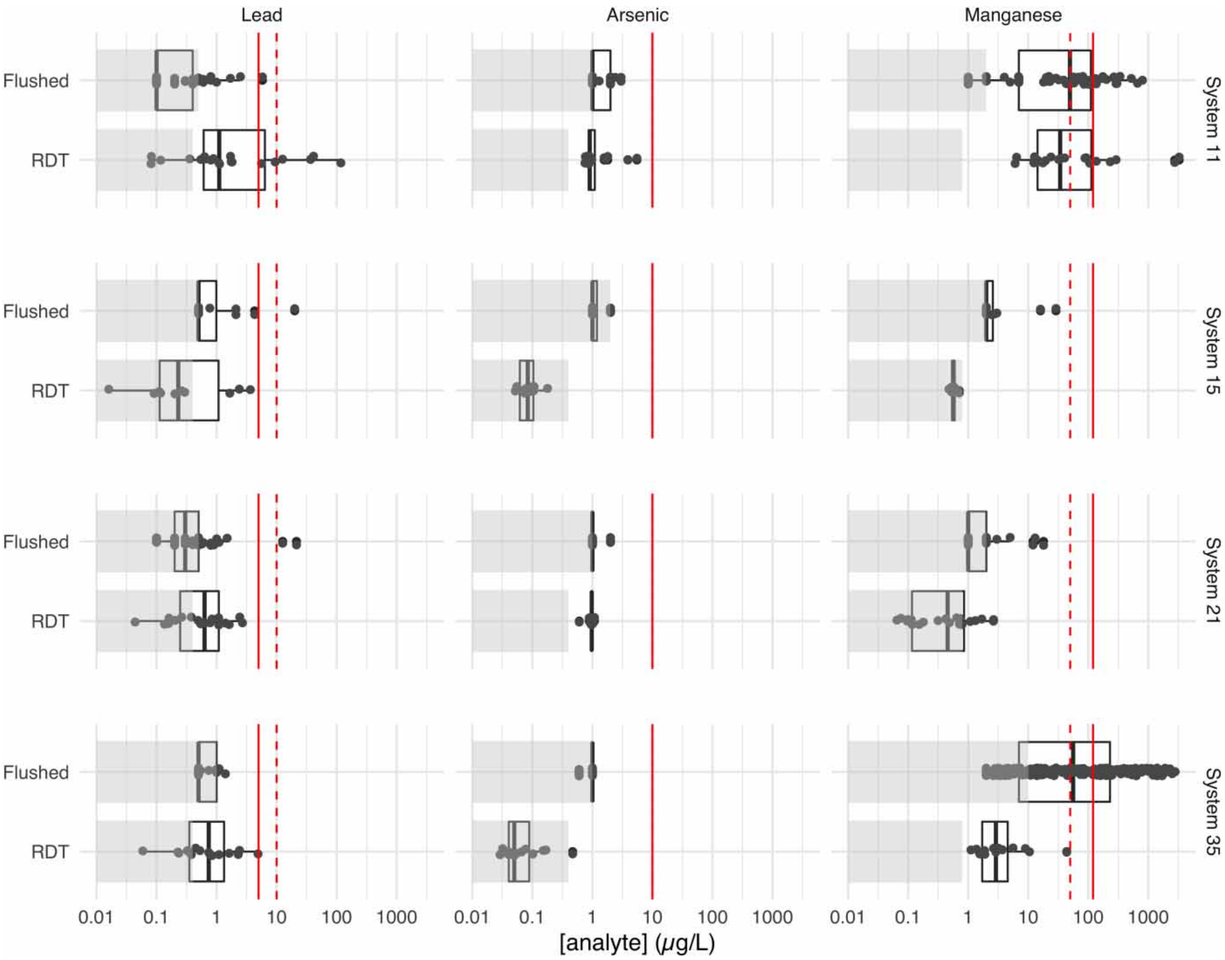


Figure 3 | Lead, arsenic, and manganese concentrations as determined by random daytime and flushed sampling. Maximum censoring limits by the community water system and protocol are represented as shaded gray regions. Boxplots are represented as follows: boxes enclose the interquartile range (25th–75th percentile), bold black lines denote medians, horizontal lines outside the boxes extend to the most extreme value about the median that is less than or equal to 1.5 times the interquartile range, and more extreme values are plotted as points. Solid red lines indicate the current maximum acceptable concentrations for lead, manganese, and arsenic; dashed red lines indicate the maximum acceptable concentration for lead and aesthetic objective for manganese before 2019. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wh.2020.185.

notable in that it is the only system where the extra samples for lead were not accompanied by additional data for arsenic or manganese. Generally, a high volume of samples in a single year accompanied a guideline exceedance in the same year; notable exceptions to this trend include system 16. However, this system exceeded guidelines in other years.

Comparison with regulatory guidelines

Of the two community systems that have collected at least one sample for each analyte each year, neither has met the regulatory guidelines for all three analytes in all 12 years (Figure 2). Overall, 26 systems have exceeded a maximum concentration in at least 1 year (Figure 2). Of the three contaminants in the dataset, manganese most often exceeded its regulatory threshold (Figure 2); 22 systems have exceeded the manganese guideline at least once in the past 12 years. Fourteen of these systems exceeded the guideline in 100% of samples in at least 1 year, and eight systems exceeded it in more than 1 year. The arsenic guideline was exceeded by five systems, and two of these have exceeded it in 100% of samples, in two separate years each. Eleven systems have exceeded the lead guideline: three have exceeded it in 100% of samples in at least 1 year, and one did so in more than 1 year. Lead exceedances have occurred in 0–2 years per system, with the exception that system 18 exceeded the lead guideline in 100% of samples in 9 years (Figure 2).

One guideline exceedance does not necessarily represent failure of a particular community system. However, continued exceedances may point to larger issues: lack of financial capacity, remoteness, and policy constraints have been identified as sources of concern in small communities (Kot *et al.* 2011; Murphy *et al.* 2015; Hickel *et al.* 2018). Fragmented water governance may also contribute to poor communication of sampling requirements from federal agencies to individual bands. There are several agencies with overlapping mandates for safe water on reserve: responsibility for water is divided between federal, provincial, and territorial governments (Loë 2017). Misalignment of policies has been shown elsewhere to lead to inconsistencies in Indigenous community water safety (Bradford *et al.* 2017).

While the majority of community water systems did meet the one sample per year guideline on average over the 12-year period, this may not be enough to represent exposure. For example, many lakes experience seasonal stratification (White & Driscoll 1987) which drives seasonal variation in manganese concentrations (Granger *et al.* 2014). That is, a sample collected yearly in January may not be an accurate representation of the source water in July. Seasonally heavy rainfall can also change surface and groundwater quality, with impacts on the concentrations of manganese, arsenic, and even lead (Zaw & Barry 1999; Nienie *et al.* 2017). Water use can also vary seasonally: in general, more water is used in the summer months for recreation and other activities. This may change typical flow rates seen in the distribution system and in premises plumbing (Fullerton *et al.* 2013). Changes in water use can impact lead release (Del Toral *et al.* 2013), as can seasonal variation in distributed water temperature (Masters *et al.* 2016b). Even under controlled conditions, there is large inherent variability in lead release due to semi-random particle detachment (Masters *et al.* 2016a). These and other factors limit the accuracy of exposure estimates based on the current recommended sampling frequency.

Trends over time

Over the study period and the dataset as a whole, the rate of sample collection did not increase. We computed Kendall's τ, by community system and analyte, as metric for the monotonic trend in the number of samples collected per year. Tau ranges from -1 to 1, with positive values indicating positive trends (i.e., more samples collected in later years) and vice versa. Here, 43% of Tau values were positive, 47% were negative, 3% were effectively zero, and 7% were indeterminate because there were insufficient data to compute a value.

While most community systems were universally compliant with most individual guideline concentrations, the rates of elevated contaminant concentrations did not decrease over the study period. We also computed Kendall's τ to detect changes in the rates of compliance with guideline concentrations; most trends (73%) were indeterminate, and this was almost always because samples were all below the relevant guideline concentrations in every year samples were collected. Sixteen percent of the remaining trends were positive (i.e., more guideline exceedances in later years), and 12% were negative.

Here, comparisons of First Nation sampling and regulatory compliance are made against the Health Canada Guidelines for Canadian Drinking Water Quality (Health Canada 2014b). While First Nations are accountable to them, previous studies have shown that there is little-to-no First Nation involvement or consultation on their feasibility and appropriateness (Bradford *et al.* 2017; Castleden *et al.* 2017). Resource and personnel capacity concerns have been raised in several studies: remote location, inadequate funding for sampling programs, high turnover rates, and competition for infrastructure funding within communities have all been reported (McCullough & Farahbakhsh 2012; Jiménez *et al.* 2014; Murphy *et al.* 2015; Bradford *et al.* 2017).

Random daytime sampling

We compared fully flushed samples in the regulatory compliance dataset with random daytime samples collected in a subset of four First Nation community systems (11, 15, 21, and 35). As expected based on previous work (Riblet *et al.* 2019; Locsin *et al.* 2020), random daytime sampling yielded higher lead concentrations in at least some communities. In systems 11, 21, and 35, lead levels were significantly greater as determined by random daytime compared with flushed sampling (according to at least one of the two statistical tests employed). In those systems, lead in flushed samples was an estimated 45, 90, and 100% (Table 2) of lead in random daytime samples (a ratio of 100% is the result of a large fraction of censored observations). There were no significant differences between the two sampling methods in system 15 by either statistical test.

Random daytime samples were collected between January and August, representing predominantly cold-water conditions. These samples stagnated in contact with premises plumbing for, by definition, an unspecified length of time. With long stagnation, they would be expected to reach ambient indoor temperatures, and so, we would expect random daytime sample temperatures to be distributed between flushed cold season and ambient indoor temperatures. Since flushed samples were collected over the year and included both cold-water and warm-water conditions, we assumed that temperature was not a major factor in our analysis. However, it cannot be ruled out as a potential confounder.

In general, manganese and arsenic levels in random daytime samples were not significantly different from those in flushed samples, with two exceptions. In system 21, arsenic levels were significantly greater in flushed samples, but overall levels were low – at most, 1 μg/L – and the difference estimate was not practically significant. In system 35, manganese concentrations were greater in flushed samples by a factor of more than four (Table 2). Manganese levels are strongly seasonal in this water system, with peak levels occurring between August and October. Random daytime samples were collected in June and would, therefore, have missed the seasonal manganese peak.

Comparisons of arsenic and manganese concentrations between random daytime and flushed sampling should be interpreted with care, as seasonality may be an important consideration. Health Canada (2019b) recommends that sampling for manganese be conducted quarterly throughout the year and weekly when manganese is most likely to be elevated. In lakes, this may be during summer thermal stratification and fall turnover. Health Canada (2019b) also recommends that groundwater sources be monitored semi-annually and that all wells in a well field be monitored; there may be large variation in manganese concentrations among wells in close proximity.

Implications for First Nation sampling policies

Indigenous water systems face unique challenges in delivering safe drinking water, and despite targeted programs to

Table 2 | Statistical comparisons between flushed and random daytime samples, by the community water system

Community water system	Element	Generalized Wilcoxon test *p*-value	Signed rank test *p*-value	Ratio difference estimate[a]	95% CI lower bound	95% CI upper bound	N_{flushed}	N_{RDT}
11	Mn	0.505	0.514	0.672	0.233	1.907	68	20
	As	0.488	0.209	1.000	1.000	1.010	68	20
	Pb	<0.001	<0.001	0.448	0.280	0.609	69	20
15	Mn	0.059	0.061	1.000	1.000	1.256	16	10
	As	1	NA	NA	NA	NA	16	10
	Pb	0.923	0.949	1.000	1.000	1.000	16	10
21	Mn	0.404	0.222	1.000	1.000	1.000	47	20
	As	0.002	0.005	1.010	1.000	1.010	47	20
	Pb	0.081	0.004	0.902	0.631	1.000	47	20
35	Mn	<0.001	<0.001	4.905	1.301	14.015	245	15
	As	1	NA	NA	NA	NA	27	15
	Pb	0.017	0.096	1.000	1.000	1.000	28	15

NA, not possible to calculate due to censoring; Pb, lead; Mn, manganese; As, arsenic. [a]Estimates the ratio of population medians: median (flushed)/median (RDT).

improve water quality and services, there has been little progress in the past decade (McCullough & Farahbakhsh 2012; Morrison *et al.* 2015; Murphy *et al.* 2015; Baijius & Patrick 2019; Patrick *et al.* 2019). More evaluation of government policies and programs is needed (McCullough & Farahbakhsh 2012; Baijius & Patrick 2019).

Indigenous communities tend to have small populations and less access to basic amenities than non-Indigenous ones (McCullough & Farahbakhsh 2012). In one study, the proportion of operators with certification decreased with distance from service centers (Murphy *et al.* 2015). Variation in community governance gives rise to a host of local factors affecting water operator retention and the ability to secure funding and complete infrastructure projects (McCullough & Farahbakhsh 2012; Murphy *et al.* 2015). Operators often have more than one role in a community, and currently, no agency exists that can equitably compensate all operators across Indigenous water systems (Murphy *et al.* 2015). There is also a documented lack of funds dedicated to water operations (McCullough & Farahbakhsh 2012; Murphy *et al.* 2015; Bradford *et al.* 2017; Castleden *et al.* 2017). Government, via Chief and Council, funds the current monitoring program in Atlantic Canada, and while it engages community members and has generated a substantial quantity of data, it is not sufficient. The sampling gaps documented here are explained at least in part by a lack of funding, resources, and possibly by a lack of awareness of the health risks these contaminants pose.

An increase in inorganic contaminant sampling will require the collaboration of multiple stakeholders in the Indigenous water sphere: operators and monitors, Chief and Council, provincial and federal government agencies, and the research community. Government needs to devote more effort and funding to sampling that best characterizes inorganic contaminants in Indigenous drinking water. Seasonal variations in contaminant concentrations mean that bi-annual sampling is needed at a minimum (quarterly sampling is recommended). Funding for sample analysis by accredited laboratories is also needed, as is stronger communication between government agencies and Chief and Council. Given the number of competing infrastructure projects typical in Indigenous communities (McCullough & Farahbakhsh 2012; Bradford *et al.* 2017; Castleden *et al.* 2017), the importance of inorganic contaminant monitoring needs to be communicated to Chief and Council to ensure that funding is appropriate. Communicating information on sampling protocols to water monitors is also necessary. For instance, yearly workshops are conducted in the Atlantic region and can serve as a platform for delivering new procedural guidelines.

Finally, the research community can support community-driven contaminant monitoring studies to characterize water quality problems in Indigenous water systems and to understand the shortcomings of sampling procedures. Recent research has documented multiple instances of concerning lead levels in non-Indigenous water systems (Pieper *et al.* 2015b, 2018), but research focus is noticeably lacking in the context of Indigenous communities. The disparate volume of research available on inorganic contaminants in Indigenous and non-Indigenous water systems is further evidence of the unique challenges Indigenous communities face.

CONCLUSION

Sampling programs in the studied water systems are impacted by policy constraints, lack of financial capacity, high staff turnover, and remoteness. And while most lead, arsenic, and manganese concentrations were below their guideline values, sample collection in First Nation community water systems should increase in frequency to fully characterize contaminant occurrence. The suggested one sample per year frequency was not met in 45 community systems for at least 1 year out of the 12 for at least one of the three analytes. Overall, no clear trends in either sampling frequency or the rate of regulatory compliance were observed. Manganese was the contaminant most often above its limit, although the occasional lead and arsenic exceedances are concerning as well. Moreover, since lead monitoring data were collected as flushed samples, these data probably underestimate exposure. Future study characterizing exposure to lead should be conducted using a random daytime (or similar) protocol at multiple locations within each system. Since lead release profiles differ by site (Pieper *et al.* 2015a), the collection of multiple consecutive sample liters would also be beneficial. Policy changes, training initiatives, and better communication will be instrumental in improving understanding of inorganic contaminants in First Nation community systems.

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