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A Review of Private Well Contaminants, Testing, and Mitigation Behaviours in Nova Scotia

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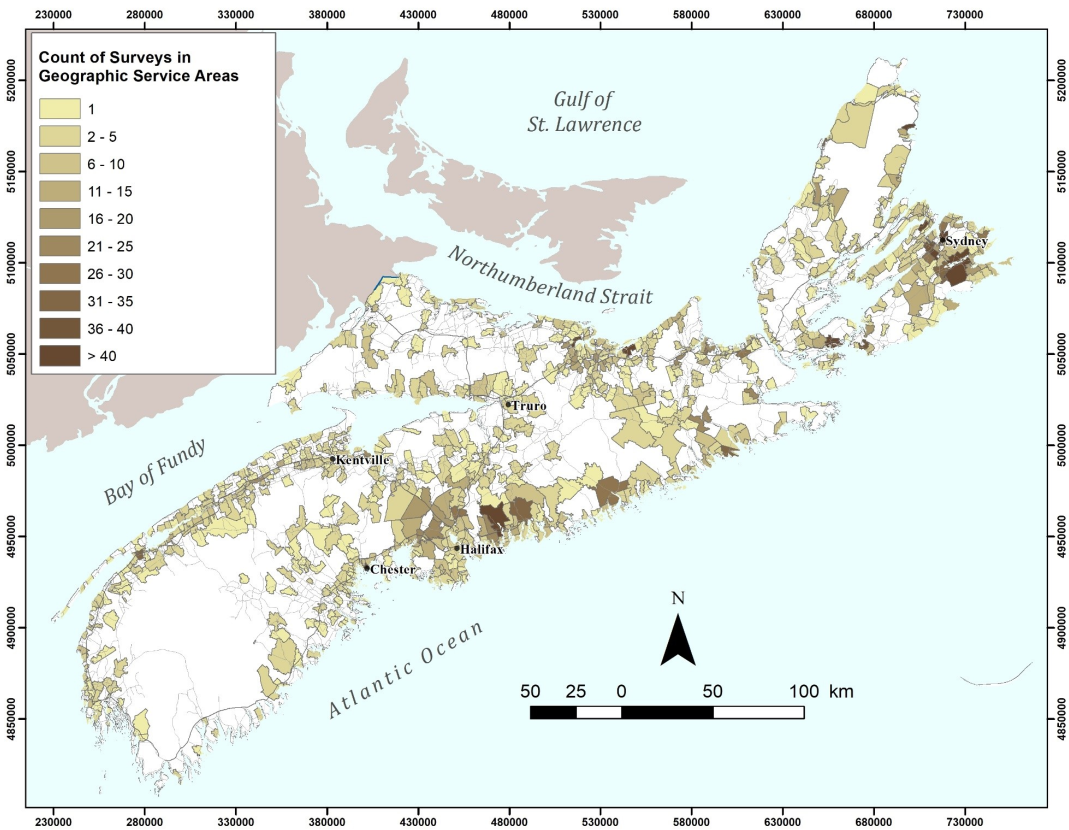

NOVA SCOTIA

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Cover

Count of private wells in Nova Scotia's geographic service areas that have been surveyed during regional well water survey programs (Nova Scotia Department of Transportation and Infrastructure Renewal, unpub. data, 2005-2018; Nova Scotia Environment, unpub. data, 2007-2015; CBCL Limited, 2018).

A Review of Private Well Contaminants, Testing, and Mitigation Behaviours in Nova Scotia

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Abstract

Nova Scotia has a high reliance on privately owned wells for domestic water (>40%). Well owners are responsible for monitoring the drinking water quality of their well water and ensuring that it is safe to drink. Various contaminants, both naturally occurring (e.g. Mn, As, U) and anthropogenic (e.g. nitrate, bacteria), are common in groundwater supplying the province's private wells. Based on the available evidence, it is estimated that one third of private wells in Nova Scotia have a health-based exceedance of one or more chemical contaminants in their untreated water and that about 25 to 40% of private wells may have total coliform in their drinking water. Epidemiological studies have shown that the province's private well users tend to have an elevated body burden of metals such as lead, arsenic, and uranium relative to municipal water users, and exposure to contaminants in private well water is associated with a range of adverse health effects.

Analysis of data collected during various private well surveys in Nova Scotia showed that there is poor adherence to the province's recommended frequency for water testing. It is estimated that over 50% of the province's private well owners have never tested, or can't recall testing, the chemical quality of their well water, compared with 23% for bacteriological quality. Analysis of the survey data also indicates that there are multiple important barriers to testing, such as procrastination, cost, inconvenience, and a lack of knowledge or awareness. Strategies for improving the safety of drinking water from private wells should target a specific audience and consider how barriers or motivations to well stewardship may vary with population characteristics and geography. The development of effective strategies to improve the safety of private well water would have a beneficial impact on the health of the province's private well owners, while lowering associated costs to the health care system.

Introduction

Kennedy and Polegato (2017) estimated that about 42% of Nova Scotians rely on private wells for their domestic water source. Private water supplies in Nova Scotia mainly consist of drilled wells in fractured bedrock aquifers. A smaller proportion of supplies consists of either shallow drilled-wells that are installed in surficial aquifers, or dug wells that are typically constructed in thin, low- to moderate-permeability tills. It is the responsibility of Nova Scotia's private water supply owners to ensure that the water is safe to drink and to mitigate any potential health risks associated with their drinking water.

Over the past 45 years, various studies have characterized the occurrence of contaminants in Nova Scotia private well water (i.e. privately owned household domestic water wells) (e.g. Grantham and Jones, 1977; Grantham, 1986; Moerman and Briggins, 1994; Kennedy and Drage; 2017; Kennedy, 2019; Kennedy and Drage, 2020). The distribution of these contaminants in the province's groundwater has primarily been related to bedrock geology and to hydrogeological and land-use controls (Nova Scotia Environment, 2012; Kennedy and Drage, 2017; Kennedy and Drage, 2020). Groundwater contaminants such as arsenic, uranium and manganese occur naturally in the province's aquifers, while other contaminants such as nitrate and pathogens are both naturally occurring and associated with human activities. The occurrence of some metals, such as lead and copper, in private well drinking water is related to the chemistry of the source water and the availability of these metals in premise (e.g. household) plumbing system components.

Evidence has shown that well water testing is a critical determinant in motivating some private well owners to take action to reduce their exposure to contaminants (e.g. Severtson et al., 2006; Flanagan et al., 2015a). Well owners that are unaware of well water quality problems are less likely to implement treatment or other mitigative behaviours. In central Maine, researchers discovered that the magnitude of the exceedance of the arsenic limit was a significant predictor of mitigative action (Flanagan et al., 2015a). Several private well surveys have published information on testing rates in Nova Scotia and, in some cases, information on barriers to well water testing (e.g. McCamon, 2014; Chappells et al., 2015). Various other private well surveys conducted in the province have collected this type of information but did not report on the data. The evidence suggests that most private well owners do not routinely test their well water according to the Province's recommendation of twice per year for bacteriological quality and once every two years for chemical quality, or sooner if a noticeable change in water quality is observed (McCamon, 2014; Chappells et al., 2015).

A chemical test by a private well owner in Nova Scotia typically involves the laboratory analysis of a drinking water sample for a suite of general water chemistry parameters and metals, whereas a bacteriological test typically involves testing the water sample for the presence/absence of total coliform and *E. coli* bacteria. The Province recommends routine testing because 1) well water quality can be highly variable and regular testing is important for establishing baseline/representative groundwater quality; 2) the performance of treatment systems, if present, need to be periodically assessed; and 3) the safe limit of water quality parameters are periodically reviewed by Health Canada and, where justified, lowered according to the latest toxicological and epidemiological evidence.

There is a poor understanding of the barriers to mitigating unsafe levels of contaminants in private wells in Nova Scotia. Well water treatment solutions can be complex, but in most cases, conventional, affordable treatment for the typical contaminants found in Nova Scotia well water is available. In Maine, a lack of concern about arsenic in their well water and the cost of installing a treatment system were reported to be significant barriers to implementing protective behaviours amongst the survey participants that had been notified of elevated arsenic in their drinking water (Flanagan et al. 2015a).

The preventable health care costs associated with exposure to contaminants in private well drinking water have not been quantified, in part due to the complexity of correlating health outcomes with private well contaminant exposures. The correlation of disease to exposure to contaminants in private wells may be complex due to factors such as 1) the range of potential adverse health effects, 2) the potential additive or synergistic effect of multiple contaminants on health, 3) the difficulty in measuring the non-acute health effects of persistent exposures to low concentrations of contaminants, 4) underreporting of illnesses, 5) the confounding effect of other lifestyle behaviours, such as smoking, and 6) variability in lifetime exposure due to behavioural change (e.g. Postma et al., 2011; Saint-Jacques et al., 2014). The relationship between prevention and the treatment of waterborne disease is highlighted in a cost-benefit analysis reported by the World Health Organization (WHO) (2010). The WHO estimates that for every US$1 spent to reduce lead hazards in drinking water in the United States, there is a benefit of US$17 to US$220.

The objectives of the current study are to summarize available information related to the exposure of the province's private well users to common contaminants occurring in their drinking water, epidemiological studies related to these exposures, well testing rates and mitigative behaviours, and the province's current risk-management approach.

Reliance on Private Wells in Nova Scotia

Kennedy and Polegato (2017) estimated that there are over 197,000 private wells in Nova Scotia, which represents about 42% of all domestic water use in the province. This estimate assumes that all private water-supply sources are from wells, although there is a small percentage (<5%) of Nova Scotians that use alternative sources for their private water supplies, such as surface water (e.g. lakes), springs, and rainwater cisterns. The use of these alternative water supplies is not tracked by the Province.

Based on an analysis of the proportion of drilled wells compared to dug wells in the Nova Scotia Well Logs Database (Kennedy and Fisher, 2018), it is estimated that about 90% of the province's private well users rely on bedrock aquifers, while the remaining 10% obtain their groundwater supply from surficial wells (e.g. dug wells or shallow drilled wells in surficial aquifers). It should be noted, however, that dug wells are underreported in the well logs database relative to drilled wells and thus the percentage of private well users relying on surficial aquifers may be significantly underestimated. Analysis of compiled available private well survey information collected by the Province (2005–2018, Fig. 1) suggests that there may be a higher proportion of dug wells (30–40%, n=4003) than indicated in the well logs database (Nova Scotia Department of Transportation and Infrastructure Renewal, unpub. data, 2005–2018; Nova Scotia Environment, unpub. data, 2007–2015; CBCL Limited, 2018[1]). These surveys, however, tend to be concentrated in older, more rural areas of Nova Scotia, whereas newer suburban subdivisions tend to rely more heavily on drilled wells. The highest density of private well usage is observed in areas surrounding population centres, such as the cities of Halifax and Sydney (Fig. 2).

The reliance on private wells for domestic water is about four times greater in Nova Scotia relative to the Canadian average (Fig. 3) (Statistics Canada, 2019). Other Atlantic provinces, such as Prince Edward Island (44%) and New Brunswick (45%) also have a greater reliance on private wells compared to the national average. According to Statistics Canada (2019), New Brunswick has the highest percentage of domestic water use from private wells (non-municipal water) in Canada, whereas Alberta and British Columbia have the lowest (7%). It is not clear why there exists a greater reliance on private wells in the Atlantic provinces, but this trend may be related to older settlement

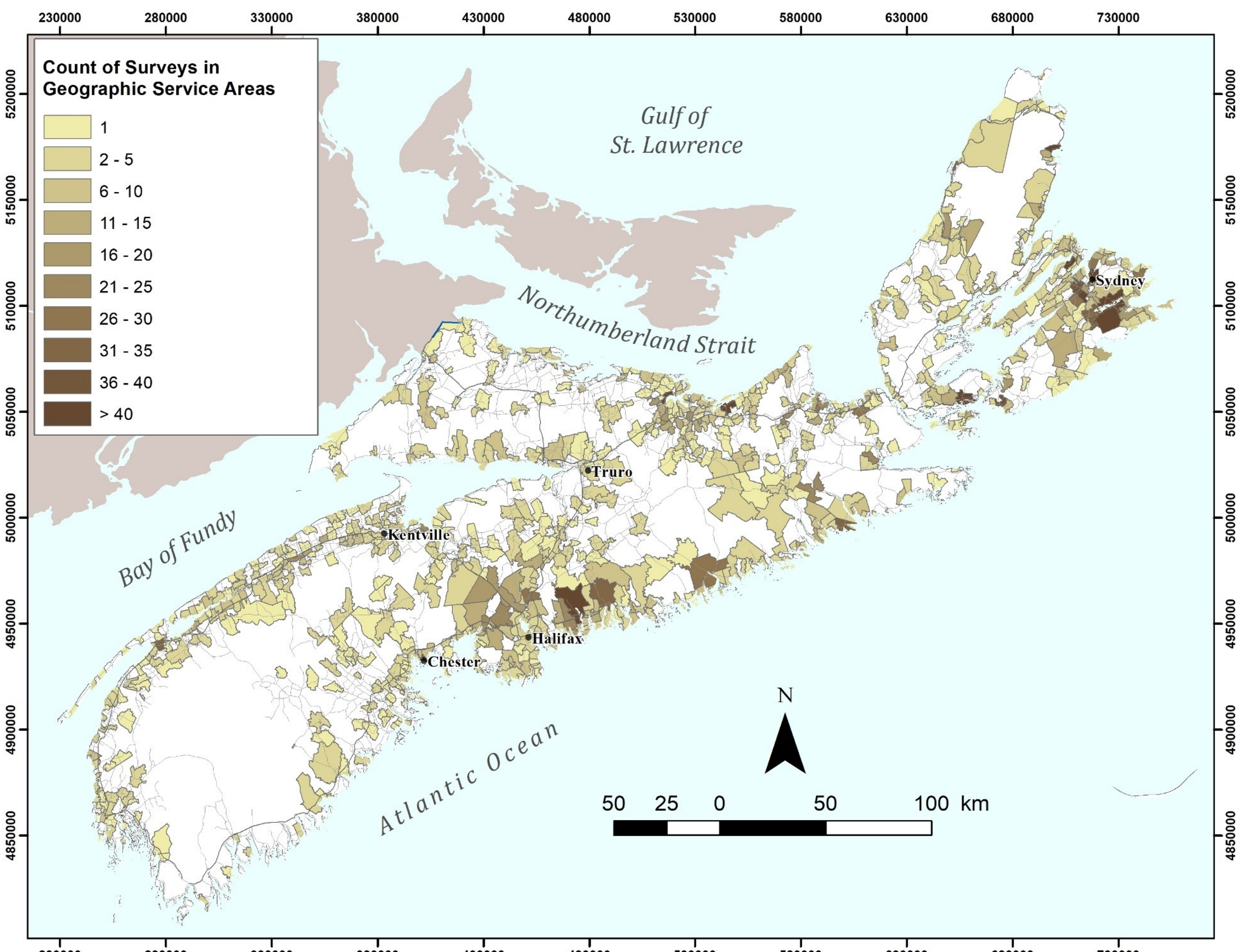


Figure 1. Count of private wells in Nova Scotia's geographic service areas that have been surveyed during regional well water survey programs (Nova Scotia Department of Transportation and Infrastructure Renewal, unpub. data, 2005-2018; Nova Scotia Environment, unpub. data, 2007-2015; CBCL Limited, 2018).

[1]CBCL Limited, 2018. Preliminary Groundwater Supply Assessment, Village of Chester Central Water System: Needs Assessment and Options Analysis – Final Report, CBCL Limited, August, 2017; 49 p.

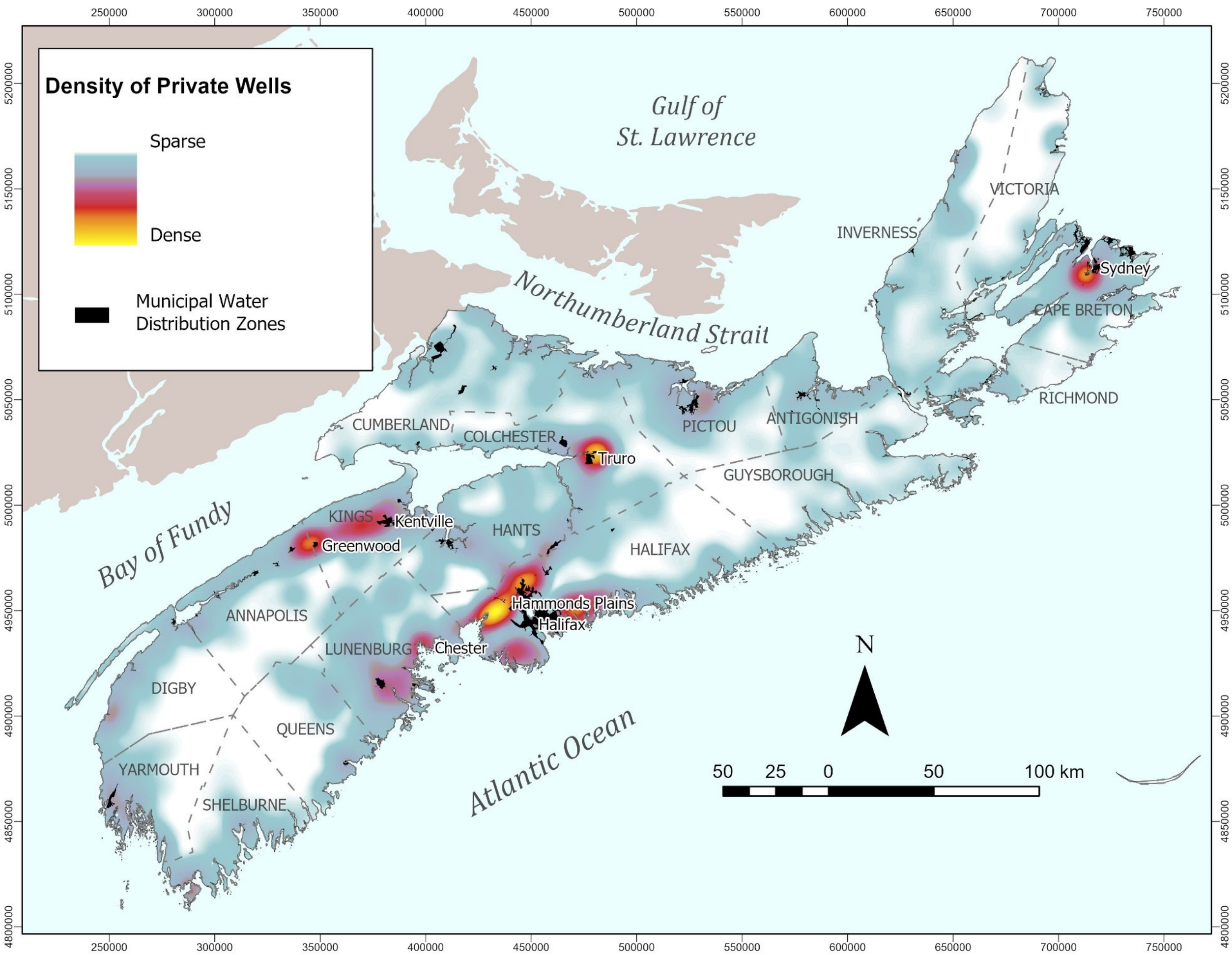


Figure 2. Relative density of private wells in Nova Scotia (after Kennedy and Polegato, 2017).

patterns and ages, lower population density, lower availability of high-volume water sources (e.g. large lake or groundwater systems), or the greater cost of installing water supply infrastructure where bedrock often occurs near the surface.

Exposure to Naturally Occurring Contaminants

A number of studies in Nova Scotia have investigated the exposure of private well users to anthropogenic and naturally occurring contaminants in groundwater (e.g. Cross, 1975; Grantham and Jones, 1977; Grantham, 1986; Moerman and Briggins, 1994, Kennedy and Drage; 2017; Kennedy, 2019; Kennedy and Drage, 2020). Most of these studies have focused on naturally occurring contaminants associated with bedrock geology, such as arsenic and uranium, or contaminants associated with anthropogenic sources, such as nitrate (e.g. fertilizer application), bacteria (e.g. on-site sewage disposal systems), and road salt. Vulnerable populations, such as fetuses, infants and children, are often most at risk to well water contaminant exposures.

Chemical

The most recent assessment of arsenic exposure in Nova Scotia (Kennedy and Drage, 2017) indicates that as many as 20% of private wells in the province may have arsenic exceeding the current Health Canada (2006) maximum acceptable concentration (MAC) of 10 µg/L in their raw (i.e. untreated) well

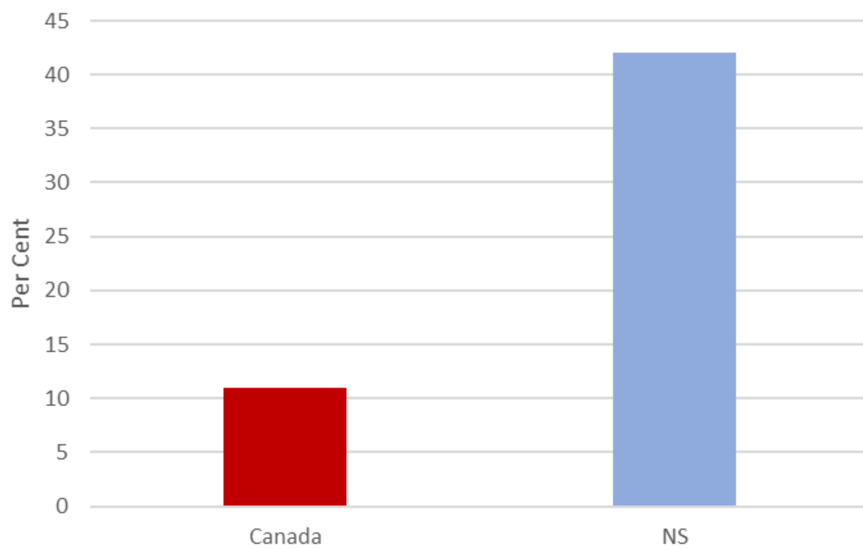


Figure 3. Comparison of the reliance on private wells (dwelling main source of water is a private well) for drinking water between Canada and Nova Scotia based on the results of the Household and Environment Census 2017 Survey (Statistics Canada, 2019).

water (Table 1, Fig. 4). Arsenic is a Class I human carcinogen and has been associated with an increased incidence of skin, lung, kidney, bladder, and liver cancers (Hughes et al., 2011; Saint Jacques et al., 2014). Based on the province's delineation of risk zones (Kennedy and Drage, 2017), it is estimated that 37% of private wells are located in a high-risk zone for arsenic in well water (Table 1).

The most recent exposure assessment and risk map for uranium (Kennedy and Drage, 2020) shows that about 6.5% of private wells may exceed the Health Canada MAC for uranium and about 13% of private wells are located in a high-risk zone for uranium (Table 1, Fig. 4). Ingestion of uranium in drinking water is primarily associated with impaired kidney function (Health Canada, 2019a).

Historically, manganese in well water has been considered an aesthetic concern; however, in 2019 Health Canada established a new health-based guideline for manganese based on emerging toxicological and epidemiological evidence (Health Canada, 2019b). Exposure to elevated concentrations of manganese in drinking water can cause neurological and behavioural effects, especially in infants. To date, a province-wide risk evaluation has not been conducted; however, based on the distribution of manganese in the province's bedrock groundwater regions (Kennedy, 2019), it is estimated that 29% of private wells may exceed the new MAC (Table 1, Fig. 4), ranking manganese as the most widespread contaminant in Nova Scotia well water.

Table 1. Estimated per cent of private wells exceeding the Health Canada (2019e) Maximum Acceptable Concentration (MAC) for various common chemical contaminants. These estimates assume that 91% of private wells are drilled wells in bedrock aquifers and 9% of private wells are constructed in surficial aquifers.

Chemical contaminant	Health Canada MAC	Estimated per cent of private wells exceeding MAC in raw water	Estimated per cent of private wells in the highest risk zone
Manganese	120 µg/L	29% (57,245 wells)	-
Arsenic	10 µg/L	20% (39,479 wells)	37% (73,036 wells)
Lead	5 µg/L	10% (19,740 wells)	56% (110,541 wells)
Uranium	20 µg/L	6.5% (12,831 wells)	13% (25,661 wells)
Fluoride	1.5 mg/L	2% (3948 wells)	-

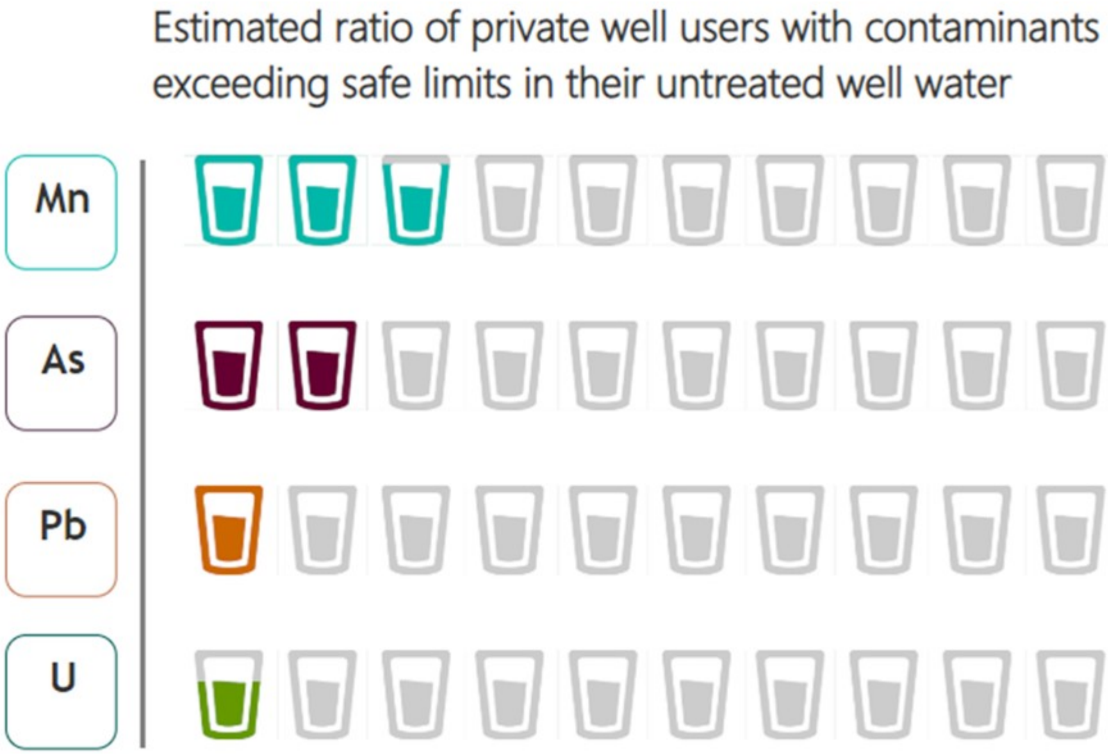


Figure 4. Comparison of exceedance rates for Mn, As, Pb and U. For example, it is estimated that about three out every ten wells may have unsafe levels of manganese in untreated drinking water.

Lead in drinking water is also a common health concern in Nova Scotia. The prevalence of thin tills, weakly alkaline rocks, and short groundwater flow-paths in Nova Scotia contribute to an elevated risk of having corrosive groundwater throughout most of the province (Kennedy, 2019). Corrosive groundwater can result in elevated levels of lead and other metals, such as copper, in private well water supplies due to leaching of these metals from plumbing system components. An evaluation of the potential corrosivity of groundwater showed that 111,100 private wells (56%) are supplied by aquifers that are considered high risk for potentially corrosive groundwater (Kennedy, 2019) (Table 1). Lead in drinking water is associated with a range of adverse health effects, including neurological effects in children and cardiovascular and kidney effects in adults (Health Canada, 2019c). Based on the distribution of observed exceedances of lead in the province's groundwater regions, it is estimated that about 10% of private wells may exceed the Health Canada (2019c) MAC, which was lowered from 10 to 5 µg/L in 2019 (Table 1, Fig. 4). Copper also has a health-based guideline (2000 µg/L) (Health Canada, 2019d); however, the copper MAC is much higher than the lead MAC, and therefore copper seldom exceeds the Health Canada guideline compared to lead.

Fluoride is another naturally occurring contaminant in groundwater and is associated with certain types of minerals that occur primarily in granitoid rocks (Kennedy and Finlayson-Bourque, 2011). It is estimated that less than 2% of private wells in Nova Scotia may have fluoride exceeding the Health Canada (2010) MAC of 1.5 mg/L (Table 1). Fluoride may also be elevated in some naturally softened waters in sedimentary rocks.

Groundwater quality issues with respect to nitrate in Nova Scotia well water tend to be in areas with intensive agricultural land-use due to the use of agricultural fertilizers and manures. Nitrate levels greater than 10 mg/L can be toxic to human babies, and infants six months or younger who are fed water, or formula made with water, that contains a high concentration of nitrate can develop methaemoglobinaemia (blue baby syndrome) (Health Canada, 2013). The issue of nitrate in water wells in Nova Scotia emerged in the early 1970s based on the random sampling of 50 domestic wells by the

Province in Kings County, a fertile agricultural region (Thomas, 1974). A subsequent study, which involved the sampling of over 350 water wells in the county from 1973 to 1974, revealed that about 25% of the wells exceeded 10 mg/L of nitrogen (as NO_3) (Table 2) (Thomas, 1974). Long-term monitoring of nitrate levels in approximately 150 randomly selected private wells on farms in Kings County was later conducted by the Province between 1989 and 2011 (Nova Scotia Environment, 2012). This monitoring showed that exceedances of the Health Canada (2013) nitrate MAC generally ranged from 15% to 25% (Nova Scotia Environment, 2012) (Table 2).

In comparison, the Clean Annapolis River Project (CARP) conducted a survey of private wells from 2012 to 2014 in western areas of the province, including Kings County. The project reported that 80% of the wells tested had detectable concentrations of nitrate, but none exceeded the Health Canada (2013) MAC (n=148) (McCamon, 2014) (Table 2). The objective of the Clean Annapolis River Project 'Rural H_20 Water Guardians' initiative was to provide outreach and education for homeowners with wells and septic systems. In 2004, a rural private well water quality program in Kings, Hants, and Colchester counties conducted by the Women's Institute of Nova Scotia (WINS), with funding from the province, observed that about 4% of the wells tested exceeded the nitrate MAC (n=75) (Nova Scotia Environment, unpub. data, 2006). An older study by McLeod and Fulton (1985) recorded some of the highest exceedance rates of nitrate in well water, with 7% of wells province-wide exceeding the nitrate MAC (n=3594), and a much higher percentage of wells exceeding the MAC in agricultural areas (e.g. 29% in Kings County). The authors noted, however, that the study was biased towards the sampling of problem wells.

Pesticide occurrence in private wells on farms has also been investigated in Kings County, which, as mentioned earlier, is one of the most intensively farmed areas of Nova Scotia. Three pesticide surveys were conducted in the county by the Province of Nova Scotia between 1989 and 2008 (Moerman and Briggins, 1994; Nova Scotia Environment, unpub. data, 2000, 2008) (Table 3). All three surveys had similar findings, indicating that pesticides were frequently detected (22% to 71%) in wells at low concentrations (<3 µg/L), and that Atrazine was the most commonly detectable pesticide. None of the surveys found pesticides at concentrations exceeding their drinking water MACs.

Various studies have documented well water quality impacts to private wells in Nova Scotia due to seawater intrusion and road salt application (Cross, 1975; Briggins and Cross, 1995; Kennedy, 2012; Drage et al., 2016). Briggins and Cross (1995) reported that there were approximately 30 to 40 Nova Scotia Department of Environment investigations per year into cases of salt-contaminated private wells associated with road de-icing activities (e.g. salt storage and de-icing of provincially owned roads and highways). According to Health Canada (2019e), both sodium and chloride are aesthetic concerns in drinking water (taste and odour), but sodium in drinking water can be a health concern for individuals on low-sodium diets due to hypertension. Chloride can also mobilize heavy metals in aquifers, exacerbating

Table 2. Estimated per cent of private wells with nitrate exceeding the Health Canada (2014) MAC for various surveys.

Area	Number of wells	Estimated per cent of private wells with nitrate > 10 mg/L	Date	Source
Kings County	359	25%	1973-1974	Thomas (1974)
All Nova Scotia	3594	7%	<1985	McLeod and Fulton (1985)
Kings County	150	15-25%	1989-2011	University of Cape Breton (Nova Scotia Department of Health, unpub. data, 2006)
Kings, Hants and Colchester Counties	75	4.0%	2004	WINS (Nova Scotia Environment, unpub. Data, 2006)
Kings, Annapolis, Digby and Yarmouth Counties	148	0.0%	2012-2014	McCamon (2014)

impacts from naturally occurring contaminants (e.g. Bäckström et al., 2004; Drage and Kennedy, 2013). At a more local scale, point sources of other types of groundwater contamination, such as perchloroethylene (e.g. Village of Greenwood, Village of Hammonds Plains), have affected small numbers of private wells in the province.

Bacteriological

Various factors, such as the hydrogeological setting, the integrity of on-site wastewater systems and land-use, can affect the bacteriological quality of groundwater. The presence of coliform bacteria in well water is indicative of insufficient natural filtration or poor well construction (Moerman and Briggins, 1994), and a greater risk of contracting gastrointestinal illnesses. A recent guideline technical review by Health Canada (2019f) for enteric viruses reported that water wells that are more susceptible to bacteriological contamination may also be at greater risk of being impacted by other waterborne pathogens, such as protozoa and viruses.

A study was conducted from 1999–2004 by the University of Cape Breton and government partners to investigate both the prevalence of, and important risk factors associated with, total coliform and *E. coli* contamination in private wells. The study involved a review of approximately 6000 bacteria samples submitted to two provincial laboratories on Cape Breton Island over the five-year period (Table 4) (Nova Scotia Department of Health, unpub. data, 2006). It was discovered that almost 40% of all wells tested had coliform bacteria present, and 14% of the samples tested positive for *E. coli*.

In comparison, a study from 1989–1994 in Kings County, reported that coliform bacteria was detected in 24.5% of the wells tested (Table 4) (n=102) (Moerman and Briggins, 1994), and the rural private well water quality program conducted by the Women's Institute of Nova Scotia (WINS) reported that 33% of wells tested had total coliform and 3% had *E. Coli* (n=75) (Table 4) (Nova Scotia Environment, unpub. data, 2006).

Epidemiological Studies in Nova Scotia

A growing body of evidence supports the linkage between human exposure to contaminants in private well drinking water and a wide range of acute and chronic effects on human health. Epidemiological studies in Nova Scotia have focused mainly on the relationship between exposure to naturally occurring contaminants in bedrock aquifers, such as arsenic and uranium, and human health impacts (Limson Zamora et al., 1998; Saint-Jacques et al., 2014). Many of these studies have also correlated the body burden of contaminants (total amount of contaminant in a person's body) measured in Nova Scotians with private well water exposures (e.g. Cull, 2011; Yu et al., 2013; Sweeney et al., 2017).

Following the detection of arsenic in well water in the community of Waverley in 1976, Hindmarsh et al. (1977) conducted clinical studies and found chronic arsenicalism in the community's population. Approximately 94% of the study participants (n=86) with high arsenic (>100 μg/L) in their well water also had high arsenic in their hair, and approximately 70% of these people exhibited mild symptoms consistent with arsenic poisoning, such as peripheral neuritis. High levels of arsenic (270 to 1460 μg/L) were also detected in 1977 in a cluster of eight drilled wells located in the community of Lower Sackville, with some of the residents reporting symptoms consistent with arsenic poisoning. Records at Nova Scotia Environment indicate that limited hair, blood, urine, and nervous system tests were conducted, although a published account of the clinical findings could not be located.

Under the Atlantic PATH project, Yu et al. (2013) evaluated the relationship between arsenic concentrations in drinking water and toenail clippings among a larger cohort and broader geographic distribution of Nova Scotians (n=960). The study participants came from across the province, although most participants were located near the Halifax and Sydney population centres. A significant relationship was detected between drinking water and toenail arsenic concentrations among the participants with levels of arsenic ≥1 μg/L in their drinking water. The study concluded that arsenic

Table 3. Summary of results from pesticide surveys of wells in Kings County.

				Atrazine results (μg/L) (drinking water MAC=5 μg/L)				
Date	Number of wells	Per cent of wells with pesticides detected	Per cent of wells with pesticides above MAC	Detection limit	Number of wells with detects	Max.	Mean	Source
1989	102	41%	0%	0.02	29	1.97	0.21	Moerman and Briggins (1994)
2000	27	22%	0%	0.2	4	1.9	0.1	Nova Scotia Environment (unpub. data, 2000)
2008	24	71%	0%	0.05	14	2.32	0.22	Nova Scotia Environment (unpub. data, 2008)

Table 4. Estimated per cent of private wells with total coliform or E. Coli detected for various surveys.

Area	Number of wells	Estimated per cent of private wells with Total Coliform	Estimated per cent of private wells with *E. coli*	Date	Source
Kings County	102	24.5%	-	1989-1994	Moerman and Briggins (1994)
Cape Breton	6000	40.0%	14.0%	1999-2004	University of Cape Breton (Nova Scotia Department of Health, unpub. data, 2006)
Kings, Hants and Colchester Counties	75	33.0%	3.0%	2004	WINS (Nova Scotia Environment, unpub. data, 2006)
Kings, Annapolis, Digby and Yarmouth Counties	183	30.6%	6.0%	2012-2014	McCamon (2014)

ingested in the drinking water of private wells is the most important contributor to arsenic body burden. Similarly, a joint study by researchers at Health Canada and Acadia University of 108 households in the communities of Hubbards and Fall River, two rural communities reliant on private well water in areas known to be associated with elevated concentrations of arsenic, showed that arsenic levels in toenail and hair samples were related to arsenic in well water (Cull, 2011). Epidemiological modelling by Saint-Jacques et al. (2014) showed that an increased risk of bladder cancer, and potentially kidney cancer, was associated with exposure to arsenic in private well water in Nova Scotia, even at low levels (<5 µg/L). Age-standardized incidence rates of bladder and kidney cancer in Nova Scotia are 4 to 14% and 28 to 46% greater, respectively, compared to the national average (Canadian Cancer Statistics Advisory Committee, 2019).

Similar to arsenic, the issue of uranium in well water in Nova Scotia emerged in the late 1970's during a study by Dalhousie University on the concentrations of various heavy metals in the general population (Moss et al., 1983). Elevated levels of uranium were found in random hair samples of a subject in Harrietsfield relative to levels found in other subjects. Following this discovery, members of the community of New Ross, which was known to have elevated well water concentrations of uranium, were recruited for a study on drinking water exposure and urinary concentrations of the metal (Moss et al., 1983). Two subsequent studies on the toxicological effects of uranium ingestion from drinking water (Limson Zamora et al., 1998) and gastrointestinal uranium uptake from water and food (Limson Zamora et al., 2002) were conducted in the community. These two studies showed that impaired kidney function was associated with chronic ingestion of uranium in drinking water and contributed evidence towards the establishment of the current Health Canada (2019a) MAC (20 µg/L).

A recent study by Sweeney et al. (2017) of lead in drinking water sources across Nova Scotia, also under the Atlantic PATH project, showed greater than two times higher average concentrations of lead in private well water compared to municipal water, and detected a significant correlation between lead body burden (as measured in toenails) and lead in drinking water.

Based on the analysis presented in Murphy et al. (2016), it is estimated that there are 7290 projected cases of acute gastrointestinal illness every year in Nova Scotia (range of 3591 and 11,963, 90% probability interval) due to exposure to *Giardia*, *Cryptosporidium*, *Campylobacter*, *E. coli* O157, or norovirus in private well drinking water.

Well Water Testing Rates

As outlined previously, there are various potential sources of contamination in well water in Nova Scotia. Well water quality testing is critical to understanding whether well water is safe for drinking, and what mitigation measures may be necessary to make well water safe. Many well owners, however, have never tested their well water, especially the chemical quality, or do not test their water in accordance with the province's recommended frequency.

To date, there has not been a comprehensive provincial survey of bacteriological and chemical well water testing rates across Nova Scotia, but there has been a large scientific survey of arsenic testing rates in five areas of the province (Chappells et al., 2015). In addition, Statistics Canada (2019) reports on whether non-municipal water users have conducted a test in the last 12 months as part of their Household and Environment census survey, which is administered every 2 years. There are various other existing sources of private well survey data in Nova Scotia that were compiled and evaluated for this study, as described below, to provide insight into well testing rates and behaviours in the province.

According to the most recently published 2017 Household and Environment census results (Statistics Canada, 2019), about 17% of Nova Scotia respondents had a test (chemical or bacteriological) completed in the last 12 months, which is below the national average for non-municipal water supply testing (Fig. 5). There is no evident trend with respect to the sampling rate over the period of 2009 to 2017, which ranged from 14% to 23% (Fig. 6).

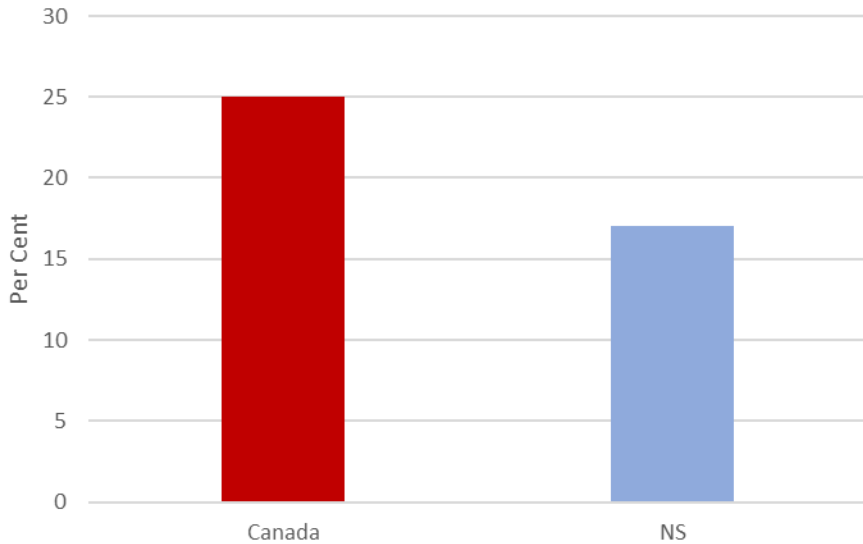


Figure 5. Comparison of the per cent of non-municipal water supplies in Canada and Nova Scotia testing their drinking water (chemical or bacteriological test in the last 12 months) based on the results of the Household and Environment Census 2017 Survey (Statistics Canada, 2019).

The survey of arsenic testing rates in Nova Scotia, conducted under the Atlantic PATH project, represents the most rigorous published analysis of testing rates and behaviours in the province (Chappells et al., 2015). The survey assessed risk behaviours amongst a total of 420 private well owners in five separate areas of Nova Scotia considered to represent a demographic cross-section of the province, although it should be noted that the majority of well owners surveyed were classed as urban residents. About 11% of the survey respondents reported that they routinely test the chemical quality of their private well water according to the provincial recommendation (once very two years). The majority of the survey respondents (62.4%) reported that they irregularly test their water, or only tested their water once (e.g. usually following well construction or during a real estate transaction), whereas 17% of respondents had never tested the chemical quality of their water or did not recall the approximate date of the last test.

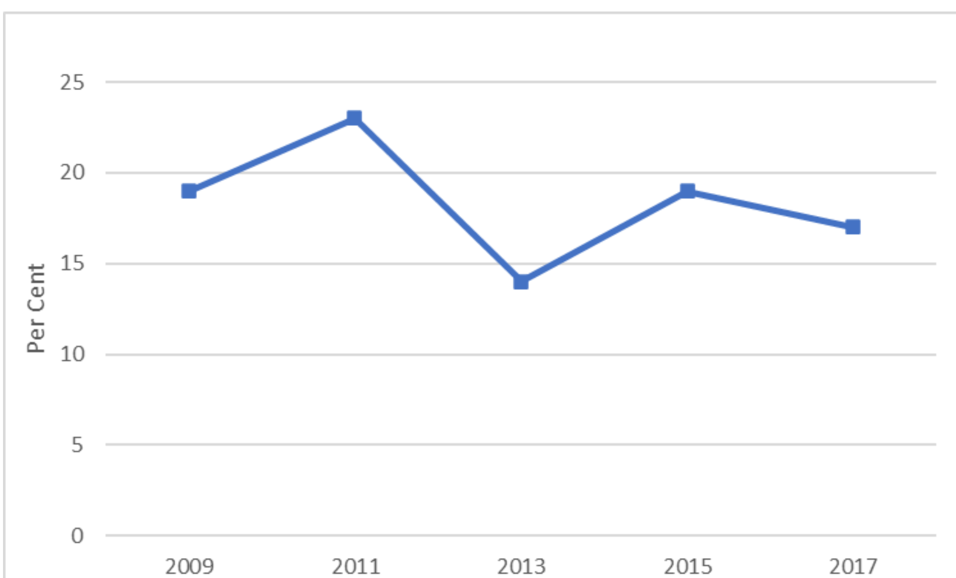
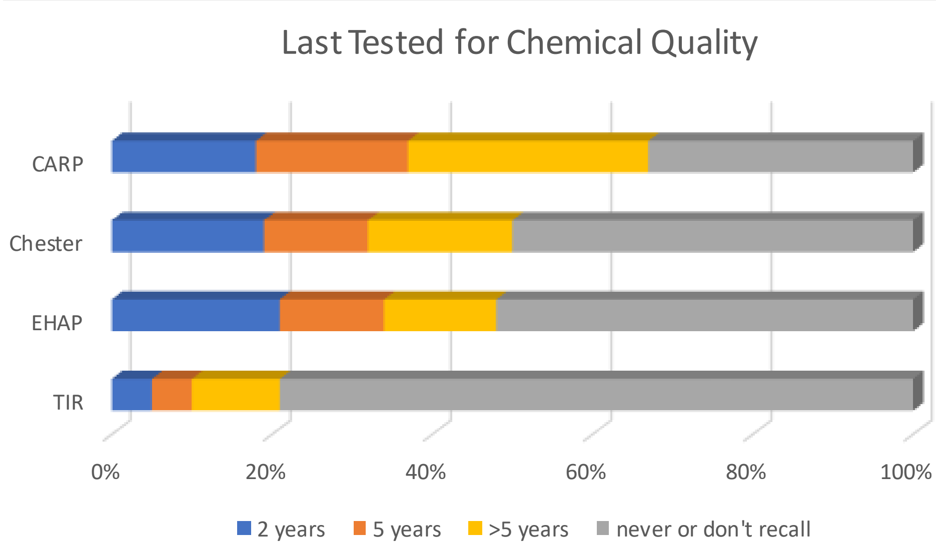


Figure 6. Long-term trend in the rate of laboratory testing (chemical or bacteriological test in the last 12 months) of drinking water from non-municipal water sources in Nova Scotia based on the results of the Household and Environment Census 2017 Survey (Statistics Canada, 2019).

The questionnaire results of the 2012 to 2014 private well survey by the Clean Annapolis River Project (McCamon, 2014) indicated that only 5% of respondents (n=71) adhered to the province's recommended bacteriological testing frequency and that 3% adhered to the province's recommended chemical testing frequency. The majority (57%) of survey respondents had, however, completed a bacteria test within the last five years, whereas only 37% of respondents had completed a chemical test within the last five years (Fig. 7). About 10% of respondents indicated that they had never completed a bacteria test or didn't know whether their water had been tested for bacteriological quality, compared with 33% of respondents for chemical quality (Fig. 7).

A private well water quality survey of over 250 households in the Village of Chester was conducted by CBCL Limited in 2017 (CBCL Limited, 2018). Analysis of the survey data indicates that 45% and 32% of respondents had tested the bacteriological and chemical quality, respectively, of their well water within the last five years (Fig. 7). It should be noted, however, that about a quarter of these respondents (where the water tester was indicated, n=110) had their well water tested by the Municipality in the previous five years as part of government-led water quality surveys. The majority (67%) of well owners did the testing themselves, although in some cases third party water-testing companies, home inspectors,



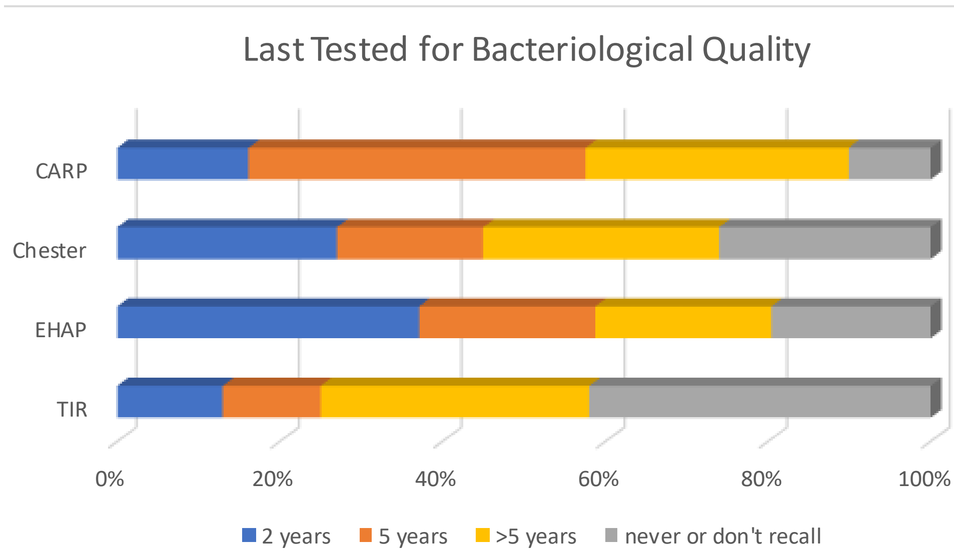


Figure 7. Survey responses regarding when the chemical and bacteriological quality of the water was last tested.

real estate agents, or water treatment suppliers performed the testing. About 26% of survey respondents indicated that they had never tested, or could not recall testing, the bacteriological quality of their well water, compared to 50% for chemical quality (Fig. 7).

As part of the current investigation, unpublished survey data from 2005 to 2018 collected by the Nova Scotia Department of Transportation and Infrastructure Renewal (NSTIR), was compiled and evaluated. These surveys are routinely conducted by NSTIR to document the condition of potable water supplies prior to earthwork activities associated with infrastructure work. Analysis of available pre-construction survey data shows that 79% of respondents had never tested the chemical quality of their water or did not recall having conducted a water test (Fig. 7), which is a significantly higher percentage than was recorded in the other surveys reviewed here. About 42% of surveyed households had never tested, or could not recall testing, the bacteriological quality of their well water. In the previous two years, 13% of the surveyed households had tested for bacteriological quality compared with only 5% having tested for chemical quality. It should be noted that the survey areas tend to be located near existing highway corridors and regional roads, and therefore the NSTIR pre-construction surveys may be capturing older rural residential areas and under-representing newer subdivisions using private wells. Chappells et al. (2015) reported that survey participants in rural areas of Nova Scotia were significantly less likely to have had an arsenic test and more likely to report difficulties in conducting a water test.

In addition to the NSTIR dataset, unpublished data collected by Nova Scotia Environment as part of the Environmental Home Assessment Program (EHAP) from 2007 to 2015 was evaluated. The EHAP was established in 2006 to use education tools and incentives to address drinking water quality in private wells, sewage contamination from failing on-site sewage disposal systems, and oil contamination from heating oil spills. The program provided training and grants to various environmental non-governmental organizations (ENGO's) to conduct community education, the promotion of the EHAP to homeowners, and home visits to well and septic system users throughout the province that had requested an assessment. As part of the home visit, well owners were educated about water well stewardship. Water sample bottles and a voucher worth $100 that could be used towards the cost of a water test were provided to interested homeowners in some years of the program (2012–2015).

The data compiled from this project shows that about 35% (n=3010) of the survey respondents had tested the bacteriological quality of their well water in the previous two years, whereas 19% had tested the chemical quality (Fig. 7). Most survey respondents (57%) had tested bacteria levels in their well water in the previous five years, compared with only 33% of respondents having performed chemical testing. About 52% of the survey respondents had never tested, or could not recall having tested, the chemical quality of their well water (19% for bacteriological testing).

To investigate whether well type was a predictor of well water testing behaviours, the Chester, NSTIR, and EHAP surveys were combined, and the dug and drilled well survey populations were compared for the percentage of respondents that tested for bacteria and chemistry in the last two years and the percentage of respondents that had never tested, or could not recall testing, for bacteria and chemistry (Fig. 7). A two-sample test of proportions showed that significantly ($p<0.05$) more drilled well owners had tested the chemical quality of their well water (n=3688) in the previous two years compared with dug well owners, whereas significantly more dug well owners (n=3687) had tested the bacteriological quality of their well water compared with drilled well owners in the previous two years (Table 5). In general, significantly ($p<0.05$) more private well owners tested for bacteriological quality compared to chemical quality, and dug well owners had the greatest percentage of users that had never tested, or could not recall having tested, the chemical or bacteriological quality of their well water (Table 5).

Barriers to Testing and Mitigative Behaviours

There has been limited research in Nova Scotia on the barriers that constrain actions related to good private well stewardship practices, including routine water well testing and water treatment. Private well stewardship can be complex, and exposure can occur due to a failure to implement the necessary action

Table 5. Comparison of the date of the last well water quality test for both the type of water quality analysis and the type of well using compiled data (i.e. EHAP, Chester, NSTIR datasets).

	Per cent of wells tested within the last two years		Per cent of wells never tested or not known when tested	
Well type	Bacteria	Chemistry	Bacteria	Chemistry
Drilled well	20.4% (n=2433)	19.6% (n=2432)	19.5% (n=2433)	51.9% (n=2432)
Dug well	29.5% (n=1243)	13.6% (n=1256)	27.0% (n=1254)	62.8% (n=1256)

at any given stage of private well stewardship (e.g. water testing, purchase and installation of treatment system, proper maintenance of treatment system) (Zheng and Flanagan, 2017).

Well water testing has been shown to be an important predictor of mitigative behaviours (Flanagan et al., 2015a). Complacency, procrastination, cost, inconvenience, and a lack of knowledge or awareness are commonly cited as barriers to water testing in Nova Scotia (Chappells et al., 2015) and other jurisdictions (e.g. Jones et al., 2006; Hexemer et al., 2008; Roche et al., 2013; Flanagan et al., 2015b). When *E. coli* was found in private wells in a Sydney area subdivision, less than a third of homeowners in the subdivision made an attempt to test their well water despite numerous media releases and encouragement by officials at the Nova Scotia Department of Environment and Labour (Nova Scotia Department of Health, unpub. data, 2006).

Various studies have highlighted the importance of income and education levels as determinants on water testing behaviours (Flanagan et al., 2015b; Flanagan et al., 2016a; Morris et al., 2016; Zheng, 2017; Colley et al., 2019). Well owners at higher education and income levels also tend to benefit disproportionately from testing promotion (Flanagan et al., 2016b). Another commonly cited influence on well testing behaviour is the aesthetic condition of drinking water. Water that does not have any objectionable taste, smell, or colour is more likely to be perceived as safe to drink (Roche et al., 2013; Munene and Hall, 2019).

Chappells et al. (2015) reported that the most important barriers to conducting routine chemical sampling as per the province's recommended frequency was a lack of understanding of why testing is necessary and why they should be concerned about well water quality (total of 41% of respondents), and the inconvenience of testing (23% of respondents). About 16% of respondents cited cost as their primary reason for not testing their well water, but the offer of a free water tests was commonly viewed as helpful in encouraging one-time testing. Chappells et al. (2015) also noted that many survey respondents (35%) welcomed the idea of a home visit offering one-on-one advice, similar to the design of the Environmental Home Assessment Program. The survey data did not show an association between concern over arsenic in well water and the presence of children in a household or other demographic factors. Based on the survey responses, the most difficult aspects of well water testing were 1) determining what to test for and 2) delivering the sample bottles to the lab following a test (Chappells et al., 2015).

The study by the Clean Annapolis River Project (McCamon, 2014) reported that cost was the largest barrier to conducting routine sampling according to the Province's recommended frequency (29–31% of respondents). The inconvenience of testing and remembering to do the testing were also cited as important barriers to more frequent testing. Respondents were less concerned about chemical quality compared with bacteriological quality, with 20% of survey respondents unsure of the importance of chemical testing compared to 12% unsure of the need for bacteriological testing.

During the Province's Environmental Home Assessment Program, follow-up phone surveys were attempted approximately six months following a site visit to check if the well owner had tested their well water. Analysis of the survey data indicates that about 30% of respondents had conducted either a bacteria or chemical test following the site visit. Most of the respondents that had not tested their water indicated that they planned to do it soon (37%), but this answer is likely skewed by the fact that homeowners had been personally visited and wanted to appear responsive to the program. In comparison, about 12% of respondents did not plan to test because they were unconcerned about their water quality (Fig. 8). A large percentage of respondents (22%) suggested that factors relating to the inconvenience of water testing (e.g. too busy, forgot about it, haven't got to it yet) was the reason they had not tested, whereas 11% of respondents cited cost as the main barrier to not having tested (Fig. 8).

There are no data available that assess the barriers to mitigative behaviour (e.g. purchase and installation of treatment systems) following the detection of an exceedance of the Canadian drinking water quality guidelines during well water testing. According to the most recent Statistics Canada (2019) Household and Environment census survey, there is a slightly lower percentage of Nova Scotians that treat their well water compared to the national average, although it should be noted that the survey does not qualify whether the well owner's existing treatment strategy is resulting in the provision of safe water (Fig. 9). Southwestern Nova Scotia experienced severe drought conditions in 2016, resulting in over 1000 private well users (mostly dug wells) experiencing water shortages (Kennedy et al., 2017). In response to the water shortages, the Province made legislative amendments in the fall of 2016 to allow municipalities to provide programs for financing private water supply upgrades. Currently, about 13% of Nova Scotia's 52 municipalities offer a lending program for water supply upgrades, which could be used by municipalities as a mechanism to assist well owners with the financing of water treatment systems.

Risk Management

Risk communication is a critical aspect of the public health risk management of private well water supplies. Studies (e.g. Hexemer et al., 2008; Flanagan et al., 2015a; Morris et al., 2016; Colley et al., 2019) have confirmed that risk knowledge is an important predictor of risk mitigation behaviours, and therefore education and risk communication can encourage well owners to take action to ensure that their drinking water is safe through routine water testing and treatment.

The Province has an important role in monitoring the distribution of anthropogenic and naturally occurring contaminants in the province's aquifers and communicating risk to private well users. For example, risk maps of arsenic and uranium in Nova Scotia well water have been available for over 35 years and were recently updated (Kennedy and Drage, 2017; Kennedy and Drage, 2020). A new risk

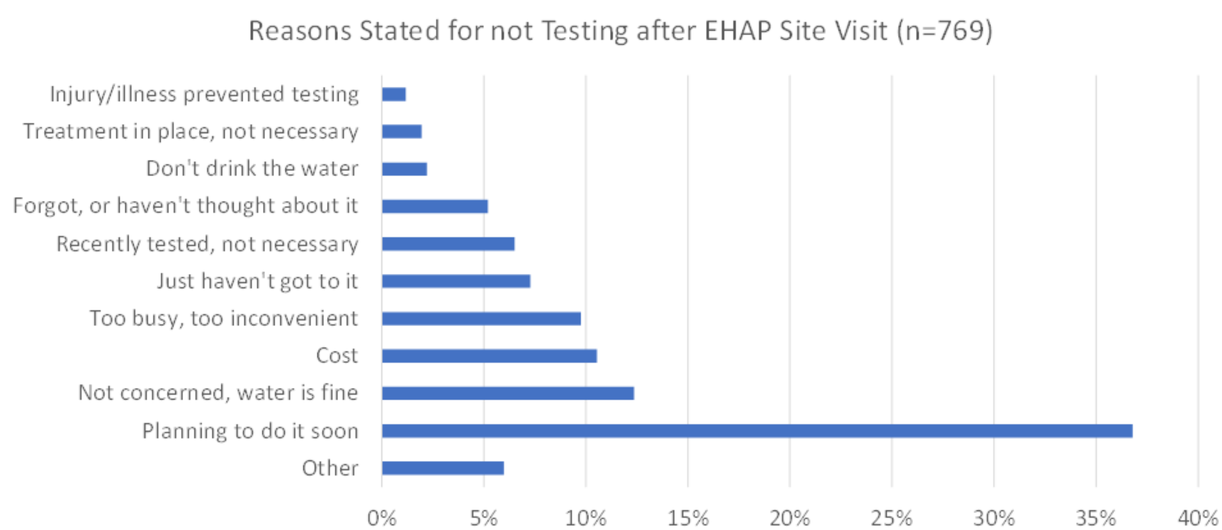


Figure 8. Reasons cited by EHAP survey participants for not testing their well water. The information was collected during a follow-up telephone interview conducted approximately six months following the initial site visit.

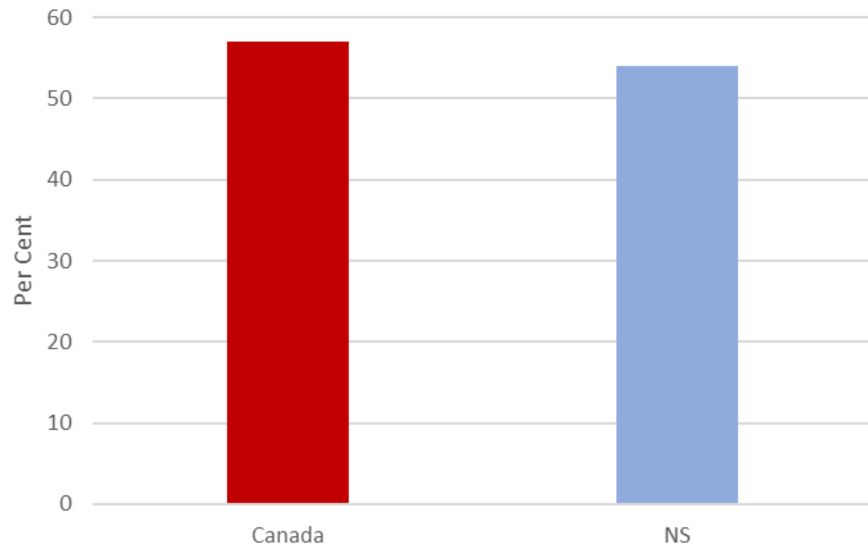


Figure 9. Comparison of per cent non-municipal water supplies in Canada and Nova Scotia treating drinking water prior to consumption based on the results of the Household and Environment Census 2017 Survey (Statistics Canada, 2019).

map was also developed in 2019 that characterizes the relative risk of having corrosive groundwater and therefore indicates which areas of Nova Scotia are at greater risk of lead and other metals, such as copper, being released from plumbing system components (Kennedy, 2019). These maps are published to raise awareness about well water quality risks and to promote routine testing. Other key government channels for risk communication include websites and factsheets. Government information on well water quality in Nova Scotia, however, currently resides with multiple departments, which may create confusion on where to find authoritative advice.

According to the 2014 survey work by Chappells et al. (2015), existing risk communication efforts were largely failing to reach target audiences, and the quality of the information conveyed through formal channels was rated by survey respondents as below average. New, Internet-based, tools have been developed by the Province since the 2014 survey, such as an online tool for interpreting water quality results, where users can enter their laboratory results and the tool will flag any exceedances of drinking water guidelines and provide information on, and recommendations for, treatment (Nova Scotia Environment, undated). Dedicated risk web map applications for arsenic and uranium in bedrock aquifers, and for the corrosivity of groundwater, have also been developed to assist homeowners with understanding their risk profile (Nova Scotia Department of Natural Resources, 2017; Nova Scotia Department of Energy and Mines, 2019, 2020). Public uptake of the tools and information provided by government, however, has not been evaluated, and it is recognized that for some private well users, government websites may not be effective for conveying well water stewardship information. From December 2019 to March 2020 there were an average of 87 visits per month to the Nova Scotia arsenic in well water risk web map and 31 visits per month to the potential corrosivity of groundwater web map.

As discussed previously, the Province has funded various ENGOs in the past to conduct home visits to communicate well water (and wastewater) information directly to well owners. For example, the EHAP operated between 2007 and 2015, offering home assessments by the ENGOs to individual homes served by water wells and on-site septic systems. Between 2007 and 2015, about 6000 assessments were conducted. The ENGOs also led other community education initiatives, such as well water education exhibits at home shows. The EHAP program was designed to be confidential and there were limited measures of the program's effectiveness. Other programs funded by the Province of Nova Scotia to communicate risk directly to well owners via home visits included 'Rural H2O Water Guardians' (McCamon, 2014) and the WINS rural well water quality program (Nova Scotia Environment, unpub. data, 2006). More recently the Province provided seed funding to Rural Water

Watch to assist with well water stewardship promotion in the communities of Shelburne and Lincolnville.

Summary and Discussion

About 40% of Nova Scotians rely on private wells for domestic water (Kennedy and Polegato, 2017), which is significantly higher than the average percentage of households relying on private wells for domestic water across Canada. Private well owners are solely responsible for ensuring that their water is safe to drink and for mitigating any potential health risks, which usually involves water treatment or drinking bottled water.

Naturally occurring contaminants, such as manganese, arsenic, and uranium, are widespread in private well water due to their availability in aquifer materials and the mobility of these contaminants in the province's groundwater systems (Kennedy and Drage, 2017; Kennedy and Drage, 2020). The prevalence of thin tills, weakly alkaline rocks, and short groundwater flow paths in Nova Scotia contribute to lower groundwater alkalinity (carbonate and bicarbonate ions) and pH, which is associated with increased corrosivity of groundwater and therefore an elevated risk of lead and other metals being leached from plumbing system components (Kennedy, 2019). Based on the evidence compiled, it is reasonable to conclude that at least one third of private wells (~65,798 wells or 128,803 persons) in Nova Scotia have a health-based exceedance of one or more chemical contaminants in their raw water.

Available studies (e.g. Moerman and Briggins, 1994; McCamon, 2014) have also shown that bacteriological contamination of private well water is common in Nova Scotia, with surveys indicating that about 25 to 40% of private wells may have total coliform in their drinking water. Most private well water supplies in the province rely on aquifers that are vulnerable to surface contamination due to short groundwater flow paths, such as shallow dug-wells in tills, or drilled wells in fractured bedrock aquifers overlain by shallow tills. Land use can contribute to an elevated risk of well water exposures to bacteria, pesticides, and nitrates (Moerman and Briggins, 1994, Nova Scotia Environment, 2012).

Epidemiological studies have shown that metals such as arsenic, uranium, and lead are present in human biomarkers, such as hair and toenails, and private well users tend to have an elevated body burden of these metals relative to municipal water users (Cull, 2011; Yu et al., 2013; Sweeney et al., 2017). Although epidemiological modelling of the relationship between well water contaminant exposure and disease is complex, elevated rates of some cancers in Nova Scotia have been associated with exposures to contaminants such as arsenic in private well water (e.g. Saint-Jacques et al., 2017). Private well water exposures to pathogenic bacteria, viruses, and protozoa can also significantly affect population health. It is estimated that between 3591 and 11,963 cases of acute gastrointestinal illness in Nova Scotia per year can be attributed to the presence of five pathogens (*Giardia*, *Cryptosporidium*, *Campylobacter*, *E. coli* O157 or norovirus) in private well drinking water (Murphy et al., 2016).

Despite the province's significant reliance on private wells for drinking water and the widespread occurrence of drinking water contaminants in groundwater, private well testing rates in Nova Scotia are lower than the national average and various surveys of private well owners (e.g. CARP, Chester, EHAP, NSTIR) have demonstrated that there is poor adherence to the province's recommended water testing standard. For example, 5 to 21% of survey respondents had tested the chemical quality of their well water in the two years prior to the survey date. Based on a evaluation of all the survey data compiled here, it estimated that over 50% (n=4380) of Nova Scotian private well owners have never tested, or can't recall testing, the chemical quality of their well water, although a wide range is indicated (17 to 79%). In comparison, it is estimated that 23% (n=3960) of private well owners have never tested, or can't recall testing, for bacteriological quality (range of 10 to 42%).

The survey data showed that well owners were more likely to have recently (in the last two years) tested the bacteriological quality of their well water compared to the chemical quality, and dug well owners were more likely to have never tested the bacteriological and chemical quality of their well water compared to drilled well owners. The available survey data also suggests that dug well users are more concerned about the bacteriological quality of their well water, whereas drilled well users are more concerned about the chemical quality of their well water.

The EHAP survey information collected on the barriers to well water testing and mitigative actions in Nova Scotia showed considerable variability. The data suggest that there are multiple important barriers that constrain good well water stewardship behaviours. It is not clear, however, how the importance of these barriers vary by demographic factors (e.g. age, socioeconomic status), social norms, geography, or even well type. In other jurisdictions, income and education have been demonstrated to be significant predictors of appropriate well stewardship behaviours (e.g. Flanagan et al., 2016a; Colley et al., 2019). A better understanding of the motivations and barriers that influence private well stewardship behaviours in Nova Scotia for different population groups would help inform the design of strategies to improve private well water safety.

The inconvenience of water testing was commonly cited as a barrier to following the provincial recommendation for routine water testing. Hexemer et al. (2008) showed that facilitating the ease of sample collection and drop-off doubled water testing rates in a rural community in Ontario. The Nova Scotia Health Authority expanded the network for water chemistry sample bottle collection and drop-off in February of 2019 to include most of the Province's hospitals, which was predicted to reduce barriers associated with the convenience of private well testing. Already, the Health Authority has recorded a greater than 30% increase in water sample submissions from private well owners (Nova Scotia Health Authority, pers. comm., February 2020).

Provincial risk communication efforts currently involve Internet-based tools and information materials (available from multiple departmental websites), but the uptake of these materials is not well understood, and a misalignment of scientific and public risk perception persists. Improved metrics and feedback mechanisms on public usage of government information materials would provide a clearer understanding of whether these materials are effective in communicating the risk of exposure, instructions for well testing, and options for risk mitigation. It is evident from the survey responses that better risk communication is needed as a large percentage of private well users across the surveys showed a poor level of risk knowledge. Chappells et al. (2015) recommended using local knowledge brokers and existing community-based networks to deliver risk messaging, combined with improved supports for well water testing. To more effectively stimulate behavioral change, Morris et al. (2016) highlighted the importance of understanding the target audience and employing multiple strategies designed to address the motivations and barriers specific to each audience.

The safety of private well drinking water in Nova Scotia remains a significant public health challenge and the development of effective private well stewardship tools, programs, and interventions would benefit the health of private well owners and reduce the associated costs to the provincial health care system.

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