GEOSCIENCE AND MINES BRANCH

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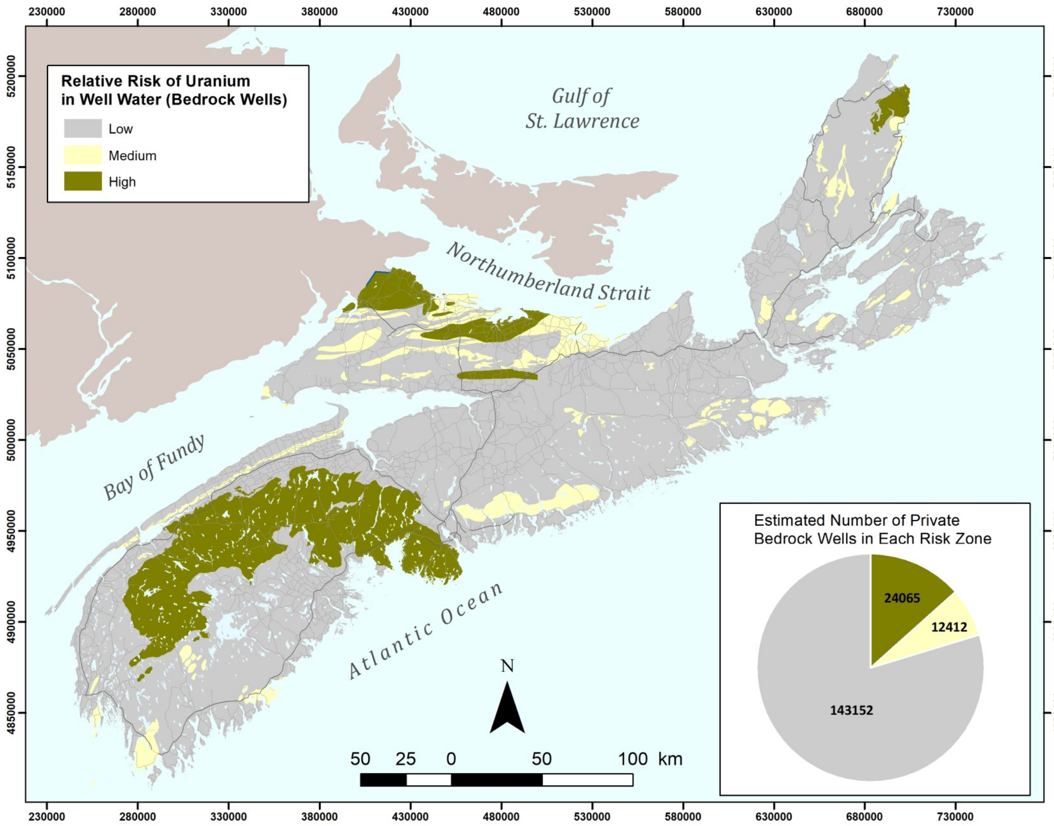

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A Uranium in Well Water Risk Map for Nova Scotia Based on Observed Uranium Concentrations in Bedrock Aquifers

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Abstract

At the levels of uranium detected in some bedrock aquifers in Nova Scotia (>20 µg/L), long-term ingestion of well water from these aquifers can cause kidney disease. About 42% of Nova Scotians are supplied by private wells and these water sources are not monitored or regulated with respect to water quality. Effective communication of the health risks associated with the ingestion of uranium in drinking water from private wells is critical for reducing uranium exposure and protecting human health.

The relationship between uranium in well water, bedrock lithogeochemistry, and aquifer geochemistry was investigated to develop a new uranium in well water risk map, which will be used to communicate risk to well owners and inform groundwater supply development. Available uranium in well water data were compiled for bedrock wells and classified by the source aquifer (i.e. bedrock unit). The frequency of uranium in well water samples exceeding Health Canada's maximum acceptable concentration (MAC) of 20 µg/L was tabulated for the province's five major bedrock groundwater regions and over 65 individual bedrock units.

Bedrock geology was shown to be the most important provincial-scale control on the distribution of uranium concentrations in well water. Both the highest concentrations (i.e. >100 µg/L) and exceedance rates of the Health Canada MAC were associated with the plutonic (30.3%) and sedimentary (6.3%) groundwater regions of Nova Scotia, largely due to the higher content of uranium in aquifer materials. Well water samples from the South Mountain Batholith and Black Brook granitic suite plutonic aquifers, and from the Pictou Group sedimentary bedrock aquifers, were associated with the highest frequency of uranium exceeding the Health Canada MAC for uranium in drinking water.

The study highlighted other controls on uranium occurrence and mobility, including the influence of pH and total alkalinity (as $CaCO_3$). It was generally observed that higher levels of uranium in groundwater were associated with alkaline pH and higher groundwater alkalinity.

Based on the relationship between uranium in well water and bedrock geology, a uranium in well water risk map was developed. Demographic analyses show that approximately 26,445 private wells are in high risk areas (>15% exceedance rate), and the overall percentage of private well water exceeding safe drinking water limits in Nova Scotia may be as high as 6.5% (~25,100 persons).

Introduction

Uranium in well water can be both chemically and radiologically toxic, but the main human health concern associated with the ingestion of uranium in drinking water is the toxic effect (chemical toxicity) of uranium on kidneys (Health Canada, 2019). The current Health Canada (2019) maximum acceptable concentration (MAC) of 20 micrograms of uranium per litre (µg/L) in drinking water was established based on studies of kidney effects in male rats. Ingestion of uranium in drinking water has also been linked to other potential health effects. For example, bones have a high affinity for uranium and intake of the element may interfere with normal bone functions (Arzuaga et al., 2015; Kurttio et al., 2005). The element's radioactivity has also raised concerns that ingestion of uranium in drinking water may be associated with an increased risk of cancer; however, the epidemiological research to date has not demonstrated a clear linkage (Health Canada, 2019).

Uranium is a relatively widespread naturally occurring contaminant in Nova Scotia's groundwater and has been a concern for many of the province's groundwater users since the emergence of the issue in the late 1970s (Grantham, 1986). A review was recently published (Kennedy and Drage, 2018) summarizing the past forty years of research and activities related to the occurrence of uranium in water wells in Nova Scotia. The review found that drilled wells were associated with a significantly higher probability of elevated levels of uranium compared to dug wells, and that the source of uranium in water wells in Nova Scotia is naturally occurring (geogenic source). Few dug wells in Nova Scotia have elevated concentrations of uranium because the province's tills are less likely to host uranium minerals and the geochemical conditions in shallow groundwater are generally not favourable for uranium mobilization (Kennedy and Drage, 2018).

It is estimated that approximately 38% of Nova Scotians (Kennedy and Polegato, 2017) obtain their domestic water supply from a privately owned, drilled well intercepting a fractured bedrock aquifer (4% obtain water from private wells in surficial aquifers) and these well users are not regulated with respect to water quality. Routine uranium in well water testing by private well users, and appropriate water treatment, if required, are therefore critical for the management of the human health risks associated with uranium. Uranium, along with other contaminants of concern, such as arsenic, can usually be removed from well water using conventional point-of-use reverse osmosis treatment systems. In a 2013 survey of the risk behaviours of private well owners in five separate areas of Nova Scotia considered to represent a demographic cross-section of the province, Chappells et al. (2014) showed that (1) existing risk communication efforts were largely failing to reach target audiences, (2) the quality of the information conveyed through formal channels was below average, and (3) there was poor compliance with recommended standards for private well water testing.

Exceedance rates of Health Canada's (2019) MAC of 20 µg/L of uranium in drinking water have generally been reported to be 5 to 10% for drilled wells across the province (overall exceedance rate for bedrock aquifers), although much higher exceedance rates (>40%) have been reported in some communities using private wells, especially those underlain by granitoid rocks of the South Mountain Batholith in Halifax County (Fig. 1) (Kennedy and Drage, 2018). Generally, water wells located in some igneous (plutonic) and sedimentary aquifers have been found to be more likely to contain elevated levels of uranium than other aquifer types (Dyck et al., 1976; Grantham, 1986; O'Reilly et al., 2009; Drage and Kennedy, 2013; Kennedy and Drage, 2018).

A mineralogical source of uranium in contact with the groundwater flow system, coupled with favourable geochemical conditions for the uranium to be mobile, are required for uranium to be present in well water. In Nova Scotia, concentrations of uranium in well water can exceed the Health Canada (2019) MAC because uranium (1) is relatively abundant in various types of earth materials, (2) is mobile under the range of typical pH and redox conditions observed in the province's aquifers and (3) has a low drinking-water limit relative to its abundance (MacFarlane, 1983). The U(VI) (or U^{+6}) oxidation state of uranium is the most important form of uranium with respect to groundwater supplies (Langmuir, 1978) because it is a constituent of the uranyl ion, UO_2^{2+}, which readily forms mobile, stable complexes with carbonate (e.g. $UO_2(CO_3)_3^{-2}$) and other ions.

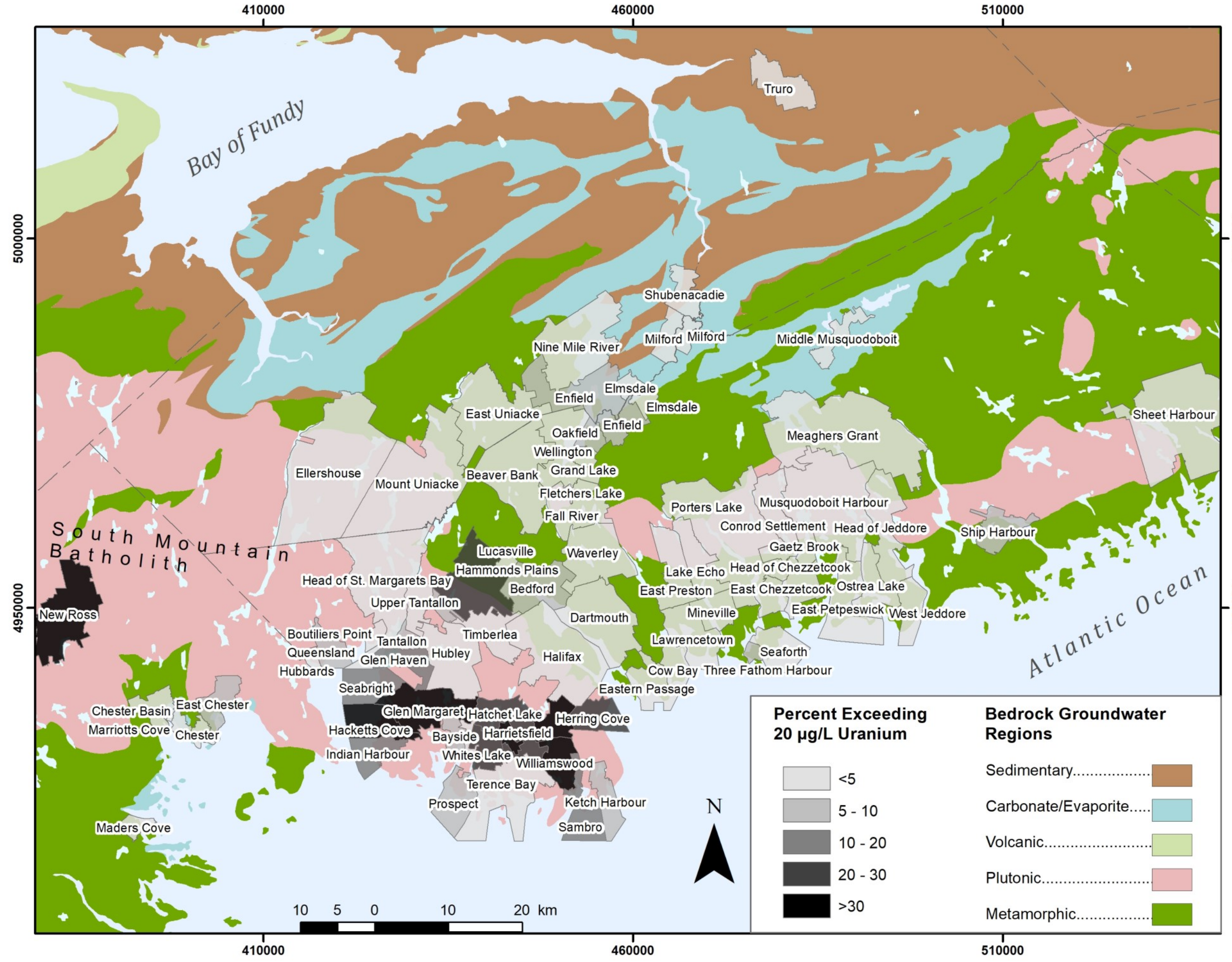

Figure 1. Percentage of samples exceeding 20 µg/L uranium in well water for various communities, compared to the province's five major bedrock groundwater regions (after Kennedy and Drage, 2018).

The distribution of uranium in bedrock aquifers is highly heterogeneous and the result of complex hydrogeochemical processes. On a regional scale, bedrock composition and mineralogy tend to control patterns of uranium concentrations in well water, whereas local variability is controlled by water-rock interactions and various factors affecting uranium mobility, such as groundwater pH and redox potential, the abundance of carbonate ions, the presence of organic matter, and the availability, solubility and mobility of competing ions (e.g. Langmuir, 1978; Cumberland et al., 2016; Coyte et al., 2018). Studies in Nova Scotia have shown that the mobility of uranium in well water is positively associated with the susceptibility of the mineralogical host to weathering (Blume, 2016; Letman et al., 2018), the availability of complexing ions, such as carbonate and calcium (Drage and Kennedy, 2013; Letman et al., 2018), and the presence of alkaline (e.g. MacFarlane, 1983), oxidizing conditions (Samolczyk et al., 2012; Finlayson-Bourque et al., 2010).

Risk maps for uranium in well water have been used over the last 35 years in the province as a tool to communicate the relative risk of unacceptable levels of uranium, and to inform land development, groundwater supply development, and risk communication and mitigation strategies. The most recent uranium in well water risk map was published in 2009 and included the risk of related radionuclides occurring in groundwater (Fig. 2) (O'Reilly et al., 2009). Details on the province's past activities related to uranium in well water risk mapping are available in Kennedy and Drage (2018).

The main objectives of the current research are to further advance the understanding of the relationship between uranium occurrence in well water and bedrock geology in Nova Scotia, and to develop a

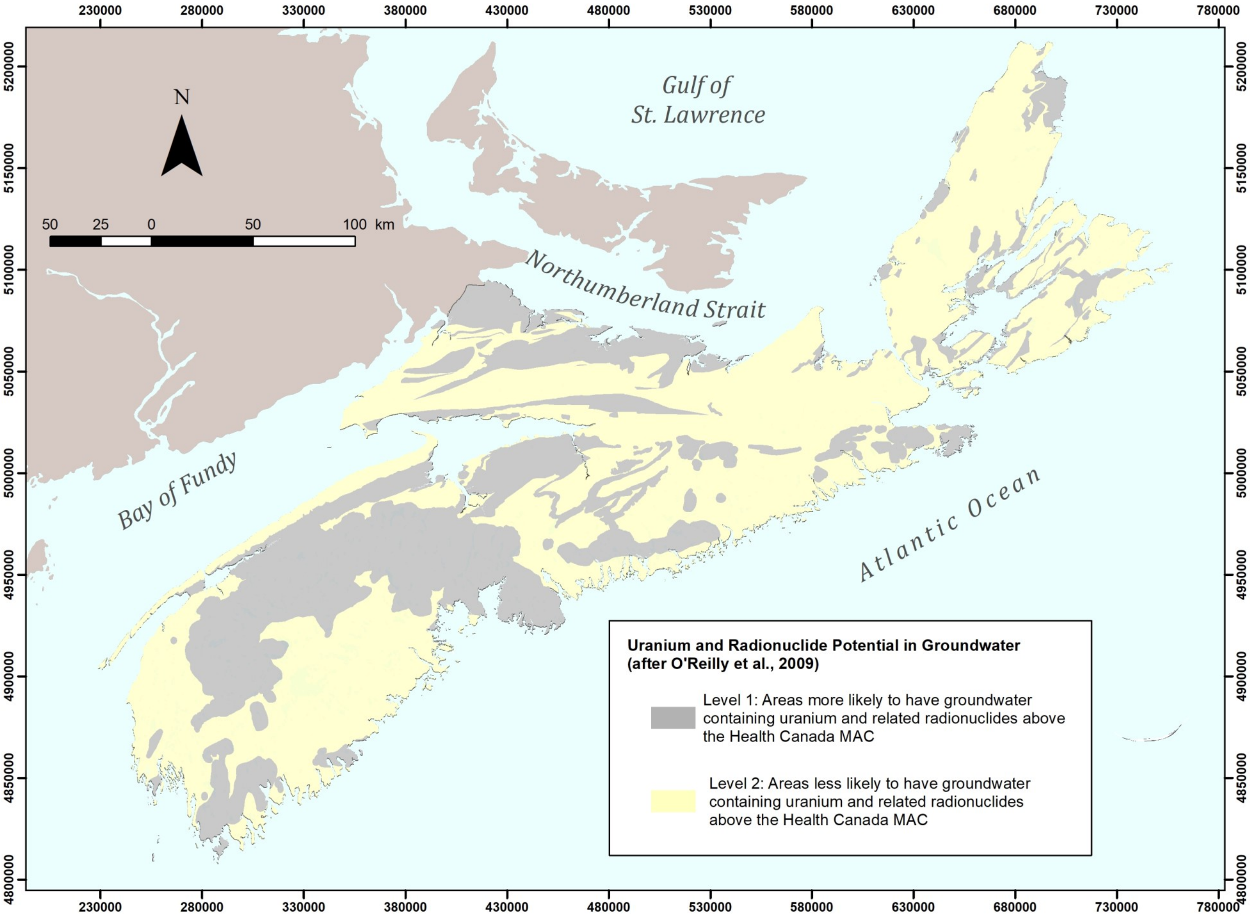

Figure 2. Second-generation uranium in well water risk map for the province (O'Reilly et al., 2009).

refined risk map, using a similar approach to the risk map for arsenic in bedrock aquifers (Kennedy and Drage, 2017). In contrast to the 2009 uranium and related radionuclides risk map by O'Reilly et al. (2009), the current risk map will focus only on uranium because radon ingestion from well water is not considered a health hazard by Health Canada (2009), and other related radionuclides do not usually occur at unacceptable concentrations in Nova Scotia well water (Grantham, 1986; Drage et al., 2005). Inhalation of radon released to air from well water could still be a health hazard where radon levels are high. Health Canada (2009) recommends mitigative action where radon levels in well water exceed 2000 Bq/L, a threshold that has been exceeded in some areas of Nova Scotia (Grantham, 1986). A provincial risk assessment of the potential for radon in indoor air has been previously published by O'Reilly et al. (2013). Uranium levels rarely exceed the Health Canada MAC in well water from surficial aquifers (e.g. dug wells) in Nova Scotia (Kennedy and Drage, 2018), and therefore these aquifers were excluded from the risk evaluation.

The refined risk map will be used to help communicate the risk of uranium exposure in well water to private well users, and to promote the appropriate testing and treatment of well water with the goal of preventing disease associated with uranium exposure and reducing associated health care costs. The risk map considers all available bedrock well-water chemistry data, including recently compiled uranium in well water survey datasets (see Kennedy and Drage, 2018) and the most recent bedrock geology mapping. A considerable portion of the province's bedrock geology was recently mapped and/or compiled at a scale of 1:10 000 and published at scale of 1:50 000 by Horne et al. (2009) (south-central Nova Scotia), White et al. (2012) (southwestern Nova Scotia), Barr et al. (2017) (Cape Breton Island) and White et al. (2018) (Antigonish Highlands area).

Methods

The analysis of uranium in well water in Nova Scotia is based on data from the Nova Scotia Groundwater Chemistry Database (NSGCDB) (Nova Scotia Department of Energy and Mines, 2019), which was recently updated to include uranium in well water survey legacy data (Kennedy and Drage, 2018). The NSGCDB is maintained by the Nova Scotia Department of Energy and Mines and consists mostly of non-domestic well-water sample results collected between 1954 and the present. The provincial database was compiled from various federal, provincial, and municipal data sources of ambient groundwater chemistry, including water-quality-monitoring data from government buildings with well water supplies, community well water surveys, and Nova Scotia Department of Environment groundwater chemistry data from registered public drinking-water supplies, pumping tests, municipal groundwater systems, and provincial observation wells. Most of these data are publicly available (Grantham, 1986; Nova Scotia Department of Energy and Mines, 2019). Some data (including part of the data used for this study; current to 2019), however, are not public due to privacy considerations.

Uranium in well water data were filtered to include only data where the laboratory method detection limit was ≤5 μg/L and where there was adequate confidence in the sample location (i.e. only water sample locations accurate to the land parcel scale were included), aquifer type (i.e. only water samples where source is known to be bedrock aquifer were included), and sample type (i.e. only raw or suspected raw water samples were included). The uranium data were plotted on digital versions of the most recent bedrock geology maps for Nova Scotia (e.g. Fisher, 2006a, b; Fisher and Poole, 2006; Horne et al., 2009; White et al., 2012, 2017, 2018; Barr et al., 2017; Nova Scotia Department of Energy and Mines, unpublished data, 2019) in ArcGIS^{TM}10 (Esri, Inc.) geographic information system software, and a bedrock unit was assigned to each water sample.

The Groundwater Regions Map of Nova Scotia (Kennedy and Drage, 2008) subdivides the province into five major bedrock groundwater regions based on the dominant rock type in each bedrock unit shown on the compiled provincial bedrock geology map (Keppie, 2000) (Fig 3). For example, all granitoid rocks mapped in the province are combined into the plutonic groundwater region. Statistical summaries of uranium concentrations in well water were produced for each of the bedrock groundwater regions, and for each region summaries of uranium exceedance rates, compared to the Health Canada (2019) MAC, were also generated for constituent bedrock units (or aquifers) that had a minimum of five water-sampling locations. Uranium in well water concentrations in the 10 to 20 μg/L range were also summarized to capture the percentage of samples that were elevated but did not exceed the Health Canada (2019) MAC.

For the purposes of the analysis, each bedrock unit was considered to be a hydrostratigraphic unit (or aquifer) having characteristic hydrogeochemical properties. Where multiple sample results were available for a given well location (i.e. time series), the maximum uranium result was used for the estimation of the exceedance rate of the Health Canada (2019) uranium in drinking water MAC. Each bedrock unit was assigned to a low- (<5%), medium- (≥5 to <15%) or high- (>=15%) risk category in terms of the percentage of well water samples exceeding the acceptable limit of 20 μg/L, similar to the risk categorization framework presented in Kennedy and Drage (2017) for arsenic in well water.

Non-parametric statistical tests, such as the Tarone-Ware and Kruskal-Wallis tests, were used to determine whether various groupings of samples were statistically different populations, with an assumed alpha of 0.05 (95% confidence interval) as an indication of significance. The rejection of the null hypothesis (i.e. all samples originate from the same distribution) indicates that at least one sample stochastically dominates at least one other sample, meaning that a randomly drawn sample from at least one group is more likely to be larger than a randomly drawn sample from a different group. The post-hoc Dunn's pair-wise comparison test (Benjamini-Hochberg correction) was applied following the Kruskal-Wallis test to evaluate stochastic dominance within the groupings (Dinno, 2018). Statistical analyses were conducted using STATA® (StataCorp, LP) and ProUCL 5.0 software (U.S. Environmental Protection Agency, 2013).

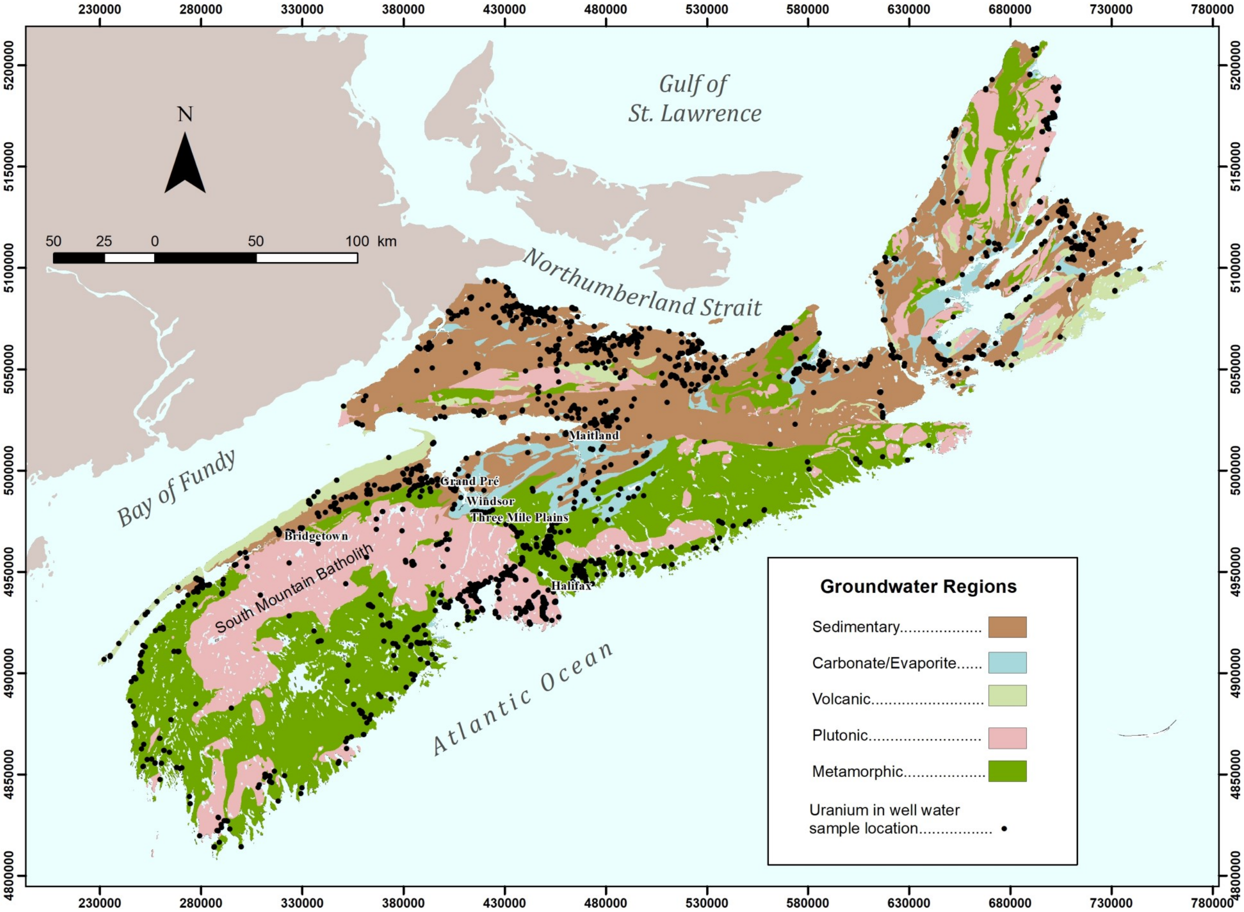

Figure 3. Groundwater regions of Nova Scotia (Kennedy and Drage, 2008) and distribution of uranium in well water data.

Limitations of the Approach

The risk-mapping approach assumed that areas of the province with significant data control for uranium in well-water chemistry and related bedrock geology can be extrapolated into areas without such data control. The spatial coverage is not regularly distributed across the province and is biased because the dataset includes uranium in well water surveys that targeted areas of the province where elevated concentrations of uranium in rock or groundwater had previously been detected. The spatial coverage is also biased toward developed areas of the province, where water wells and chemistry data may be available. Another limitation of the risk-mapping approach includes the assumption that bedrock geology is the dominant control, rather than other factors, such as till lithology or the pH and Eh environment, which may be independent of bedrock geology. Because bedrock maps of varying scales (from 1:10 000 to 1:500 000) were merged to cover the province, the reliability of the derivative provincial-scale uranium risk map at a given location is constrained by the quality (i.e. accuracy, scale, level of detail) of the original bedrock map. The uncertainty associated with the definition of risk zones increases near geologic boundaries due to factors such as map scale, interpolation of geologic boundaries, and gradational contacts between units.

The compiled water chemistry data span a period of over 40 years and come from a variety of sources, ranging from samples collected by homeowners, who have shared their uranium results with government, to well water quality surveys conducted by groundwater professionals. Hence, sampling and laboratory analytical methods are not consistent across the dataset. Field measurements of relevant geochemical parameters, such as dissolved oxygen, pH and Eh, were not part of the dataset. Although the quality of the well water chemistry data used in the analysis varies, it is still considered useful for detecting regional-scale (e.g. >1:50 000) trends.

Results and Discussion

A total of 2574 uranium in well water sample locations from bedrock aquifers were used in the analysis, with the greatest sample density occurring in suburban Halifax (Fig. 3). Statistical summaries of the data classified by groundwater region (Fig. 4, Table 1) show that the highest concentrations of uranium are generally associated with the plutonic groundwater region. For comparison purposes, statistics are also presented in Table 1 for surficial aquifers (n = 541). As noted earlier, however, the focus of the present analysis is on bedrock aquifers because these aquifers are associated with a much higher probability of having elevated levels of uranium (Kennedy and Drage, 2018). Based on the available data, the overall province-wide exceedance rate of the Health Canada (2019) MAC was 8.9% (10.7% if surficial aquifers are excluded), although as noted in the previous section, sample locations are not randomly distributed and areas with known uranium in well water issues are likely overrepresented in the dataset.

The Kaplan-Meier mean was about an order of magnitude higher for plutonic rock aquifers compared to other bedrock aquifer types. Statistical comparison of uranium in well water concentrations using the Kruskal-Wallis non-parametric test followed by the Dunn test showed a significant difference ($p<0.05$) between each of the groundwater regions, except for between the sedimentary and carbonate/evaporite groundwater regions. A summary of uranium in well water exceedance rates of the Health Canada (2019) MAC for various bedrock aquifers within each of the five bedrock groundwater regions, and a more detailed exploration of the potential controls on uranium occurrence in groundwater with respect to lithogeochemistry and aquifer geochemistry, are presented below.

Plutonic Groundwater Region

Distribution of Uranium and Summary of Exceedance Rates

Low to high (<0.1 to >100 µg/L) concentrations of uranium are observed in the plutonic groundwater region of Nova Scotia (Fig. 5). The overall exceedance rate of the Health Canada (2019) uranium in

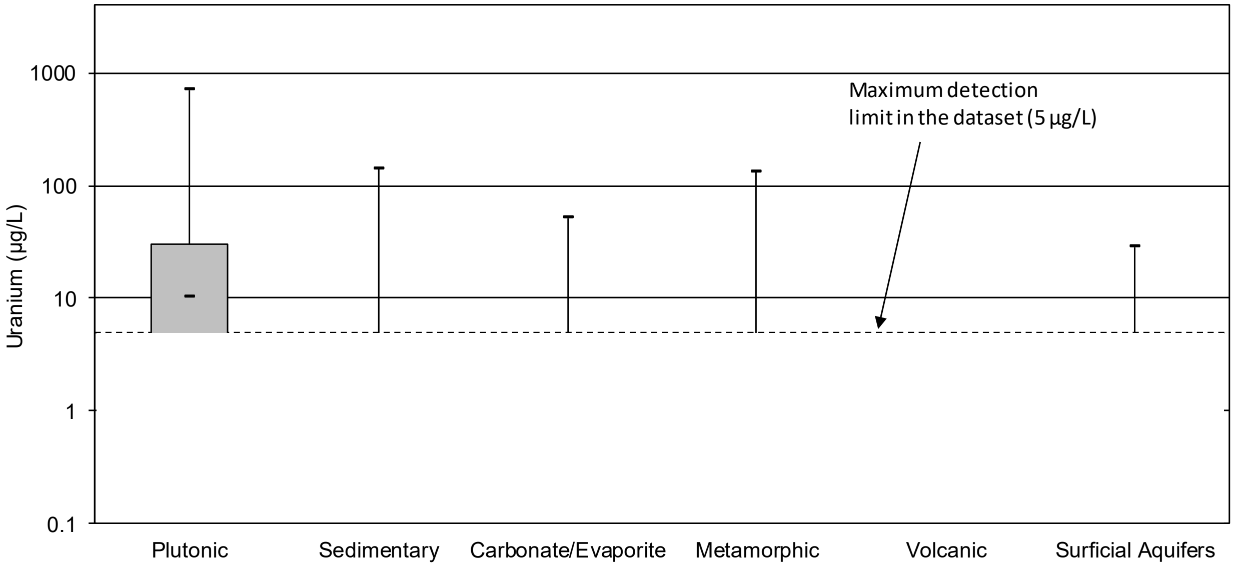

Figure 4. Censored box and whisker plot summarizing the minimum, 25%, median, 75%, and maximum uranium concentrations for the province's five groundwater regions. The portion of the plot below the highest reported detection limit (e.g. 5 µg/L) is not shown.

Table 1. Statistical summary of uranium concentrations (µg/L) classified by groundwater region. The highest reported laboratory detection limit is 5 µg/L.

										Detects Only	
Groundwater Region	**Count Observa-tions**	**Count Detects**	**Per cent Detects**	**Per cent Exceed[1]**	**K-M[2] Mean**	**Min**	**Median**	**95% ile**	**Max**	**Mean**	**Median**
Plutonic	638	557	87.3%	30.3%	25.7	<0.1	10.0	90.0	700.0	29.3	10.0
Sedimentary	1173	926	78.9%	6.3%	4.7	<0.1	-	22.0	141.0	6.0	1.2
Carbonate/ Evaporite	212	188	88.7%	1.9%	2.8	<0.1	-	10.7	50.6	3.1	1.2
Metamorphic	485	323	66.6%	1.0%	2.0	<0.02	-	7.0	130.0	2.8	1.0
Volcanic	68	43	63.2%	0.0%	0.4	<0.1	-	-	-	0.6	0.4
Surficial	541	246	45.5%	0.4%	0.6	<0.1	-	5.0	28.0	1.2	0.4
TOTAL	**3117**	**2283**	**73.2%**	**8.9%**							

1. Per cent of uranium in well water results exceeding the maximum acceptable concentration of 20 µg/L
2. Kaplan-Meier

drinking water MAC for plutonic rock aquifers is approximately 30% (n = 638), ranging from 0 to 53% for individual bedrock aquifers (Table 2). Based on the observed patterns of uranium in well water in plutonic rock aquifers, there appears to be a higher likelihood of uranium exceeding safe limits in the South Mountain Batholith and Neils Harbour areas of the province (Table 2, Fig. 5). It should be noted that a small body of metamorphic rock (Neils Harbour orthogneiss) that is intruded by numerous granitic pegmatites of the nearby Black Brook granitic suite was included as part of the plutonic groundwater region (Table 2, Fig. 5).

Relation of Uranium to Lithogeochemistry

Broadly, most studies of the distribution of uranium in well water in plutonic aquifers have shown a relationship between the rock type and the concentrations of uranium (e.g. MacFarlane, 1983; Ayotte et al., 2007; Colman, 2011; Yang et al., 2014). Average whole-rock concentrations of uranium in granitoid rocks in Nova Scotia are in the 1 – 9 ppm range (Kennedy and Drage, 2018). A median value of 6 ppm was reported for the late Devonian South Mountain Batholith, the largest body of granitoid rocks in the province (MacDonald et al., 1992). Due to the strongly peraluminous chemical affinity of the South Mountain Batholith, higher background concentrations of uranium are generally expected in these plutons compared to the more calc-alkaline granitoid rocks in the northern parts of the province, such as the Antigonish and Cobequid highlands, and Cape Breton Island (e.g. Barr et al., 1982, MacDonald et al., 1992). The melt process that characterizes peraluminous (or two-mica) granites results in the enrichment of incompatible elements such as uranium, as the magma progressively crystallizes. In a study of eight granitoid plutons across Cape Breton Island, Barr et al. (1982) identified the White Point pluton, which is part of the Black Brook granitic suite, as the only pluton that was clearly peraluminous, with whole-rock concentrations of uranium as high 12 ppm. The Black Brook granitic suite is one of the few plutonic rock units on Cape Breton Island that has been associated with elevated uranium in well water (Table 2). Since that study, other peraluminous plutons have been recognized in Cape Breton Island (Barr et al., 2018) that may have elevated levels of uranium in groundwater but are in areas that are uninhabited, and therefore, well water chemistry data are not available.

Uranium-rich minerals tend to be especially enriched in the later phases of igneous differentiation, and background whole-rock concentrations of uranium have been related to the grade of the magma or granitoid rock type, increasing from the more mafic rock types, such as diorite and granodiorite, to the

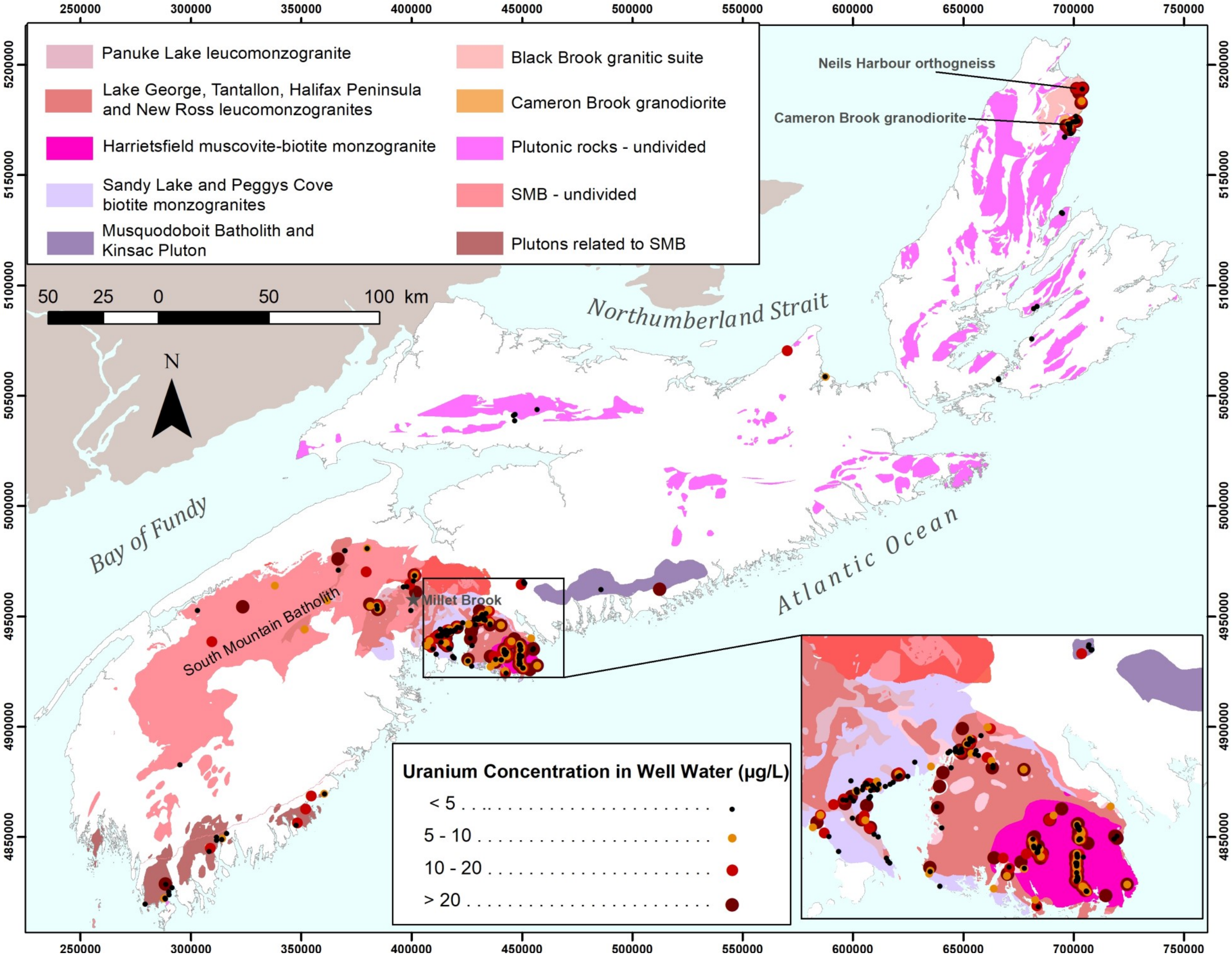

Figure 5. Concentrations of uranium in well water in the plutonic groundwater region compared to bedrock geology.

more felsic and silica-rich rock types, such as monzogranite, syenogranite, and leucogranite (e.g. Chatterjee and Muecke, 1982; MacDonald et al., 1992). This trend was observed by the uranium task force (MacFarlane, 1983) and is supported by analysis of the available uranium data (i.e. Nova Scotia Groundwater Chemistry Database) from the province's plutonic aquifers. Higher concentrations of uranium are generally associated with the more evolved, felsic granites compared to mafic granitoid rocks (Fig. 6). Monzogranites are the predominant type of granitoid rocks of the South Mountain Batholith; when combined with leucogranites they represent over 90% of the batholith (MacDonald et al., 1992).

It is evident from Table 2, however, that some granodiorite aquifers are associated with higher uranium in well water exceedance rates than some monzogranite aquifers (e.g. Panuke Lake leucomonzogranite). Uranium in well water, therefore, is not consistently associated with the more evolved granitoid rocks. This is likely because granodiorite bodies can host late-stage intrusions of magmatic fluids enriched with uranium, where uranium minerals precipitate in regions of lower pressure and temperature, such as veins, fractures and shear zones. Hydrothermal vein-type deposits have been discovered in South Mountain Batholith rocks, with concentrations as high 3180 ppm reported in mineralized zones of the granodiorite-hosted Millet Brook deposit (Fig. 5, Chatterjee and Muecke, 1982). Where these types of deposits occur, granodiorite-hosted uranium minerals can be a significant source of uranium to groundwater.

In addition to magmatic-type and vein-type enrichment of uranium in granitoid rocks, MacFarlane (1983) also suggested that redox-controlled uranium enrichment may occur in granitoid rocks due to the

Table 2. Percentage of water samples exceeding 10 and 20 µg/L of uranium in well water based on available data for various plutonic bedrock units (aquifers) with at least five samples.

Bedrock Unit	Count	Per cent of uranium concentrations >10 µg/L	Per cent of uranium concentrations >20 µg/L
PLUTONIC GROUNDWATER REGION	**638**	**43.73%**	**30.25%**
Plutonic Rocks - Cape Breton Island	**78**	**24.36%**	**10.26%**
Cameron Brook granodiorite	46	21.74%	6.52%
Black Brook granitic suite and Neils Harbour orthogneiss	11	81.82%	45.45%
Remainder of Cape Breton Island plutonic rocks	21	0.00%	0.00%
Plutons Related to South Mountain Batholith in Southwest Nova Scotia	**27**	**18.52%**	**3.70%**
Barrington Passage Pluton	9	11.11%	11.11%
Port Mouton Pluton	8	37.50%	0.00%
Shelburne Pluton	10	10.00%	0.00%
South Mountain Batholith	**519**	**48.55%**	**35.26%**
Sandy Lake biotite monzogranite	75	32.00%	16.00%
Granodiorite (unnamed biotite granodiorite)	7	57.14%	28.57%
Panuke Lake leucomonzogranite	10	20.00%	10.00%
Tantallon leucomonzogranite	41	29.27%	17.07%
Halifax Peninsula leucomonzogranite	32	43.75%	37.50%
New Ross leucomonzogranite	19	68.42%	52.63%
Harrietsfield muscovite-biotite monzogranite	314	56.69%	43.63%
Musquodoboit Batholith and Kinsac Pluton	**7**	**28.57%**	**14.29%**
All Other Mainland Nova Scotia Granitoid Rocks	**7**	**14.29%**	**0.00%**

development of reducing zones, where soluble U(VI) in groundwater is converted to insoluble U(IV) and redeposited in the aquifer matrix.

Relation of Uranium to Aquifer Geochemistry

Although lithogeochemistry may be the most important predictor of uranium concentrations in well water in plutonic aquifers, various studies in Nova Scotia and in nearby Maine (e.g. Ayotte et al., 2007; Yang et al., 2014) have shown that the geochemical environment has an important role in controlling local variability in the distribution of uranium in groundwater.

For example, the Uranium Task Force (MacFarlane, 1983) observed higher uranium concentrations in plutonic aquifers that were overlain by thick till deposits (e.g. communities of Harrietsfield and Brookside). It was proposed that more uranium was available in these bedrock aquifers because the presence of thick, overlying, low-permeability till promotes the development of reducing conditions (e.g. lesser input of younger, oxygenated groundwater recharge) and the deposition of uranium minerals in the aquifers (MacFarlane, 1983). When circulating, more oxygenated groundwater encounters the reduced zones, the uranium may be re-mobilized. Elevated levels of uranium in these aquifers were also attributed to the more evolved groundwater (i.e. higher total alkalinity and pH) that tends to occur under thicker glacial till deposits (e.g. drumlins) compared to surrounding groundwater. This observation is supported by comparison of uranium in well water exceedance rates in the available data for various till thicknesses overlying plutonic bedrock aquifers (Fig. 7).

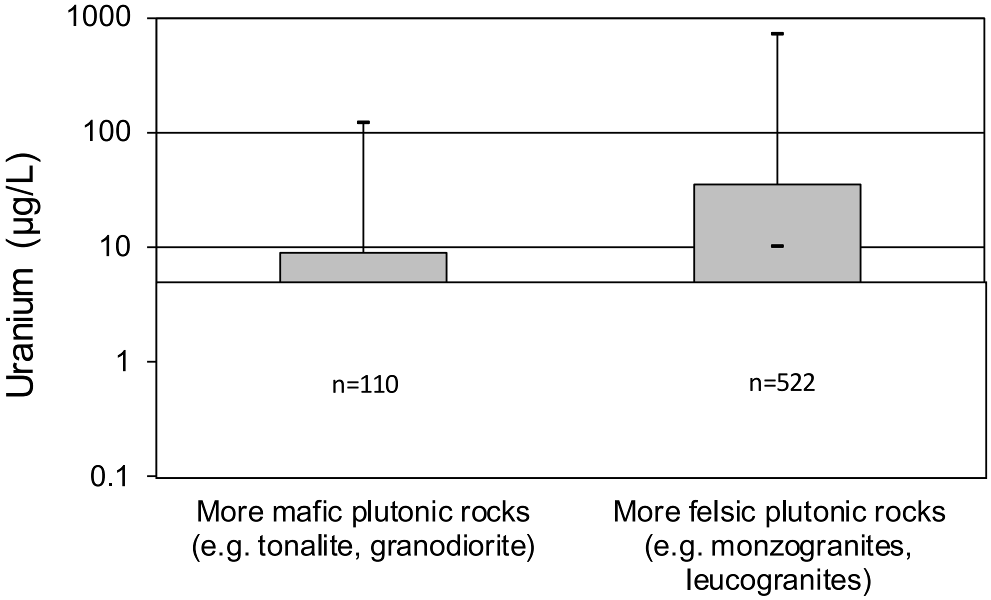

Figure 6. Censored box and whisker plot of uranium in well water in plutonic rock aquifers for major groupings of granitoid rock types. The portion of the plot below the highest reported detection limit (e.g. 5 µg/L) is not shown. A Tarone-Ware test confirms that uranium concentrations associated with the more felsic plutonic group are significantly greater than the more mafic plutonic group.

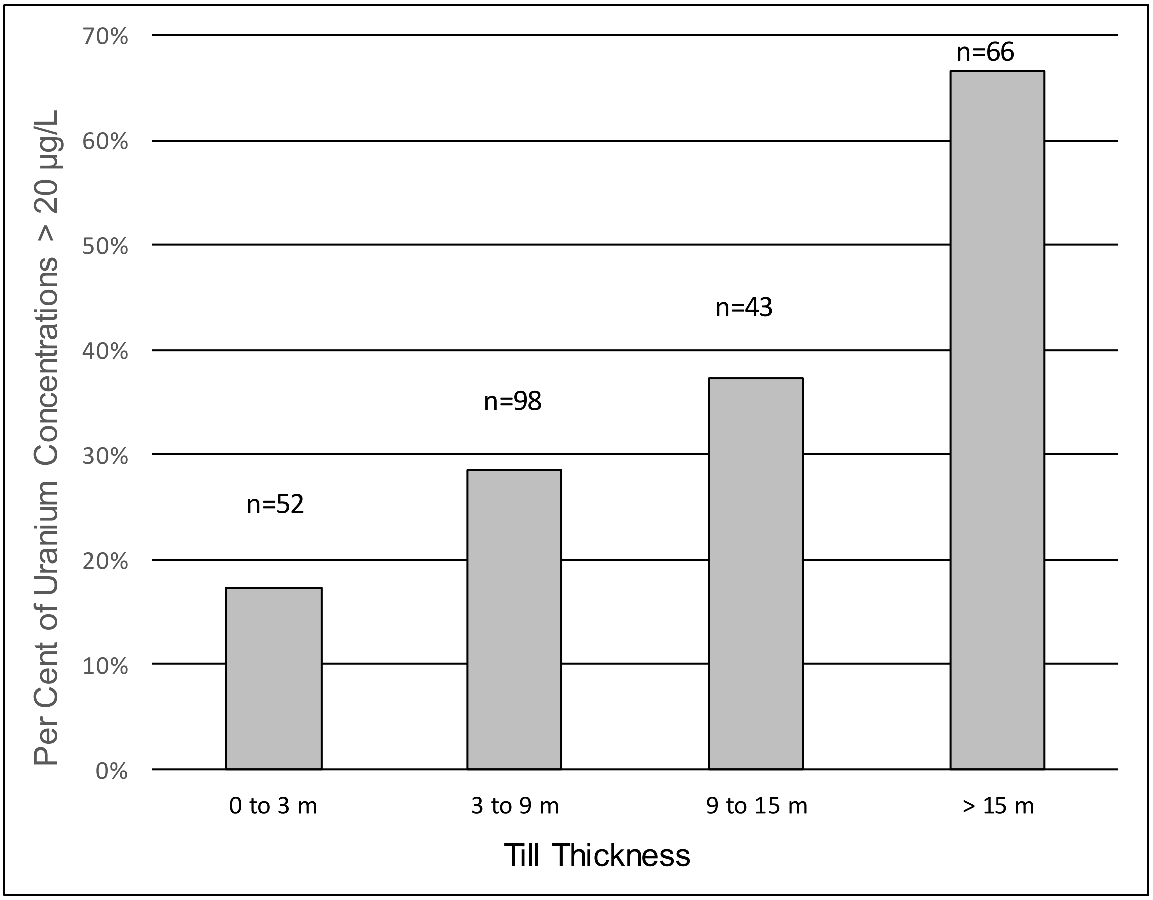

Figure 7. Per cent exceedances of the Health Canada uranium in drinking water MAC in plutonic rock aquifers for various thicknesses of overlying till.

The distribution of elevated uranium in well water observed by the Uranium Task Force coincided with areas of elevated arsenic in well water, which may be due to similar mechanisms for the enrichment of uranium and arsenic minerals in granitoid rocks, and the similar geochemical behavior of the two elements in groundwater systems, especially with respect to the sensitivity of arsenic and uranium mobility to pH and alkalinity.

Evaluation of the available well water chemistry data (i.e. NSGCDB) for plutonic aquifers agrees with the findings of the task force with respect to pH and total alkalinity. Figures 8-9 show that higher uranium in well water concentrations are associated with higher groundwater alkalinity (i.e. >50 mg/L) and pH in the 7.5 to 8 range. Approximately 32% of well water samples with alkalinity (as $CaCO_3$) ≥50 mg/L (n=111) exceeded the Health Canada uranium in drinking water MAC, whereas few exceedances (5%, n=115) were associated with alkalinities <50 mg/L.

Other studies have shown that uranium mobilization in groundwater, including plutonic aquifers, is related to the presence of complexing ions and the susceptibility of the mineral host to the effects of weathering. Drage and Kennedy (2013) and Letman et al. (2018) found good correlation between uranium in well water concentrations and uranyl complexing ions, such as calcium and carbonate, in some of the province's plutonic aquifers. In laboratory leachate tests of core samples, both Blume (2016) and Letman et al. (2018) discovered that despite lower measured whole-rock concentrations of uranium in granitoid rock core samples compared to siltstone core rock samples, approximately 3 to 5 times higher concentrations of uranium were observed in the leachate extracts from the granitoid rock samples.

Delineation of Risk Zones

Based on the available data (Table 2), the Panuke Lake leucomonzogranite of the South Mountain Batholith was assigned to the medium-risk category (≥5 to <15% of water samples exceeding the Health Canada MAC), whereas the rest of the South Mountain Batholith was assigned to the high-risk category (≥15% of water samples exceeding the Health Canada MAC). The Black Brook granitic suite and Neils

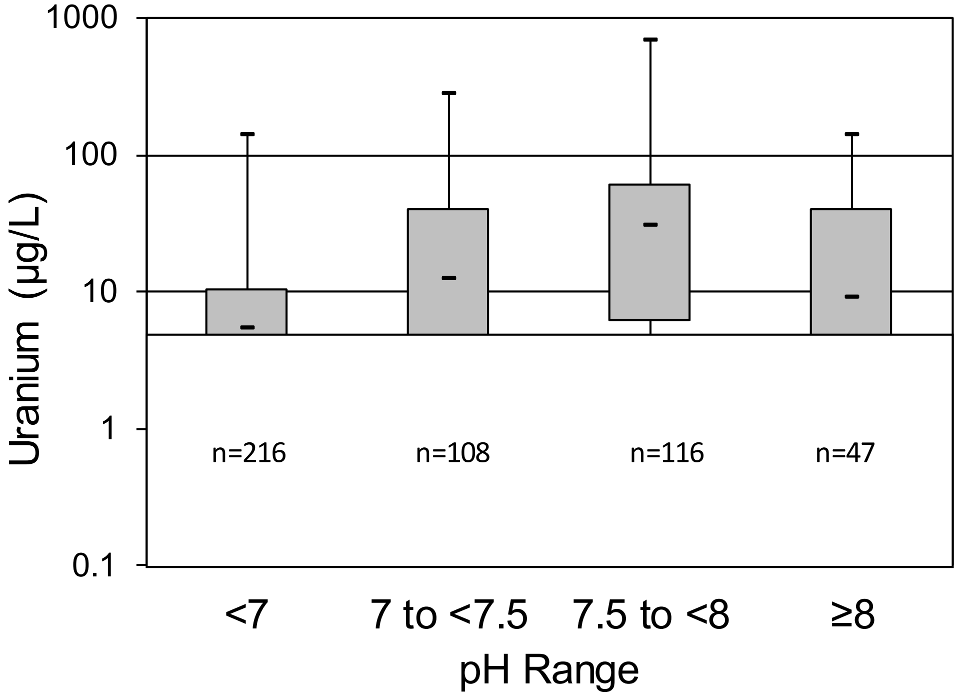

Figure 8. Censored box and whisker plot of uranium in well water in plutonic rock aquifers for various pH ranges. The portion of the plot below the highest reported detection limit (e.g. 5 µg/L) is not shown.

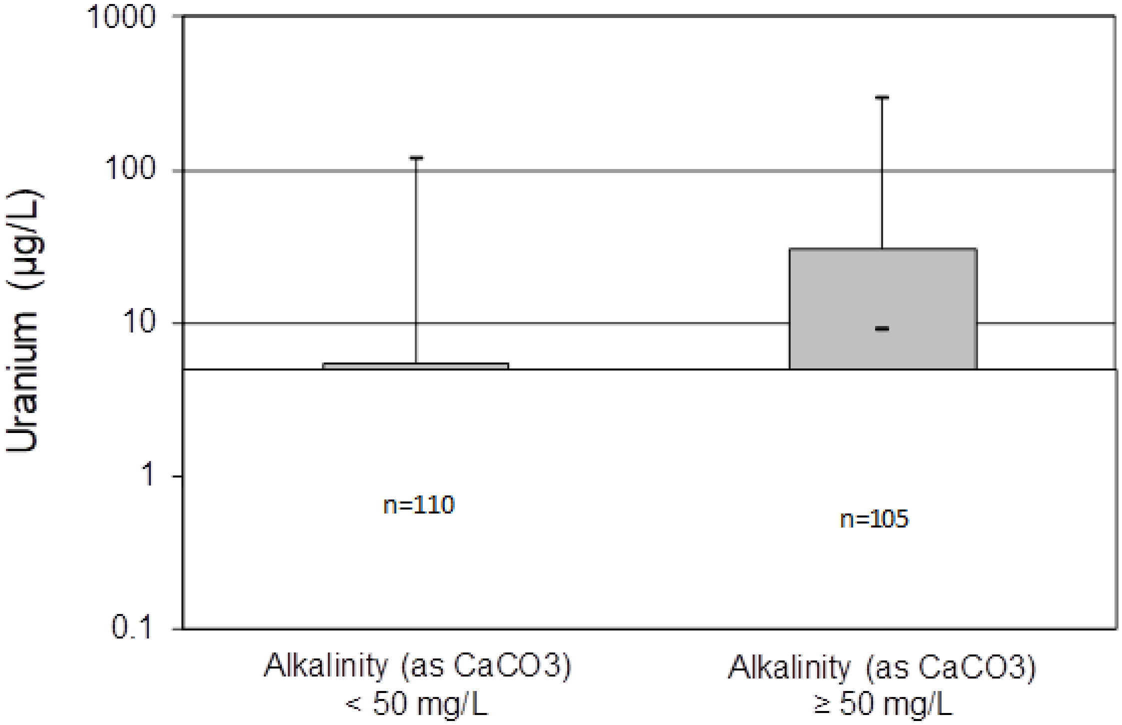

Figure 9. Censored box and whisker plot of uranium in well water in plutonic rock aquifers for alkalinity (as $CaCO_3$) <50 mg/L and ≥50 mg/L. The portion of the plot below the highest reported detection limit (e.g. 5 µg/L) is not shown. A Tarone-Ware test confirms that uranium concentrations associated with the higher alkalinity group are significantly greater than the lower alkalinity group.

Harbour orthogneiss were also assigned to the high-risk category. The Barrington Passage Pluton, the Musquodoboit Batholith (and Kinsac Pluton), and Cameron Brook granodiorite were all assigned to the medium-risk category. Although none of the wells intercepting the Port Mouton Pluton exceeded the uranium in drinking water MAC, three of the eight water samples had concentrations between 10 and 20 µg/L, and therefore, this bedrock unit was also assigned to the medium-risk category.

There are limited available uranium in well water data for the province’s plutonic aquifers in comparison to the number and diversity of granitoid rock units across Nova Scotia, especially on Cape Breton Island and the western part of the South Mountain Batholith (Fig. 5). Therefore, as a conservative approach to the evaluation of risk, the more evolved (i.e. monzogranites and leucomonzogranites) granites with insufficient available uranium concentration data were assigned to the medium-risk category. All other plutonic rock units in the province were assigned to the low-risk category (<5% of water samples exceeding the Health Canada MAC). Additional well water sampling in areas of limited sample coverage is recommended to refine the delineation of the risk zones.

Sedimentary Groundwater Region

Distribution of Uranium and Summary of Exceedance Rates

Low to high concentrations (<0.1 to >100 µg/L) of uranium are observed in the sedimentary groundwater region of Nova Scotia (Table 3, Fig. 10). The overall exceedance rate of the Health Canada (2019) uranium in drinking water MAC for sedimentary aquifers is about 6% (n = 1173), and ranges from 0 to 52% for individual bedrock units (Table 3). The highest uranium in well water exceedance rates are associated with Pictou Group aquifers, which have previously been associated with regional uranium enrichment due to roll-front deposition whereby the mobile U(VI) is converted to the immobile U(IV) at a reducing barrier (Dyck et al., 1976).

Table 3. Percentage of water samples exceeding 10 and 20 µg/L of uranium in well water based on available data for various sedimentary bedrock units (aquifers) with at least five samples.

Bedrock Unit	Count	Per cent of Uranium concentrations >10 µg/L	Per cent of Uranium concentrations >20 µg/L
SEDIMENTARY GROUNDWATER REGION	**1173**	**13.73%**	**6.31%**
Arisaig Group	**7**	**0.00%**	**0.00%**
Cumberland Group	**338**	**11.54%**	**2.07%**
Boss Point Formation	15	6.67%	6.67%
Joggins Formation	6	0.00%	0.00%
Malagash Formation	110	25.45%	4.55%
New Glasgow Formation	28	35.71%	3.57%
Parrsboro Formation	6	0.00%	0.00%
Port Hood Formation	68	0.00%	0.00%
South Bar Formation	45	0.00%	0.00%
Springhill Mines Formation	9	0.00%	0.00%
Stellarton Formation	20	0.00%	0.00%
Sydney Mines Formation	12	0.00%	0.00%
Waddens Cove Formation	7	0.00%	0.00%
Fundy Group	**247**	**8.10%**	**4.05%**
Blomidon Formation	14	21.43%	14.29%
McCoy Brook Formation	7	0.00%	0.00%
Wolfville Formation	226	7.52%	3.54%
Guysborough Group	**6**	**0.00%**	**0.00%**
Horton Group	**235**	**3.40%**	**0.85%**
Ainslie Formation	5	0.00%	0.00%
Cheverie Formation	47	10.64%	2.13%
Clam Harbour River Formation	14	0.00%	0.00%
Caledonia Mills Formation	28	0.00%	0.00%
Creignish Formation	8	0.00%	0.00%
Grantmire Formation	62	0.00%	0.00%
Horton Bluff Formation	42	4.76%	2.38%
Tracadie Road Formation	10	0.00%	0.00%
Mabou Group	**128**	**0.78%**	**0.78%**
Hastings Formation	35	0.00%	0.00%
Lismore Formation	10	0.00%	0.00%
Pomquet Formation	52	0.00%	0.00%
Watering Brook Formation	11	0.00%	0.00%
Pictou Group	**206**	**45.15%**	**26.21%**
Balfron Formation	132	40.15%	18.94%
Cape John Formation	19	31.58%	15.79%
Tatamagouche Formation	52	65.38%	50.00%

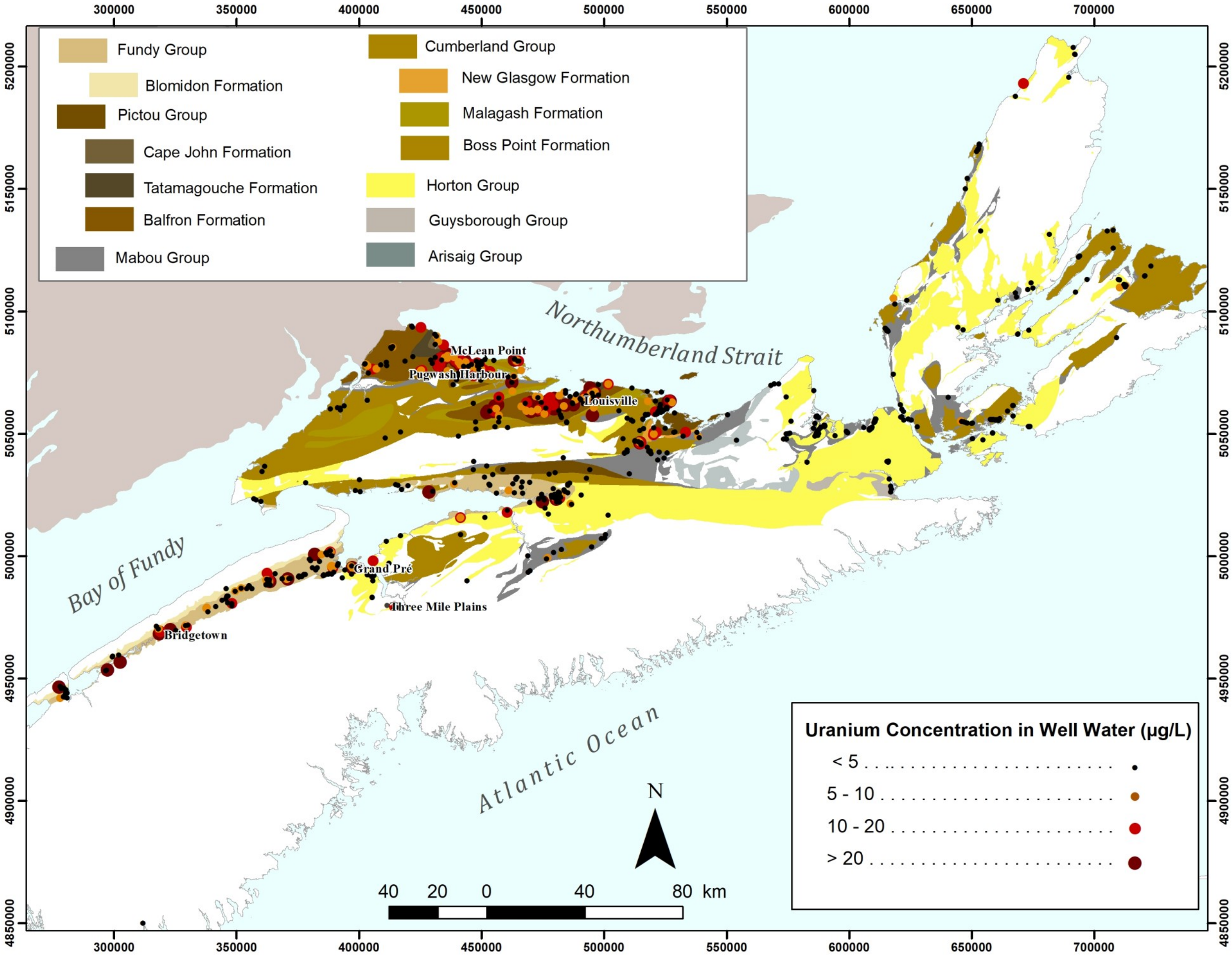

Figure 10. Concentrations of uranium in well water in the sedimentary groundwater region compared to bedrock geology.

Relation of Uranium in Well Water to Lithogeochemistry

There are limited data available with respect to whole-rock concentrations of uranium in sedimentary bedrock in Nova Scotia, although a review by Kennedy and Drage (2018) reported published average concentrations in the 2 to 4 ppm range. Uranium enrichment in sedimentary rocks in Nova Scotia has generally been attributed to roll-front deposition (Brummer, 1958; Dyck et al., 1976; Geldsetzer, 1977, Dyck and McCorkell, 1983; Ryan and O'Beirne-Ryan, 2009). Geldsetzer (1977) attributed anomalous whole-rock uranium concentrations detected in rocks of the Pictou Group (red-brown and grey sandstone, mudstone and conglomerate; carbonaceous shale) to the presence of favourable conditions for uranium mineralization, including alkaline conditions, shallow dips, the presence of carbonaceous material, and the presence of reducing agents such as pyrite. Uranium has been detected at various locations in rocks of the Pictou Group, including an outcrop at McLean Point (Brummer, 1958; Chatterjee, 1977), drill core near Pugwash Harbour (Dyck and McCorkell, 1983) and drill core near Louisville, where uranium whole-rock concentrations as high 470 ppm were detected (MacNabb, 1980) (Fig. 10).

Roll-front uranium mineralization has also been associated with Horton Group sandstones in the Windsor area of Nova Scotia (e.g. Ryan and O'Beirne-Ryan, 2007). The highest concentrations of uranium in sedimentary rocks in Nova Scotia were detected near the community of Three Mile Plains (3100 ppm) in a mineralized zone of Horton Group rocks at the contact between the top of the Horton Bluff Formation and the overlying, younger Cheverie Formation (Fig. 10, Nankamba, 2011). Black shales in southeastern Cape Breton Island are also known to host uranium mineralization, with reported uranium concentrations as high as 100 ppm (Felderhof et al., 1979; Cheve, 1980). Although uranium mineralization has been documented in sedimentary rocks at various locations in Nova Scotia, most occurrences of elevated concentrations of uranium in well water are associated with Pictou Group aquifers (Fig. 10, Table 3), which may in part be due to the broad regional distribution of roll-front deposits, but could also be due to the development of more favourable geochemical conditions for the mobilization of uranium and the greater susceptibility of the aquifer matrix to chemical weathering.

Relation of Uranium to Aquifer Geochemistry

In general, elevated uranium in sedimentary aquifers has been associated with the complexation of U(VI) with available dissolved carbonate species in alkaline, oxidizing zones of the aquifer (Smedley et al., 2006; Cumberland et al., 2016). Various studies in Nova Scotia have shown the importance of the geochemical environment in determining the mobility of uranium in sedimentary aquifers and, therefore, the likelihood of uranium exceeding acceptable levels in well water (e.g. MacFarlane, 1983; Finlayson-Bourque et al., 2010; Samolcyzk et al., 2012; Drage and Kennedy, 2013; Blume, 2016; Letman et al. 2018). Similar to plutonic aquifers, the Uranium Task Force (MacFarlane, 1983) study showed elevated uranium in well water in sedimentary aquifers was associated with alkaline pH conditions (7.5 to 8.5). Other more recent studies have also observed an association between alkaline pH and elevated uranium in sedimentary aquifers (Samolcyzk et al., 2012; Letman et al., 2018), and evaluation of the available data (i.e. NSGCDB) for Pictou Group aquifers shows a similar relationship between pH and uranium levels (Fig. 11).

Other investigations in the province, especially in the Annapolis Valley, have emphasized the importance of the redox environment in controlling uranium concentrations in well water in the province's sedimentary aquifers. In the Grand Pré and Bridgetown areas, elevated levels of uranium were linked to the development of oxidizing conditions in sandstone and shale aquifers (Samolczyk

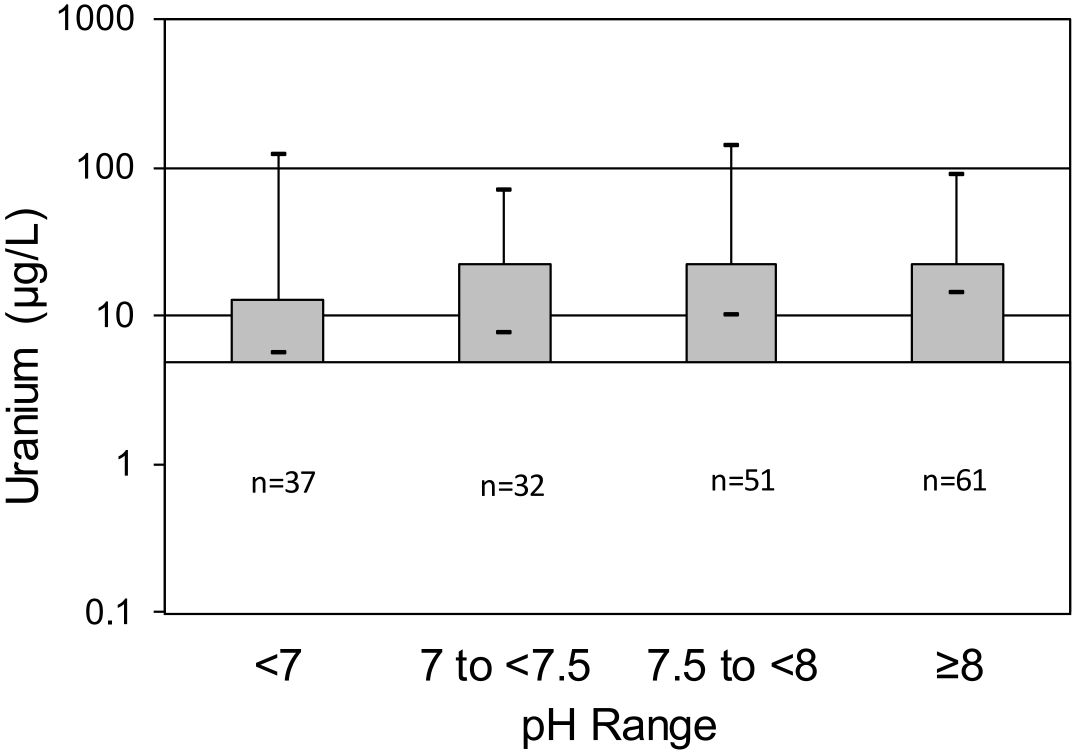

Figure 11. Censored box and whisker plot of uranium in well water in Pictou Group aquifers for various pH ranges. The portion of the plot below the highest reported detection limit (e.g. 5 µg/L) is not shown.

et al., 2012; Pothier, 2009; Finlayson-Bourque et al., 2010). The elevated levels of uranium in Pictou Group aquifers, and in some parts of Blomidon, Wolfville and Boss Point aquifers, may be associated with a marked change in the redox environment across stratigraphic or geologic boundaries, from reducing conditions to more oxidizing conditions along the groundwater flow path, with enhanced uranium mobility near these boundaries.

It is evident that the Pictou Group aquifers are more likely to be associated with elevated levels of uranium in well water compared to other sedimentary bedrock units that are known to contain uranium minerals (e.g. Horton Bluff Formation), although there is no clear explanation for this pattern. Pictou Group aquifers may have a more favourable geochemical environment (e.g. redox conditions) for the mobilization of uranium. Alternatively, the uranium present in the Pictou Group aquifers may be more susceptible to weathering compared to other sedimentary aquifers, such as Horton Group aquifers, which have more organic matter-rich sediments that may influence redox, complexation and sorption processes (Ryan and O'Beirne-Ryan, 2009; Cumberland et al., 2016; Letman et al., 2018). Smedley et al. (2006) observed that the highest concentrations of uranium in British groundwater were associated with redbed sandstone aquifers due to the desorption of uranium from iron oxides present as grain coatings and cement in the redbeds.

The importance of the availability of complexing agents, especially sulphate, calcium, chloride and carbonate, on the mobility of uranium in the province's sedimentary aquifers has been highlighted in studies by Drage and Kennedy (2013), Blume (2016), and Letman et al. (2018). This work is supported by analysis of available data (i.e. NSGCDB) for Pictou Group aquifers, which shows that higher levels of uranium tend to be associated with higher alkalinity (mainly bicarbonate and carbonate ions) and electrical conductivity, both of which indicate a greater degree of water-rock interaction (Fig. 12).

Delineation of Risk Zones

Based on the available data (Table 3), all Pictou Group rocks were assigned to the high-risk category, whereas the Blomidon Formation of the Fundy Group and the Boss Point Formation of the Cumberland Group were assigned to the medium-risk category. Although the New Glasgow and Malagash formations of the Cumberland Group had slightly lower exceedance rates than the 5% threshold for the medium-risk category, these aquifers were associated with an anomalously high percentage of water well samples with uranium concentrations in the 10 to 20 µg/L range (24 – 36%) and were assigned to the medium-risk category. All other sedimentary aquifers in the province were assigned to the low-risk category.

Carbonate/Evaporite Groundwater Region

Distribution of Uranium and Summary of Exceedance Rates

Low to moderate concentrations of uranium are observed in the carbonate/evaporite groundwater region of Nova Scotia (Fig. 13, Table 4). The overall exceedance rate of the Health Canada (2019) uranium in drinking water MAC for carbonate/evaporite aquifers is about 2% (n = 212), and ranges from 0 to 10% for individual bedrock units (Table 4). The highest exceedance rate of the Health Canada MAC was observed in the Pugwash Mine Formation of the Windsor Group (Table 4) near the contact with the adjacent Malagash Formation of the Cumberland Group. Elevated arsenic has also been reported near this geologic boundary (Kennedy and Drage, 2017). In general, however, carbonate/evaporite aquifers are more likely to have elevated levels of uranium near a contact with a plutonic aquifer (e.g. community of Ingonish, Fig. 13) or where small deposits of Windsor Group sediments overlie plutonic aquifers (e.g. community of Glen Haven, Fig. 13). Approximately 64% (n = 11) of the well sample locations with uranium concentrations greater than 10 µg/L are within 1 km of a geologic contact with plutonic rocks.

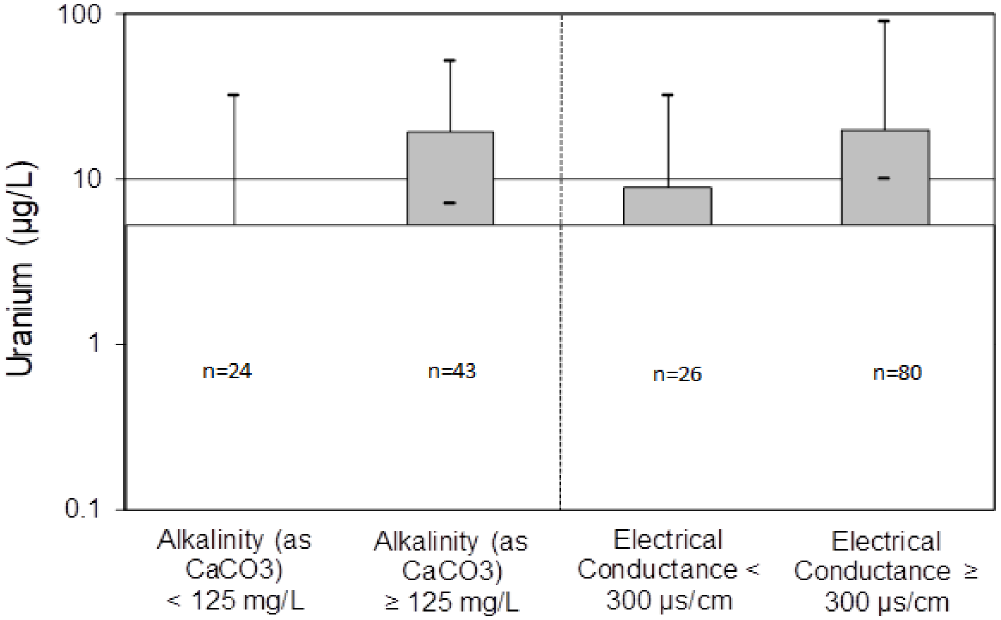

Figure 12. Censored box and whisker plot of uranium in well water in Pictou Group aquifers for alkalinity (as $CaCO_3$) <125 mg/L and ≥125 mg/L, and for electrical conductance <300 µs/cm and ≥300 µs/cm. The portion of the plot below the highest reported detection limit (e.g. 5 µg/L) is not shown. Tarone-Ware tests confirm that uranium concentrations associated with the higher alkalinity and electrical conductance groups were significantly greater than the respective lower groupings.

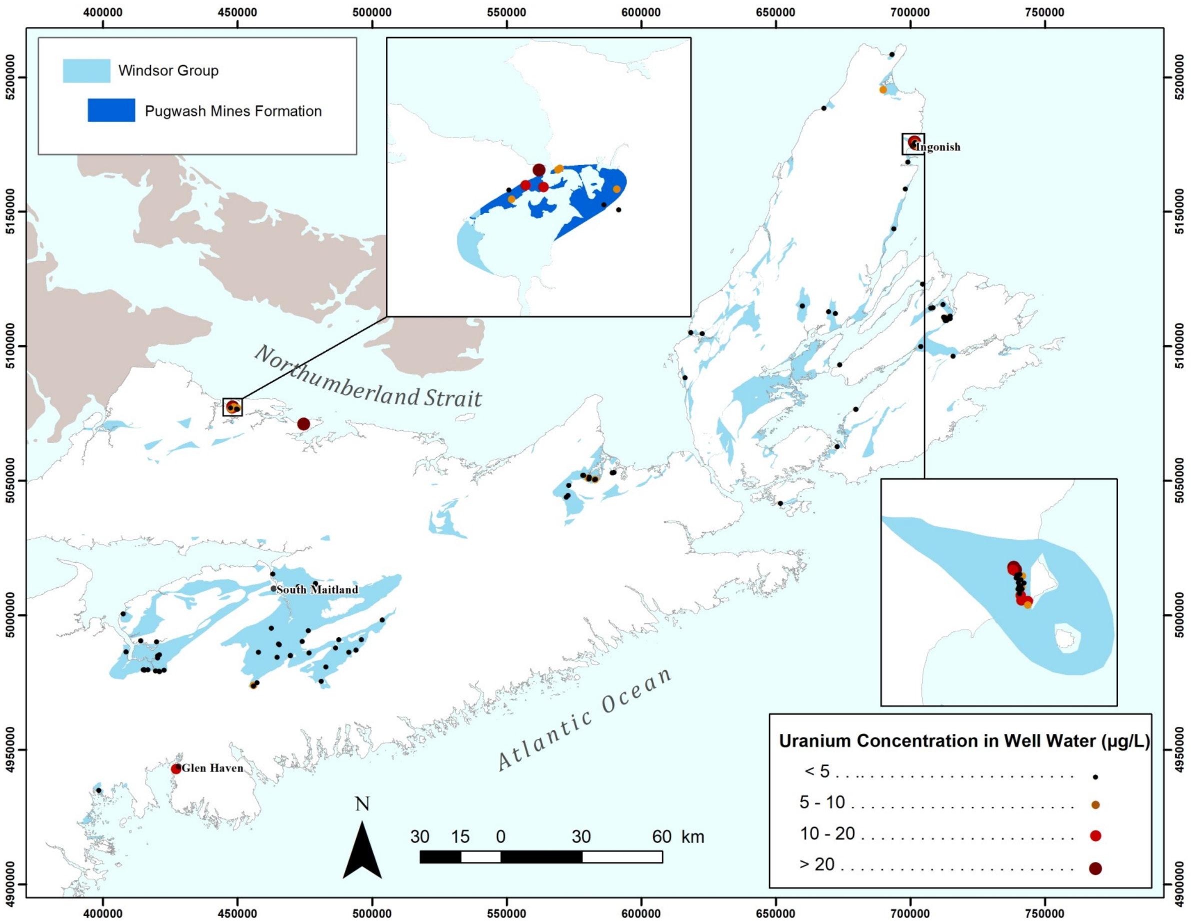

Figure 13. Concentrations of uranium in well water in the carbonate/evaporite groundwater region compared to bedrock geology.

Table 4. Percentage of water samples exceeding 10 and 20 µg/L of uranium in well water based on available data for various carbonate/evaporite bedrock units (aquifers) with at least five samples.

Bedrock Unit	Count	Per cent of uranium concentrations >10 µg/L	Per cent of uranium concentrations >20 µg/L
CARBONATE/EVAPORITE GROUNDWATER REGION (Windsor Group)	**212**	**5.19%**	**1.89%**
Carrolls Corner Formation	10	0.00%	0.00%
Green Oaks Formation	12	0.00%	0.00%
Hood Island Formation	32	0.00%	0.00%
Meadows Road Formation	18	0.00%	0.00%
Pugwash Mine Formation	10	30.00%	10.00%
Sydney River Formation	51	0.00%	0.00%
Woodbine Road Formation	8	0.00%	0.00%
White Quarry Formation	14	0.00%	0.00%
Mainland Nova Scotia - all	**87**	**5.75%**	**2.30%**
Cape Breton Island - all	**125**	**4.80%**	**1.60%**

Relation of Uranium to Lithogeochemistry and Aquifer Geochemistry

There are limited data available with respect to whole-rock concentrations of uranium in carbonate/ evaporite bedrock in Nova Scotia and few known occurrences of uranium-rich minerals in these rocks. MacFarlane (1983) reported average whole-rock uranium concentrations of about 2 ppm in Windsor Group rocks whereas a compilation of uranium whole-rock concentrations in Windsor Group rocks in central Cape Breton Island along the Windsor Group - Horton Group contact reported average concentrations of 5 ppm (Kirkham, 1978). The most widely reported occurrence of uranium enrichment in carbonate/evaporite rocks is located near the community of South Maitland at the base of the Windsor Group in the Macumber Formation (Charbonneau and Ford, 1978). Elevated concentrations of uranium, however, have not been detected in these aquifers (Table 4). In general, favourable conditions for uranium mobilization (e.g. alkaline pH, oxidizing environment) could develop in the province's carbonate/ evaporite aquifers, but groundwater concentrations of uranium in these aquifers are likely limited by low levels of uranium in the host bedrock.

Delineation of Risk Zones

Based on the uranium in well water exceedance rates of the Health Canada (2019) MAC presented in Table 4, the Pugwash Mine Formation was assigned to the medium-risk category. Where small deposits of Windsor Group rocks overlie plutonic rocks associated with a high risk for uranium in well water, the risk designation of the underlying plutonic rock aquifer was assigned to the carbonate/evaporite aquifer (e.g. near the communities of Ingonish and Glen Haven, Fig. 13). All other Windsor Group aquifers were assigned to the low-risk category for uranium in well water. Province-wide, there are fewer available uranium in well water data for Windsor Group bedrock aquifers due to the smaller areal extent of these aquifers and because dug wells are often preferred in these areas due to the unsuitable water quality (e.g. high sulphates, hardness, and total dissolved solids) of bedrock aquifers for domestic use. Additional well water sampling in areas with poor sample coverage is recommended to refine the delineation of the risk zones.

Metamorphic Groundwater Region

Distribution of Uranium and Summary of Exceedance Rates

Low concentrations of uranium are generally observed in the metamorphic groundwater region of Nova Scotia (Fig. 14, Table 5). The overall exceedance rate of the Health Canada uranium in drinking water

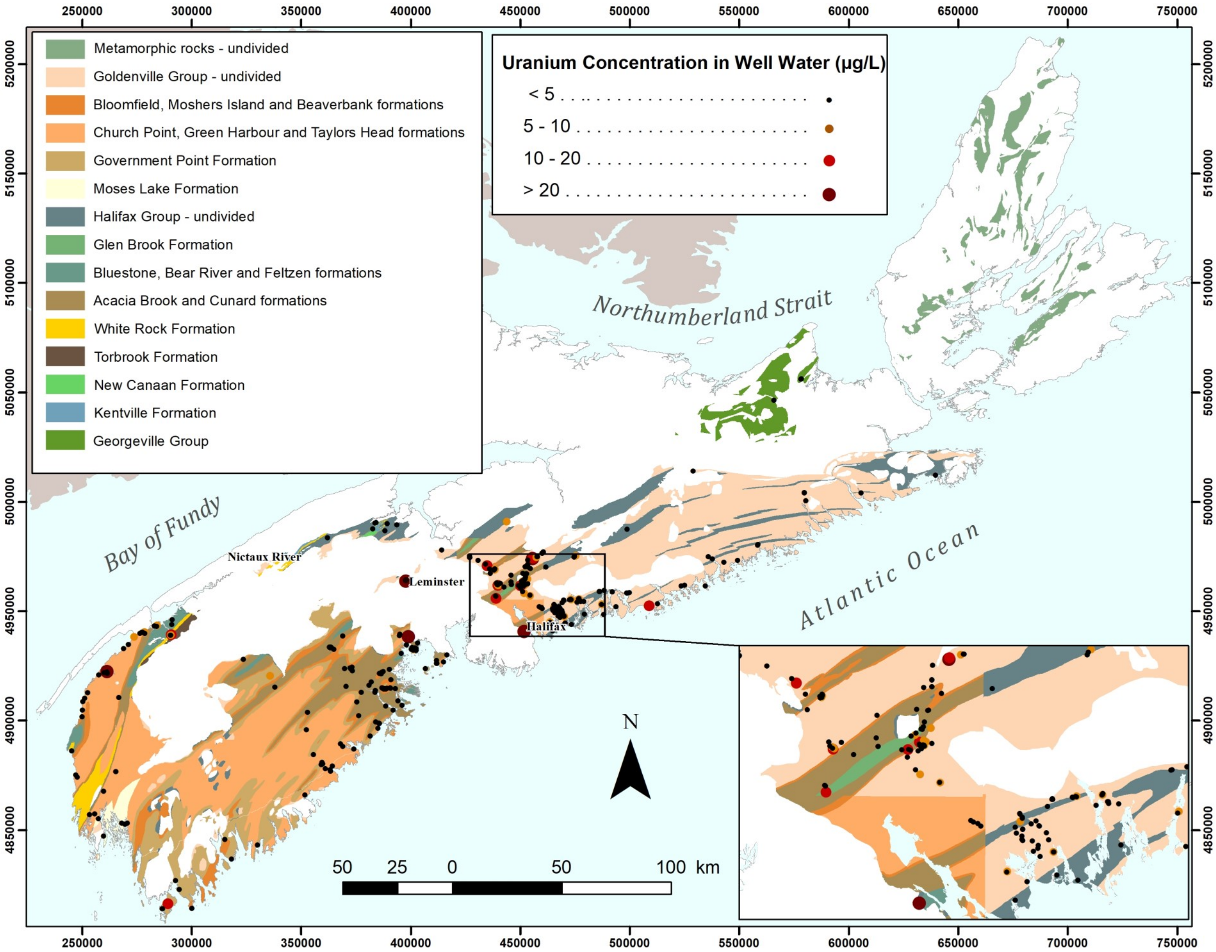

Figure 14. Concentrations of uranium in well water in the metamorphic groundwater region compared to bedrock geology.

Table 5. Percentage of water samples exceeding 10 and 20 µg/L of uranium in well water based on available data for various metamorphic bedrock units (aquifers) with at least five samples.

Bedrock Unit	**Count**	**Per cent of uranium concentrations >10 µg/L**	**Per cent of uranium concentrations >20 µg/L**
Metamorphic Groundwater Region	**485**	**3.09%**	**1.03%**
Goldenville Group	**287**	**3.14%**	**1.05%**
Goldenville Group - undivided	157	3.82%	0.64%
Beaver Bank Formation	7	0.00%	0.00%
Church Point Formation	22	4.55%	4.55%
Green Harbour Formation	31	3.23%	3.23%
Government Point Formation	32	3.13%	0.00%
Moses Lake Formation	5	0.00%	0.00%
Moshers Island Formation	25	0.00%	0.00%
Taylors Head Formation	6	0.00%	0.00%
Halifax Group	**184**	**2.72%**	**1.09%**
Halifax Group - undivided	38	2.63%	2.63%
Acacia Brook Formation	11	0.00%	0.00%
Bear River Formation	8	0.00%	0.00%
Cunard Formation	72	4.17%	0.00%
Feltzen Formation	39	0.00%	0.00%
Glen Brook Formation	9	0.00%	0.00%
Rockville Notch Group (White Rock Formation)	**9**	**12.50%**	**0.00%**

MAC for metamorphic aquifers is 1% (n = 485), and ranges from 0 to 4.5% for individual bedrock units (Table 5). Most occurrences of elevated uranium in metamorphic rock aquifers are located near a geological contact with plutonic rocks; a spatial trend that was also observed by the uranium task force (MacFarlane, 1983). As discussed earlier, the Neils Harbour orthogneiss unit (metamorphosed granitoid rocks) located in Cape Breton Island was considered as part of the plutonic groundwater region.

Relation of Uranium to Lithogeochemistry and Aquifer Geochemistry

Background average concentrations of uranium in metamorphic rocks are in the 2 to 4 ppm range (Kennedy and Drage, 2018). Favourable conditions for uranium mobilization (i.e. alkaline pH, oxidizing environment) could develop in metamorphic rock aquifers, but groundwater concentrations of uranium in metamorphic aquifers in Nova Scotia are likely limited by the low levels of uranium in the host bedrock.

There are few documented occurrences of uranium-rich minerals in metamorphic rocks in Nova Scotia, and where uranium mineralization has been identified it is typically proximal to plutonic rocks (e.g. Nictaux River mineral occurrence, Fig. 14). MacFarlane (1983) proposed that uranium mineralization could occur in metamorphosed rocks near granitoid rocks due to the migration of uranium-bearing fluids out of the cooling pluton into the surrounding rock. Three of the five uranium results from metamorphic aquifers exceeding the Health Canada (2019) MAC are within 600 m of a contact with peraluminous granitoid rocks. The distance to the contact may be even closer at depth. The highest uranium concentration associated with metamorphic rock aquifers (130 μg/L) occurs within the Leminster inlier (Fig. 14), near the contact between a thin band of intruded Halifax Group rocks and leucocratic monzogranitic rocks of the South Mountain Batholith (Fig. 14). MacFarlane (1983) also suggested that some of the wells in metamorphic rock aquifers near plutons could actually be in direct contact with the plutonic rocks at shallow depth. In comparison, Yang et al. (2014) found elevated concentrations of uranium and radon in metamorphic rocks within a distance of 5 to 10 km of exposed granite intrusions in the state of Maine, USA.

Delineation of Risk Zones

Based on the data shown in Table 5, all metamorphic bedrock aquifers had exceedance rates of less than 5%, and these aquifers were therefore categorized as low risk for uranium in well water exceeding the Health Canada (2019) MAC. In metamorphic aquifers near granitoid bedrock (i.e. <1 km), there may be a greater risk of encountering unacceptable concentrations of uranium in well water.

Volcanic Groundwater Region

Distribution of Uranium and Summary of Exceedance Rates

Low concentrations of uranium are typically found in the volcanic groundwater region of Nova Scotia (Fig. 15, Table 6). There were no exceedances of the Health Canada (2019) uranium in drinking water MAC in well water samples obtained from volcanic aquifers in Nova Scotia based on the available data (Table 6).

Relation of Uranium to Lithogeochemistry and Aquifer Geochemistry

Reported average whole-rock concentrations of uranium in volcanic rocks in Nova Scotia range from approximately 2 to 5 ppm (Kennedy and Drage, 2018). Uranium enrichment in some volcanic rocks (e.g. Paleozoic rhyolites) in Nova Scotia has been attributed to hydrothermal alteration (O'Reilly, 1982) or secondary processes (Dostal et al., 1983), such as low-grade metamorphism, which could lead to either enrichment or depletion of uranium. Although favourable conditions for uranium mobilization (e.g. alkaline pH, oxidizing environment) could develop in these aquifers, groundwater concentrations of uranium in volcanic rocks in Nova Scotia are likely limited by the low levels of uranium in the host bedrock.

Delineation of Risk Zones

Because the available data (Table 6) indicate that there are no exceedances for uranium in well water from volcanic rock aquifers in Nova Scotia, these bedrock aquifers were categorized as low risk for uranium in well water exceeding the Health Canada (2019) MAC. There are few available data for volcanic aquifers in Nova Scotia, however, due to the smaller areal extent of these aquifers relative to other groundwater regions and the low population density of areas underlain by volcanic aquifers. Additional sample coverage is recommended to address this data gap, especially in Cape Breton Island, and the Cobequid Highland and Antigonish Highland volcanic rock aquifers.

Uranium in Well Water Risk Map for Bedrock Aquifers and Demographics of Risk

The Uranium Task Force developed the first generation of uranium in well water risk map for the province, outlining two major types of bedrock in Nova Scotia where well water concentrations of uranium exceeding 10 µg/L have been detected (plutonic and Carboniferous basin rocks) (Grantham, 1986). A simplified version of this map was later republished by the Nova Scotia Department of Health (no date). In 2009, the Nova Scotia Department of Natural Resources published a revised uranium in well water risk map (Fig. 2; O'Reilly et al., 2009) that included the risk of related radionuclides occurring in well water and divided the province into areas that are 'more likely' and 'less likely' to have groundwater containing uranium and radionuclides exceeding acceptable limits.

Based on the analysis of the distribution of uranium in Nova Scotia's groundwater regions and exceedance rates of uranium in well water, compared to the Health Canada MAC for various bedrock units (Tables 1 to 5), a new risk map showing low- (<5% water samples exceeding Health Canada MAC), medium- (≥5 to <15%) and high- (≥15%) risk zones was developed (Fig. 16). The risk mapping followed a similar methodology as the approach used in the development of the arsenic in bedrock water well risk map (Kennedy and Drage, 2017). It is important to note that the risk map of uranium in bedrock water wells was developed based on bedrock geology, but occurrences of elevated uranium in Nova Scotia well water have also been shown to be locally influenced by anthropogenic activities, such as road salting (e.g. Drage and Kennedy, 2013) and the storage of construction and demolition debris (e.g. Letman et al., 2018). In addition, although it is not considered in the risk map, bedrock units generally associated with a low to moderate risk of uranium in well water may have an elevated risk of uranium near an exposed geologic contact (<1 km) with a granitoid rock aquifer.

Statistical comparison of the sample populations associated with the three zones using the Kruskal-Wallis non-parametric test found a significant difference ($p<0.05$) between the three categories of risk. The high-risk category covers about 17% of the province (Table 7) and captures approximately 88% of the exceedances of the Health Canada (2019) uranium in drinking water MAC reported in the study dataset (Table 7). The revised risk map offers significant refinement compared to the older version of the map, which had only two categories of risk. For example, only 9% of the uranium sample results less than 5 µg/L are located within the highest risk zone in the revised map, compared to 41% in the O'Reilly et al. (2009) version.

The distribution of private wells in Nova Scotia was inferred from the distribution of residential unserviced civic address points (see Kennedy and Polegato, 2017). The distribution of private wells compared to the risk zones shows that 80% of private wells in the province are located in the low-risk zone for uranium in well water, whereas 13% (~26,445 private wells or 51,483 persons) are located in the high-risk zone for uranium in well water (Table 7, Fig. 16). The ten communities with the greatest number of private wells are all located in suburban Halifax and are underlain, at least partially, by granitoid rocks of the South Mountain Batholith (Table 8). Many of the communities with the greatest

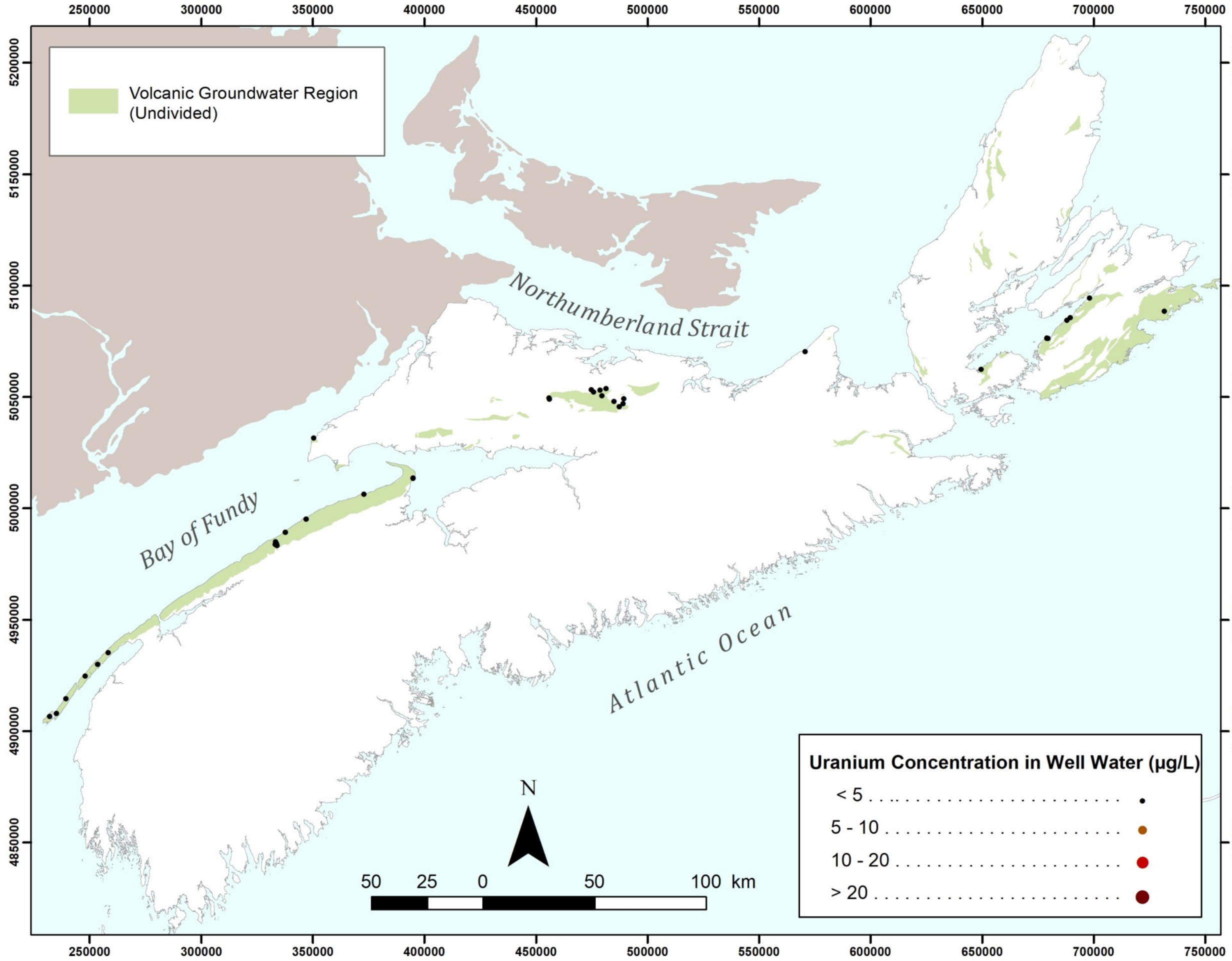

Figure 15. Concentrations of uranium in well water in the volcanic groundwater region compared to bedrock geology.

Table 6. Percentage of water samples exceeding 10 and 20 µg/L of uranium in well water based on available data for various volcanic bedrock units (aquifers) with at least five samples.

Bedrock Unit	Count	Per cent of uranium concentrations >10 µg/L	Per cent of uranium concentrations >20 µg/L
VOLCANIC GROUNDWATER REGION	68	0.00%	0.00%
East Bay Hills Group	10	0.00%	0.00%
Fountain Lake Group	12	0.00%	0.00%
Fundy Group (North Mountain Formation)	29	0.00%	0.00%

number of private wells in the high-risk zone for uranium in well water are also located in a high-risk zone for arsenic in well water (Table 8; Kennedy and Drage, 2017). The percentage of private wells (bedrock wells) with uranium exceeding the Health Canada (2019) acceptable limit of 20 µg/L was estimated by multiplying the calculated exceedance rate for each groundwater region (Table 1) by the approximate number of private wells located within each region. In total, approximately 6.5% of all private wells (~12,750 wells or 25,250 persons, adjusted for surficial wells) across Nova Scotia may have uranium concentrations exceeding the Health Canada (2019) MAC in their raw well water (Fig. 17).

Summary

At the levels of uranium found in some well water supplies in Nova Scotia, long-term ingestion of uranium can adversely affect kidney function. Bedrock geology is the most important provincial-scale control on the distribution of uranium concentrations in well water. The highest concentrations (i.e. >100 µg/L) and exceedance rates (i.e. >50%) of the Health Canada (2019) MAC were generally observed in the South Mountain Batholith aquifers, largely due to the presence of uranium in the granitoid rocks. The peraluminous South Mountain Batholith is associated with more evolved (i.e. felsic) granitoid rock units that tend to be enriched in incompatible elements, such as uranium. In addition to the South Mountain Batholith, the Black Brook granitic suite in Cape Breton Island, which also includes peraluminous granitoid rocks, and the Pictou Group in northern Nova Scotia were also associated with elevated concentrations and exceedances rates of the Health Canada (2019) MAC for uranium in drinking water. In total, approximately 95% of the uranium in groundwater concentrations greater than 50 µg/L were associated with South Mountain Batholith, Black Brook granitic suite, or Pictou Group aquifers.

Although favourable conditions for uranium mobilization could develop in other bedrock aquifer types across the province, groundwater concentrations of uranium in these aquifers are likely limited by the low levels of uranium in the host bedrock. Where well water concentrations of uranium were elevated in metamorphic and carbonate/evaporite bedrock aquifers, the water supply well was often located proximal (<1 km) to an exposed contact with a plutonic aquifer.

The present analysis demonstrated regional-scale trends, although it should be noted that there is significant spatial heterogeneity of uranium concentrations, which may be attributed to such factors as the availability of uranium minerals in contact with groundwater flow and the susceptibility of these minerals to weathering. For example, although both Horton and Pictou Group bedrock are known to have uranium enrichment and the aquifers have a similar geochemical environment, much lower uranium in well water exceedance rates were observed in Horton Group aquifers compared to Pictou Group aquifers. This finding suggests that the uranium in Horton Group rocks may be more resistant to weathering, possibly due to the presence of more organic-rich layers compared to Pictou Group bedrock. The aquifer geochemistry (e.g. pH, redox conditions, availability of complexing ions), which is influenced by local groundwater flow dynamics, is also important in determining uranium mobility. The focus of the present analysis with respect to geochemical controls on uranium mobility was the influence of pH and alkalinity (mainly bicarbonate and carbonate ions), and it was generally observed that higher levels of uranium in groundwater were associated with alkaline pH (i.e. 7 to 8.5) and higher groundwater alkalinity because carbonate ions can form soluble, stable complexes with the uranyl ion.

Province-wide it is estimated that about 6.5% (25,100 persons) of private well users may have uranium exceeding the Health Canada (2019) MAC in their raw water. The largest number of private wells users tend to occur in communities surrounding Halifax, where residential growth is concentrated. Many of these suburban Halifax communities are underlain by the South Mountain Batholith, which is associated with an elevated risk of uranium in well water.

The uranium in well water (bedrock wells) risk map (Fig. 16) offers a more refined characterization of risk across Nova Scotia compared to previous versions, and the risk characterization framework is better

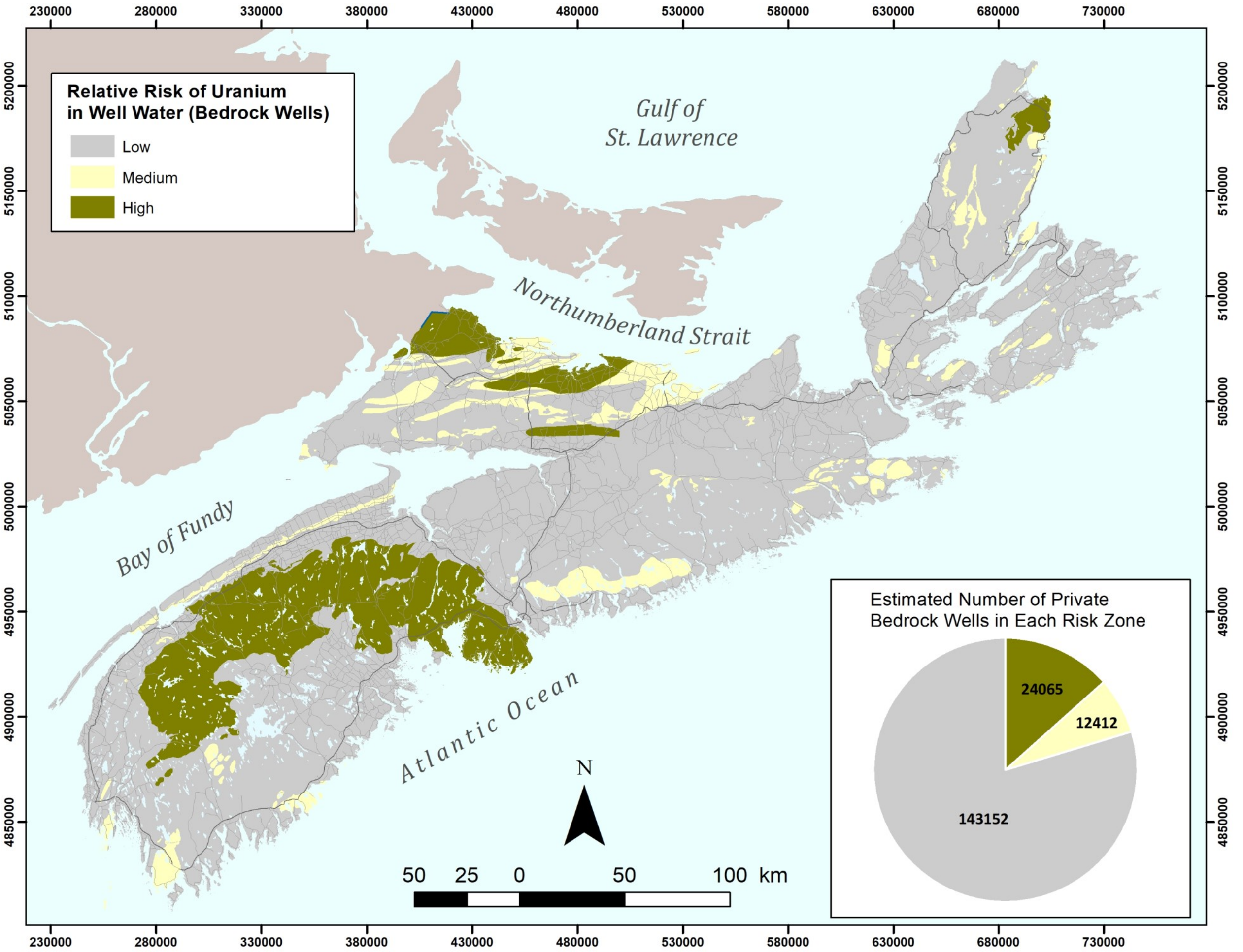

Figure 16. Risk map for uranium in well water from bedrock aquifers in Nova Scotia. The estimated number of private wells in each risk zone is also shown.

Table 7. The area of coverage, estimated number of private wells using bedrock aquifers, and per cent of well water samples exceeding 10 and 20 µg/L of uranium for each of the three risk zones. The analysis assumes that 91% of private wells are supplied by bedrock aquifers in Nova Scotia (see Kennedy and Polegato, 2017).

Risk Classification	Area of Coverage (km^2)	Per cent of Samples >10 µg/L (n = 466)	Per cent of Samples >20 µg/L (n = 276)	Estimated Number of Private Wells Using Bedrock Aquifers
High	9 374	76%	88%	24,065
Medium	4 317	14%	6%	12,412
Low	41 428	6%	6%	143,152

Table 8. The ten communities with the largest number of private wells located in a high-risk zone for uranium in well water. Communities denoted by an asterix (*) also appeared in the list of the ten communities with the largest number of private wells in a high-risk zone for arsenic in well water (Kennedy and Drage, 2017).

Community	Underlying High-Risk Bedrock Unit	County	Estimated Number of Private wells
Upper Tantallon*	South Mountain Batholith	Halifax	1342
Hammonds Plains*	South Mountain Batholith	Halifax	1205
Stillwater Lake*	South Mountain Batholith	Halifax	843
Hubley*	South Mountain Batholith	Halifax	802
Brookside*	South Mountain Batholith	Halifax	720
Williamswood	South Mountain Batholith	Halifax	675
Head of St. Margarets Bay*	South Mountain Batholith	Halifax	663
Whites Lake	South Mountain Batholith	Halifax	528
Hatchet Lake	South Mountain Batholith	Halifax	499
Boutiliers Point	South Mountain Batholith	Halifax	451

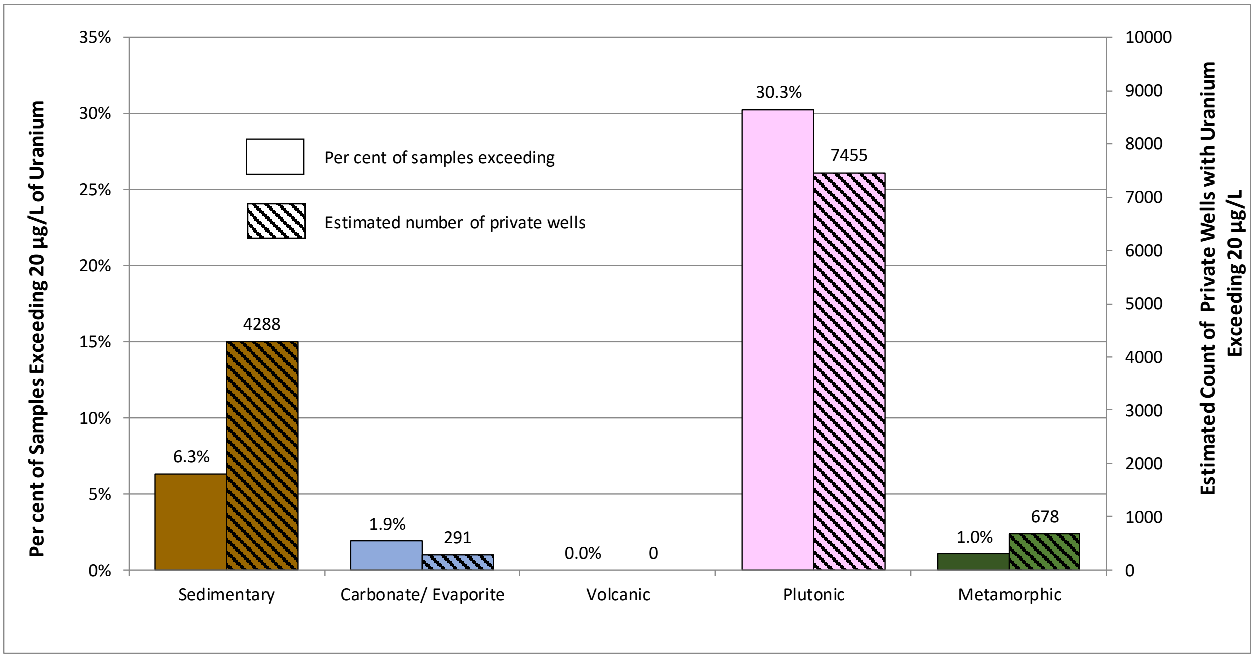

Figure 17. Exceedance rates of Health Canada's maximum acceptable concentration (MAC) of 20 µg/L uranium in drinking water for Nova Scotia's five major bedrock groundwater regions. Based on these exceedance rates, the number of affected private well owners (households) in each groundwater region is estimated.

aligned with recent provincial risk map products (e.g. radon in indoor air, arsenic, potential corrosivity of groundwater), which also include three levels of risk. The risk zones, however, should be subject to continuous evaluation as new groundwater chemistry data become available. Approximately 26,445 private wells (13%) or 51,873 persons in Nova Scotia are in the high-risk zone for uranium in well water.

The uranium in well water risk map will be used as a tool to raise risk awareness amongst private well users in Nova Scotia, and to promote appropriate testing and treatment of well water. Effective risk communication is essential to manage the risk of uranium exposure, and to reduce associated adverse health impacts and health care system costs. The uranium in well water risk map will be published as a web map application with an accompanying webpage, targeting private well owners and making it easier for them to access information about risk levels, water testing, and strategies to mitigate elevated uranium in their well water. The map may also be used to inform epidemiological research and land/groundwater supply planning and development.

Further Research

Several knowledge gaps and anomalies were identified during the preparation of the risk map. Additional targeted research, such as lab-scale analyses of how uranium is mobilized from various sedimentary rock types, would help to further develop the understanding of the distribution of, and the various hydrogeochemical controls on, uranium in well water in Nova Scotia. Additional uranium in well water sampling is recommended where there are gaps in water sample coverage, especially where there is a coincident large number of private well users relying on the aquifer for domestic water supply and the bedrock geology is associated with an elevated risk for uranium in well water.

Another important gap towards the understanding of risk to private well owners is the lack of survey information describing the percentage of well users with unsafe levels of uranium in their drinking water that have implemented successful mitigation strategies. There are also few data available on how risk communication and personal risk assessment affects the behaviours of private well owners with respect to testing their well water and implementing and maintaining appropriate water treatment (Chappells et al., 2014). This information would help inform the design of effective risk communication and public health intervention measures.

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References

Ayotte, J.D., Flanagan, S.M., and Morrow, W.S., 2007. Occurrence of uranium and 222 radon in glacial and bedrock aquifers in the northern United States, 1993–2003; U.S. Geological Survey, Scientific Investigations Report 2007-5037, 84 p.

Arzuaga, X., Gehlhaus, M., and Strong, J., 2015. Modes of action associated with uranium induced adverse effects in bone function and development; Toxicology Letters, v. 236, p. 123–130.

Barr, S.M., O'Reilly, G.A., and O'Beirne, A.M., 1982. Geology and geochemistry of selected granitoid plutons of Cape Breton; Nova Scotia Department of Mines and Energy, Paper 82-1, 176 p.

Barr, S.M., White, C.E., Fisher, B.E., McKinnon, J.S., Barras, A.L., Hapgood, D.S., 2017. DP ME 433, version 1, digital geological data generated as part of the bedrock geological mapping compilation project for Cape Breton Island, Nova Scotia; Nova Scotia Department of Natural Resources, Digital Product ME 433. < https://novascotia.ca/natr/meb/download/dp433.asp>

Barr, S.M., van Rooyen, D., and White, C.E., 2018. Granitoid plutons in Cape Breton Island, Nova Scotia, Canada: new U-Pb (zircon) age constraints and implications for correlations with peri-Gondwanan terranes in Newfoundland and New Brunswick; Atlantic Geology, v. 54, p. 21-80.

Blume, O., 2016. Synthetic leaching of uranium from South Mountain Batholith granites and Horton Group siltstones of south central Nova Scotia, using a suite of ionic complexes; B.Sc. thesis, Dalhousie University, Halifax, Nova Scotia, 76 p.

Brummer, J. J., 1958. Supergene copper-uranium deposits in northern Nova Scotia; Economic Geology, v. 53, p. 309–324.

Chappells, H., Campbell, N., Drage, J., Fernandez, C.V, Parker, L., and Dummer, T.J.B., 2014. Understanding the translation of scientific knowledge about arsenic risk exposure among private well water users in Nova Scotia; The Science of the Total Environment, v. 505, p. 1259–1273. doi:10.1016/j.scitotenv.2013.12.108

Charbonneau, B.W. and Ford, K.L., 1978. Uranium mineralization at the base of the Windsor Group, South Maitland, Nova Scotia; in Current Research, Part A; Geological Survey of Canada, Paper 78-1A, p. 419–425.

Chatterjee, A.K., 1977. Uranium mineralization at McLean Point, Cumberland County, in Mineral Resources Division, Report of Activities 1976; Nova Scotia Department of Mines and Energy, Report 77-1, p. 89-98.

Chatterjee, A.K. and Muecke, G.K. 1982. Geochemistry and the distribution of uranium and thorium in the granitic rocks of the South Mountain batholith, Nova Scotia: some genetic and exploration implications; in Uranium in Granites, (ed.) Y.T. Maurice; Geological Survey of Canada, Paper 81-23, p. 11–17.

Cheve, S., 1980. Assessment report, project 71-95 – Cape Breton, Indian Brook; Nova Scotia Department of Mines and Energy, Assessment Report 11K/02A.

Colman, J.A., 2011. Arsenic and uranium in water from private wells completed in bedrock of east-central Massachusetts- Concentrations, correlations with bedrock units, and estimated probability maps; U.S. Geological Survey, Scientific Investigations Report 2011-5013, 113 p.

Coyte, R.M., Jain, R.C., Srivastava, S.K., Sharma, K.C. Khalil, A., Ma, L., and Vengosh, A., 2018. Large- scale uranium contamination of groundwater resources in India; Environmental Science and Technology Letters, v. 5, p. 341–347.

Cumberland, S.A., Douglas, G., Grice, K., and Moreau, J.W., 2016. Uranium mobility in organic matter-rich sediments: a review of geological and geochemical processes; Earth-Science Reviews, v. 159, p. 160–185. https://doi.org/10.1016/j.earscirev.2016.05.010

Dinno, A. 2018. Dunntest: Dunn's test of multiple comparisons using rank sums; Stata software package. <https://alexisdinno.com/stata/dunntest.html>

Dostal, J., Dupuy, C., and Keppie, J., 1983. Uranium and thorium in Paleozoic rhyolites of Nova Scotia; Canadian Journal of Earth Sciences, v. 20, p. 266–274. doi:10.1139/e83-024

Drage, J. and Kennedy, G.W., 2013. Occurrence and mobilization of uranium in groundwater in Nova Scotia; Proceedings GeoMontréal 2013, Montréal, September 19 – October 3, 2013.

Drage, J., Baweja, A., and Wall, P., 2005. Naturally occurring radionuclides in Nova Scotia ground water; Canadian Radiation Protection Association Bulletin, v. 26, p. 13–22.

Dyck, W. and McCorkell, R.H., 1983. A study of uranium-rich reduction spheroids in sandstones from Pugwash Harbour, Nova Scotia; Canadian Journal of Earth Sciences, v. 20, p. 1738-1746.

Dyck, W., Chatterjee, A.K., Gemmell, D.E., and Murricane, K., 1976. Well water trace element reconnaissance, eastern Maritime Canada; Journal of Geochemical Exploration, v. 6, p. 139–162.

Felderhof, G.W., Phendler, R.W. and Park, G.M., 1979. Exploration report on Boisdale Hills claim group, EL-3469-3471; Nova Scotia Department of Mines and Energy, Assessment Report 11K/01C, 54-C-02(01).

Finlayson-Bourque, D., Kennedy, G.W., and Bickerton, G.S., 2010. Potential controls on uranium in new production wells intercepting a Triassic sandstone aquifer; Nova Scotia Department of Natural Resources, Mineral Resources Branch, Open File Illustration ME 2010-003.

Fisher, B.E., 2006a. DP ME 34, version 2, 2006, digital version of Nova Scotia Department of Natural Resources Map ME 1990-13, Cumberland Basin geology map of Oxford and Pugwash, Cumberland County, NTS 11E/12 and 11E/13, scale 1:50,000, by R.J. Ryan and R.C. Boehner; Nova Scotia Department of Natural Resources, Digital Product DP ME 34. http://novascotia.ca/natr/meb/download/dp034md.asp

Fisher, B.E., 2006b. DP ME 37, version 2, digital version of Nova Scotia Department of Natural Resources Map ME 1994-1, geological map of the South Mountain Batholith, western Nova Scotia, scale 1:250 000, by M.A. MacDonald; Nova Scotia Department of Natural Resources, Digital Product DP ME 37. http://novascotia.ca/natr/meb/download/dp037.asp

Fisher, B.E. and Poole, J.C., 2006. DP ME 43, version 2, digital version of Nova Scotia Department of Natural Resources Map ME 2000-1, geological map of the Province of Nova Scotia, scale 1:500 000, compiled by J.D. Keppie 2000; Nova Scotia Department of Natural Resources, Digital Product DP ME 043. http://novascotia.ca/natr/meb/download/dp043.asp

Geldsetzer, H.H.J., 1977. Preliminary geological interpretation of well water uranium anomalies, carboniferous basin, maritime provinces; Geological Survey of Canada, Department of Energy, Mines, and Resources, Ottawa, 16 p.

Grantham, D.A., 1986. The occurrence and significance of uranium, radium and radon in water supplies in Nova Scotia; Nova Scotia Department of Health; Nova Scotia Department of Mines and Energy, Open File Report 1986-70, 256 p.

Health Canada, 2009. Guidelines for Canadian Drinking Water Quality: Guideline Technical Document - Radiological Parameters; Radiation Protection Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario, 46 p.

Health Canada, 2019. Guidelines for Canadian drinking water quality: Guideline technical document – uranium; Health Canada, May 2019, Ottawa, 81 p.

Horne, R.J., Ryan, R.J., Corey, M.C., Fox, D.L., Ehler, A.E., McKinnon, J.S., and Fisher, B.E., 2009. DP ME 147, version 1, digital geological data generated from the Central Meguma Mapping Project, 1995-1999 and 2002-2004, in the Mount Uniacke area, Halifax and Hants counties, Nova Scotia, NTS Sheet 11D/13; Nova Scotia Department of Natural Resources, Digital Product, DP ME 147. http://novascotia.ca/natr/meb/download/dp147.asp

Kennedy, G.W. and Drage, J., 2018. A review and summary of activities related to uranium in Nova Scotia well water; Nova Scotia Department of Energy and Mines, Open File Report ME 2018-006, 34 p. <https://novascotia.ca/natr/meb/data/pubs/18ofr06/ofr_me_2018-006.pdf>

Kennedy, G.W. and Polegato, A., 2017. Where does our tap water come from? An analysis of domestic water source and supply demographics in Nova Scotia; Nova Scotia Department of Natural Resources, Open File Report ME 2016-006, 18 p. <https://novascotia.ca/natr/meb/data/pubs/17ofr04/ofr_me_2017-004.pdf>

Kennedy, G.W. and Drage, J., 2017. An arsenic in well water risk map for Nova Scotia based on observed patterns of well water concentrations of arsenic in bedrock aquifers; Nova Scotia Department of Natural Resources, Open File Report ME 2017-003, 33 p. <https://novascotia.ca/natr/meb/data/pubs/17ofr03/ofr_me_2017-003.pdf>

Kennedy, G.W. and Drage, J., 2008. DP ME 428, version 1, digital version of Nova Scotia Department of Natural Resources Open File Map ME 2008-3, Groundwater regions map of Nova Scotia; Nova Scotia Department of Natural Resources, Digital Product ME 428. <https://novascotia.ca/natr/meb/download/dp428.asp>

Keppie, J. D. (compiler), 2000. Geological map of the Province of Nova Scotia; Nova Scotia Department of Natural Resources, Minerals and Energy Branch, Map ME 2000-1, scale 1:500 000.

Kirkham, R.V., 1978. Base metal and uranium distribution along the Windsor-Horton contact, central Cape Breton Island, Nova Scotia; In Current Research Part B, Paper 78-1B, Geological Survey of Canada, Energy, Mines and Resources Canada, Ottawa, p. 121-136.

Kurttio, P., Komulainen, H., Leino, A., Salonen, L., Auvinen, A., and Saha, H., 2005. Bone as a possible target of chemical toxicity of natural uranium in drinking water; Environmental Health Perspectives v. 113, p. 68–72.

Langmuir, D., 1978. Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits; Geochimica Cosmochimica Acta, v. 42, p. 547–569.

Letman, M.M., Drage, J., Ryan, A., Lake, C., and Jamieson, R., 2018. Development of a leaching procedure to assess the risk of uranium leaching due to construction and demolition waste disposal; Waste Management, v. 78, p. 144–150. doi:10.1016/j.wasman.2018.05.038

MacDonald, M.A., Horne, R.J., Corey, M.C., and Ham, L.J., 1992. An overview of recent bedrock mapping and follow-up petrological studies of the South Mountain Batholith, southwestern Nova Scotia, Canada; Atlantic Geology, v. 28, p. 7–28.

MacFarlane, D.S., 1983. Appendix A: Uranium Task Force report: The hydrogeology and distribution of naturally occurring uranium in well water in Nova Scotia; in Grantham, D.A., 1986. The occurrence and significance of uranium, radium and radon in water supplies in Nova Scotia; Nova Scotia Department of Health; Nova Scotia Department of Natural Resources, Open File Report 1986-70, 223 p.

MacNabb, B.E. 1980. Report on exploration during 1980 for the Urancarb project, Nova Scotia, Lacana Mining Corporation; Nova Scotia Department of Mines and Energy, Assessment Report ME 1981-021, 29 p.

Nankamba, P.M., 2011. Metallogeny and environmental geochemistry of heavy metal mineralisation in the Horton Group, Windsor, Nova Scotia; M.Sc. thesis, Acadia University, Wolfville, Nova Scotia, 369 p.

Nova Scotia Department of Health, no date. Naturally occurring uranium in groundwater in Nova Scotia; Nova Scotia Department of Health, scale 1:710 000.

Nova Scotia Department of Energy and Mines, 2019. Nova Scotia Groundwater Atlas. Well water chemistry. Nova Scotia Department of Natural Resources. <https://fletcher.novascotia.ca/DNRViewer/?viewer=Groundwater>

O'Reilly, G.A, 1982. Uranium in Nova Scotia: A background summary for the uranium inquiry; Nova Scotia Department of Mines and Energy, Report 82-7, 122 p.

O'Reilly, G.A., Goodwin, T.A. and Drage, J.M., 2009. Map showing potential for uranium and related radionuclides in groundwater in Nova Scotia; Nova Scotia Department of Natural Resources, Mineral Resources Branch, Open File Map ME 2009-7, scale 1:1 000 000.

O'Reilly, G.A., Goodwin, T.A., McKinnon, J.S., Fisher, B.E., Cowper, S.L. and Drage, J., 2013. Map showing the potential for radon in indoor air in Nova Scotia; in Mineral Resources Branch, Report of Activities 2013, Nova Scotia Department of Natural Resources, Report ME 2014-001, p. 129-131.

Pothier, H., 2009. Potential for uranium mobility in a sandstone aquifer in the Bridgetown area, Nova Scotia; B.Sc. thesis, Dalhousie University, Halifax, Nova Scotia, 63 p.

Ryan, R.J. and O'Beirne-Ryan, A.M., 2007. Preliminary report on the origin of uranium occurrences in the Horton Group of the Windsor area, Nova Scotia; in Mineral Resources Branch, Report of Activities 2006, Nova Scotia Department of Natural Resources, Report ME 2007-1, p. 137-157.

Ryan, R.J. and O'Beirne-Ryan, A-M., 2009. Uranium occurrences in the Horton Group of the Windsor area, Nova Scotia and the environmental implications for the Maritimes Basin; Atlantic Geology, v. 190, p. 171–190.

Samolczyk, M.A., Spooner, I.S., and Stanley, C.R., 2012. A Model for uranium mobility in groundwater in the Grand Pré Region, Nova Scotia, Canada; Atlantic Geology, v. 48, p. 1–13.

Smedley, P., Smith, B., Abesser, C., and Lapworth, D., 2006. Uranium occurrence and behaviour in British groundwater; British Geological Survey, Groundwater Programme Commissioned Report CR/06/050N, 60 p.

U.S. Environmental Protection Agency, 2013. ProUCL version 5.0, statistical software for environmental applications for data sets with and without non-detect observations; National Exposure Research Lab, Environmental Protection Agency, Las Vegas, Nevada.

White, C.E., Fisher, B.E., McKinnon, J.S., and Ehler, A.L., 2012. DP ME 127, version 1, digital geological data generated as part of geological mapping of the Meguma terrane of southwestern Nova Scotia (1998-2010), Shelburne, Digby, Yarmouth, Annapolis, Queens, and Lunenburg counties, Nova Scotia; Nova Scotia Department of Natural Resources, Mineral Resources Branch, Digital Product DP ME 127. <http://novascotia.ca/natr/meb/download/dp127.asp>

White, C.E., MacDonald, M.A., Horne, R.J., Fisher, B.E., McKinnon, J.S., Barras, A.L., 2017. DP ME 440, version 1, digital geological data generated as part of geological mapping of the Halifax area (2007-2012), Halifax county, Nova Scotia; Nova Scotia Department of Natural Resources, Digital Product ME 440. <https://novascotia.ca/natr/MEB/download/dp440.asp>

White, C.E., Barras, A.L., McKinnon, J.S., 2018. DP ME 470, version 1, digital version of Nova Scotia Department of Natural Resources Open File Map ME 2018-001, Bedrock geology map of the Antigonish highlands area, Antigonish and Pictou counties, Nova Scotia; Nova Scotia Department of Natural Resources, Digital Product ME 470. < https://novascotia.ca/natr/meb/download/dp470.asp>

Yang, Q., Smitherman, P., Hess, C.T., Culbertson, C.W., Smith, A.E., Zheng, Y., and Marvinney, R.G., 2014. Uranium and radon in private bedrock well water in Maine: Geospatial analysis at two scales; Environmental Science & Technology, v. 48, p. 4298–4306. doi:10.1021/es405020k.