

Arsenic in private drinking water wells: an assessment of jurisdictional regulations and guidelines for risk remediation in North America

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ABSTRACT

Arsenic is a known carcinogen found globally in groundwater supplies due to natural geological occurrence. Levels exceeding the internationally recognized safe drinking water standard of 10 µg/L have been found in private drinking water supplies in many parts of Canada and the United States. Emerging epidemiological evidence confirms groundwater arsenic to be a significant health concern, even at the low to moderate levels typically found in this region. These findings, coupled with survey data reporting limited public adherence to testing and treatment guidelines, have prompted calls for improved protective measures for private well users. The purpose of this review is to assess current jurisdictional provisions for private well water protection in areas where arsenic is known to naturally occur in groundwater at elevated levels. Significant limitations in risk management approaches are identified, including inconsistent and uncoordinated risk communication approaches, lack of support mechanisms for routine water testing and limited government resources to check that testing and treatment guidelines are followed. Key action areas are discussed that can help to build regulatory, community and individual capacity for improved protection of private well water supplies and enhancement of public health.

Key words | arsenic, drinking water, North America, private wells, public health, risk remediation

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INTRODUCTION

Arsenic is a naturally occurring toxic metalloid that has been classified as a Group I human carcinogen known to cause bladder, kidney, lung and skin cancer (IARC 2004). As one of the most common poisons found in the

environment, arsenic represents a major global health risk through widespread presence in groundwater (World Health Organization 2003). Worldwide, arsenic poisoning is the second most important health hazard related to

drinking water, with only contamination by pathogenic microorganisms having a bigger impact (Van Halem *et al.* 2009). Arsenic can be introduced to the environment from anthropogenic sources, such as mining or agricultural pesticide use, or from natural geological sources due to erosion and weathering of soils and minerals. In groundwater supplies, arsenic is a particular health concern as it is present mainly in inorganic forms, as either arsenate (AsV) or arsenite (AsIII), which are more highly toxic to humans than organic forms (Health Canada 2006). The primary sources of exposure to inorganic arsenic are drinking water and foods, including rice and fruit juices (Dabeka *et al.* 1993; Meliker *et al.* 2006; Gilbert-Diamond *et al.* 2011; Davis *et al.* 2012). Uptake of arsenic from these different sources has proven difficult to quantify due to variable dietary habits, lifestyles and environments, but drinking water remains the major source of inorganic arsenic in areas of natural groundwater occurrence (Naujokas *et al.* 2013). Eating foods prepared with contaminated water is another key route for arsenic uptake.

The adverse health effects of arsenic strongly depend on dose, duration of exposure, and the nutritional status of the exposed population, but can range from skin lesions to mortality from cancers and cardiovascular diseases (Rahman *et al.* 2009). As epidemiological knowledge has developed, the list of health outcomes from long-term arsenic exposure in drinking water has expanded revealing effects on most bodily systems, including dermatological, respiratory, neurological, cardiovascular, immunological and endocrinological (Naujokas *et al.* 2013). A recent concern is that *in utero* and early childhood exposure to arsenic from drinking water can have serious long-term health implications, including cardiovascular disease, respiratory disease and mortality from cancers in adulthood (Farzan *et al.* 2013a, b).

Inorganic arsenic is naturally present at high levels in the groundwater of a number of countries, including Argentina, Bangladesh, Chile, China, India, Mexico, Canada, and the United States of America. In the most chronically affected region of Southeast Asia, it is estimated that more than 100 million people are at risk from groundwater arsenic contamination (Rahman *et al.* 2009), while in North America over 30 million people have been reported at risk of exposure to levels that pose a cancer risk (NRDC 2000). Health impact associated with drinking

water contaminants is an area of increasing policy and public concern in North America, where a large proportion of households depend on private wells that are not subject to legislated drinking water quality requirements for testing or treatment. In response to evidence of adverse health effects to children from drinking contaminated well water, the American Academy of Pediatrics (AAP) has recently called for long-term public health initiatives to promote private well water quality awareness, testing and treatment (Rogan & Brady 2009). The AAP's policy statement recommends that pediatric health care providers ask families if they drink water from a well at home and calls for state governments to make private well water testing convenient and inexpensive for families with children (Postma *et al.* 2011). However, it is unclear to what extent different state jurisdictions are currently following this recommendation for either chemical or bacterial testing, or what is being done to assist families if contaminants above drinking water guidelines are present.

The purpose of this review is to evaluate the effectiveness of current approaches to private well water management in areas of Canada and the United States where elevated arsenic levels are commonly found in groundwater. While this review focuses mainly on jurisdictions where high arsenic concentrations have been identified, a recent report by the US Geological Survey (USGS) shows that arsenic is a widespread national and regional, as well as a local, concern (Ayotte *et al.* 2011). Private water supplies are commonly defined as those that serve less than 25 people on a regular basis and/or have less than 15 service connections (Centers for Disease Control and Prevention 2011). This definition includes some small non-municipal drinking water systems on commercial premises, such as resorts, motels and restaurants. In this paper we focus on private residential wells, which we define as those that have been dug or drilled for the supply of drinking water to individual households, although we recognize that recommendations adopted for this population may be applicable to other groups. We first evaluate evidence for arsenic as a global health risk and describe how international and national standards for allowable concentrations of arsenic in drinking water have been established. Different jurisdictional approaches to private well water management in selected areas of elevated natural

arsenic occurrence are next reviewed in detail, focusing on institutional support for water testing, treatment and public awareness initiatives. The effectiveness of current management approaches in reducing arsenic risk exposure in privately sourced drinking water are subsequently assessed with reference to existing surveys of homeowner well water testing and treatment behaviors. Knowledge generated from our review is used to identify key action areas that can build regulatory, community and individual capacity for improved protection of private well water supplies.

BACKGROUND: ARSENIC IN DRINKING WATER

Public health risk evaluation of arsenic in drinking water

Arsenic has long been recognized as a carcinogen (Smith *et al.* 2002), and elevated arsenic concentrations in groundwater have been identified as a prevalent public health hazard worldwide (Hughes *et al.* 2011). A landmark epidemiological study of a southwestern Taiwanese population, published in 1968, was one of the first to document that a high level of arsenic in groundwater wells ($>300 \mu\text{g/L}$) was related to a high prevalence of skin cancer (Tseng *et al.* 1968). Later studies in the same region provided strong evidence of a dose-response relationship between drinking water arsenic concentrations and mortality due to cancers of the lung, liver, bladder and kidney (Chen *et al.* 1985, 1992; Wu *et al.* 1989). Since these seminal studies, high levels of arsenic in drinking water have been found to be associated with cardiovascular diseases, diabetes mellitus, neurological effects, adverse obstetric and pregnancy outcomes (Rahman *et al.* 2009).

Most evidence linking arsenic in drinking water with elevated risk of internal cancers comes from world regions where exposures have been high ($>100 \mu\text{g/L}$), with health associations at lower levels of exposure less frequently studied and thus more contested (Cantor & Lubin 2007). In 1999, the US National Research Council (NRC) reported, with respect to the rationale for establishing safe drinking water standards, that: 'no human studies of sufficient statistical power or scope have examined whether consumption of arsenic in drinking water at the maximum contaminant limit

[$50 \mu\text{g/L}$ at this time] results in increased incidence of cancer effects' (NRC 1999, p.7). A later review by the American Council on Science and Health found that there was little reliable evidence to determine the extent of detrimental health effects in humans from inorganic arsenic exposure at $50 \mu\text{g/L}$ or below (Brown & Ross 2002). More recently, evidence has emerged that chronic exposure to arsenic, even at low to moderate levels, is a contributor to many adverse health outcomes (Naujokas *et al.* 2013). Ingestion of drinking water with low to moderate arsenic levels has been found to increase the incidence of bladder and skin cancer, with this elevation in cancer risk seen primarily in smokers, suggesting that tobacco use is a significant modifier of arsenic toxicity (Karagas *et al.* 2001, 2004; Knobeloch *et al.* 2006). Another recent investigation of arsenic exposure from drinking water and chronic disease mortalities in Bangladesh reported increased mortality risk even at lower arsenic exposure ranges ($10\text{--}50 \mu\text{g/L}$) after adjusting for other risk factors, including smoking status, age, sex, body mass index, systolic blood pressure and education (Argos *et al.* 2010). Chronic exposure to low levels of arsenic in drinking water has been associated with increased risk for a range of other non-cancer health outcomes including hypertension, diabetes, coronary artery disease and poor cognition (Meliker *et al.* 2007; Navas-Acien *et al.* 2008; Ettlinger *et al.* 2009; O'Bryant *et al.* 2011). Arsenic is also a potent endocrine disruptor, even at low levels of exposure, producing potentially complex health effects (Hamilton 2013).

Arsenic is a contaminant of key concern for public health agencies because it has a number of intrinsic characteristics that can accentuate risk exposure, and make risk identification and remediation difficult. Risk perception studies have identified sensory or aesthetic factors as key prompts for awareness of drinking water quality issues (Doria 2010), but many contaminants, including arsenic, are not detectable in water through taste, smell or color. The presence of microbiological risk can often be detected through an immediate health effect on those that drink this water, as in the case of acute gastrointestinal illness from some strains of *Escherichia coli* (*E. coli*) where symptoms typically appear in a matter of hours or days. As a chronic health concern, arsenic ingestion produces a long latency between exposure and disease manifestation that can lead to the underestimation of risk and continued

exposure. If individuals underestimate risks from their water supply, they may fail to adopt stewardship actions (Summers 2010). Early life exposure to arsenic has been found to increase mortality from some forms of cancer (kidney, lung and bladder) for many years after high exposures have declined due to improved water supply or treatment (Yuan *et al.* 2010). The fact that people are routinely exposed to arsenic through combined contaminant pathways, including food and drinking water, can further increase exposure to health risks and make it difficult to attribute cause (Dabeka *et al.* 1993), or to apply appropriate corrective measures.

Establishing a safe limit for arsenic in drinking water

Establishing a guideline to regulate the maximum allowable concentration (MAC) of arsenic in public drinking water supplies has been a protracted process and the debate about tightening of these standards is ongoing. In 1958, the World Health Organization (WHO) recommended a MAC of 200 µg/L for arsenic in drinking water, lowered in 1963 to 50 µg/L. By the early 1990s the combined epidemiological evidence from Taiwan and other countries was sufficient to conclude that ingested arsenic was likely to cause several internal cancers (Smith *et al.* 2002). A key study at this time estimated that the lifetime risk of dying from cancer from daily ingestion of 1 L of water containing arsenic at 50 µg/L could be as high as 13 per 1,000 population exposed (Smith *et al.* 1992). The WHO arsenic guideline value was reduced to 10 µg/L in 1993, based on increasing concern regarding its carcinogenicity in humans. In the 1960s the US Public Health Service had first advised that water concentrations of arsenic should not exceed 10 µg/L (Smith *et al.* 2002), but uncertainties in quantifying the health risks from low levels of arsenic exposure meant that it took another four decades before this standard was adopted for public water supplies by the US Environmental Protection Agency (USEPA) in 2002 (Mushak & Crocetti 1995; Smith *et al.* 2002; Tiemann 2007). The Canadian standard for arsenic in public water supplies was lowered from a MAC of 25 to 10 µg/L in 2006 (Health Canada 2006). For private water supply in the USA and Canada there is no enforceable standard for

arsenic, but 10 µg/L serves as a recommended guideline for safe drinking water in most jurisdictions.

It is estimated that the attributable risk of bladder and lung cancer for US populations exposed to 10 µg/L of arsenic in drinking water over their lifetime is 12 and 18 per 10,000 population for females, respectively, and 23 and 14 per 10,000 population for males (WHO 2003). WHO guidelines usually designate that no substance should have a contributory lifetime cancer risk of more than 1 in 100,000 population, which has prompted environmental organizations, such as the US Natural Resources Defense Council (NRDC), to argue that an arsenic guideline below 1 µg/L is required to attain a negligible lifetime cancer risk (NRDC 2000). In response to scientific uncertainties in health risk evaluation, the WHO guideline value of 10 µg/L has been designated as provisional since 2008. This 10 µg/L guideline is also regarded as a practical limit by the USEPA and Health Canada given current arsenic detection capability. Reliably quantifying arsenic at levels <3 µg/L is difficult using current standard laboratory equipment (Health Canada 2006). Remediation to lower guideline levels can also be costly; USEPA data project that a national arsenic standard of 2 µg/L would cost \$2.1 billion per year to implement for public water supplies with regard to required treatment system upgrades (Van Halem *et al.* 2009).

Technical limitations and financial consequences notwithstanding, some jurisdictions have adopted stricter arsenic guidelines for drinking water than the WHO guidelines. In Denmark, the national guideline has been lowered to 5 µg/L (Van Halem *et al.* 2009) and this lower limit has also been adopted in the US state of New Jersey (New Jersey Geological Survey 2004). While most developed countries have now adopted a standard of 10 µg/L, many less developed countries retain a 50 µg/L drinking water limit for arsenic due to a lack of sampling programs, analytical equipment or funding for enforcement of lower standards (Henke 2009). Based on continued uncertainties about safe levels of arsenic in drinking water, the most recent WHO guidelines published in 2011 reiterate the provisional status of the 10 µg/L guideline on the basis of both treatment performance and analytical achievability, with the proviso that every effort should be made to keep concentrations as low as reasonably possible. This precautionary

approach is echoed in technical guidelines issued by the USEPA and Health Canada (Health Canada 2006).

Arsenic occurrence in groundwater in North America

Due to underlying geology, arsenic is known to be a contaminant of water supplies in many parts of North America but is a particular concern in areas where a high proportion of drinking water is sourced from private residential wells (Welch *et al.* 2000; Wang & Mulligan 2006; DeSimone 2009). Around 45 million people in the United States (15% of the population) obtain their water from private wells that are not required to meet the drinking water arsenic standard. Table 1 shows the proportion of private well usage for selected states where arsenic is widespread in groundwater and studies have reported elevated levels in private wells. Concentrations of naturally occurring

arsenic in groundwater vary regionally due to a combination of climate and geology. Arsenic measurements from approximately 31,000 mainly private wells and springs across the United States have been collated by the USGS. These data show that about 10% of wells exceeded the guideline standard of 10 µg/L (Welch *et al.* 2000), with significant variation in exceedances by region (see Table 1). Widespread high concentrations (>50 µg/L) are found mainly in the West, the Midwest, and the Northeast of the country. In eastern New England, the analysis of water use and arsenic concentration exceedance rates indicates that approximately 100,000 people with private wells may have water supplies with elevated arsenic concentrations above 10 µg/L (Ayotte *et al.* 2003). Arsenic in the range of the highest concentrations found in Bangladesh have also been found in private wells in the USA, with maximum recorded levels as high as 3,000 µg/L (Naujokas *et al.* 2013).

Table 1 | Evidence of arsenic exceedance in private wells in selected regions of the United States and Canada

Country	State/ Province	Number of private wells/% homes or population served ^a	Evidence of As exceedance (% of wells found to be over stated guideline) in areas specified
United States	Maine	250,000 individual wells/ 42% of homes	More than 25% of sampled wells in 44 towns exceeded 10 µg/L (Nielsen <i>et al.</i> 2010)
	Massachusetts	200,000 individual wells/ 8% of homes	13% of 478 sampled wells in east-central Massachusetts exceeded 10 µg/L (Colman 2011)
	Michigan	>1 million individual wells/29% of homes	Estimated 8% of the population in southeastern Michigan exposed to arsenic in drinking water over 10 µg/L (incl. public/private systems) (Meliker <i>et al.</i> 2006)
	Minnesota	480,000 individual wells/ 26% of homes	Statewide sampling results indicate that approximately 14% of private wells may exceed 10 µg/L. In western Minnesota 50% of 900 sampled wells >10 µg/L (Erickson & Barnes 2005)
	New Hampshire	190,000 individual wells/ 37.5% of homes	19% of 353 sampled wells tested in southeastern New Hampshire >10 µg/L (USGS 2003)
	New Jersey	300,000 individual wells/ 10% of homes	3.4% of 17,714 wells tested >10 µg/L (12% >5 µg/L, NJ State MCL) (NJDEP 2008)
	Wisconsin	680,000 individual wells/ 25% of population	11% of 2,233 wells tested in 19 rural townships >20 µg/L (Knobeloch <i>et al.</i> 2006)
Canada	British Columbia	Est. 63,000 private wells/ 8% of population	4.2% of 2,100 wells tested >10 µg/L (BC Ministry of Environment 2007). In Surrey-Langley area 43% of the 98 wells tested in 2008 >10 µg/L (Wilson <i>et al.</i> 2008). 23% of 258 wells tested in Sunshine Coast >25 µg/L (Carmichael <i>et al.</i> 1995)
	New Brunswick	100,000 private wells/22% of population	5.9% of 10, 563 groundwater samples tested >10 µg/L (Government of New Brunswick 2008)
	Nova Scotia	Est. 150,000 private wells/ 40% of population	9% of samples tested in Environmental Chemistry Laboratory (Halifax) between 1991 and 1997 above 25 µg/L (Nova Scotia Department of Environment 1998)
	Saskatchewan	Est. 66,000 private wells/ 7.7% of population	16% of 1108 wells tested >10 µg/L (Peterson & Sketchell 2003)

^aData on number of private wells and proportion of well water users are taken from US Census Bureau (1990) and Environment Canada (2011).

An estimated 13% of Canadians, or approximately four million people, rely upon private wells as a source of drinking water (Charrois 2010). Estimates for private well water quality across Canada suggest that between 20 and 40% of private wells may fall outside of safe drinking water quality guidelines for either biological or chemical contaminants (Van der Kamp & Grove 2001). Availability of information on the degree of arsenic exposure in drinking water at a national level in Canada is limited (McGuigan *et al.* 2010), but most provinces and territories report some areas where arsenic can be detected in private drinking water supplies (Table 1). Documented hotspots, where concentrations of arsenic above 10 µg/L have been consistently recorded, are southern British Columbia, Alberta, Manitoba, northeastern Saskatchewan, New Brunswick, Newfoundland and Labrador and Nova Scotia. Arsenic in groundwater is especially prevalent across parts of eastern Canada where some rock formations contain significant amounts of the mineral arsenopyrite. This includes the province of Nova Scotia where private wells with arsenic levels above 500 µg/L have been reported at multiple sites (Meranger *et al.* 1984).

CURRENT APPROACHES TO MANAGING ARSENIC RISK EXPOSURE IN PRIVATE WATER WELLS

Regulatory frameworks for private well water management

Public water systems in Canada and the USA are legally required to provide drinking water with arsenic concentrations below the standard guideline limit of 10 µg/L, but water quality in private wells is unregulated (McGuigan *et al.* 2010). In the USA, the EPA regulates public drinking water supplies under the Safe Drinking Water Act (SDWA), providing the legally enforceable standard for arsenic and other regulated contaminants. However, for the 15% of US households that use a private well the quality of drinking water is not regulated under the SDWA (Focazio *et al.* 2006; USEPA 2013a). Federal and state government monitoring and testing of water quality in these wells is minimal with the consequence that drinking water officials do not have nationally consistent data and information

about the quality of water being consumed by a large proportion of American people (Focazio *et al.* 2006). It has been observed that there are limited data on the location of unregulated drinking water sources, populations served and potential contaminants present, making assessment of public health risks a major challenge (Backer & Tosta 2011).

Health Canada has responsibility at the federal level for drinking water issues in Canada, including establishing contaminant guideline values (McGuigan *et al.* 2010). In most Canadian provinces and territories, drinking water quality issues are the responsibility of either the environment or public health agency. Regulation of drinking water quality from public municipal supply systems, including enforcement of the arsenic standard, is overseen by these agencies, but water quality from private wells serving single-family homes is unregulated. Private well users are advised by the relevant government agency to have their supply tested regularly for arsenic and other chemical and bacterial contaminants but there is no legal requirement to comply with these recommendations (Charrois 2010). The 13% of Canadian households that receive drinking water from a private well are thus responsible for monitoring their own drinking water quality. As in the USA, the management of private water wells in Canada has been found to pose a number of problems with one report on well water stewardship in Ontario concluding that: 'Management (of private water wells) is typically not undertaken in a dedicated way and intervention to correct well problems is usually carried out reactively. Much of this situation can be attributed to a general lack of awareness about water wells, water quality issues and well maintenance procedures by the well owner' (Novakowski *et al.* 2006, pp. 7–8).

Although there is no formal regulation for water quality in private wells, national and local government agencies have a key role in promoting contaminant risk awareness and in advising on water testing and treatment practices. To evaluate and compare these jurisdictional interventions in private well management, we comprehensively reviewed published and online materials produced by government drinking water agencies (federal, state, provincial and territorial) regarding well water testing and treatment. This material was used to assess the current capacity of these agencies to deliver effective groundwater protection and health promotion strategies for private well water users. In our assessment of this material

we compared testing and treatment recommendations in over 20 Canadian and US jurisdictions where it has been reported that well users are potentially exposed to drinking water arsenic at levels above recommended health guidelines. Key findings were selected to indicate points of consistency and variance in jurisdictional guidelines for well water safety. Cases of managerial best practice in promoting well water protection are further highlighted and the role of non-government agencies, such as realtors, private testing and treatment companies, and community-based water and health organizations, in assisting with delivery of these programs is discussed. Data from well water user surveys are drawn upon to assess the effectiveness of current public awareness approaches, particularly with relation to reported homeowner compliance with government testing and treatment recommendations.

Well water testing activities

Table 2 summarizes recommendations for frequency of well water testing for arsenic issued by drinking water authorities across selected Canadian and US jurisdictions with known arsenic occurrence. While this does not include all jurisdictions where arsenic can be found in wells it provides a useful demonstration of the range of variability in testing guidelines. Uncertainties about arsenic variability in well water are reflected in different recommendations for arsenic testing frequency issued to well owners, with some authorities advising testing annually, while others suggest that testing only once ever is adequate. In some jurisdictions it is observed that testing only once is adequate as arsenic in groundwater will not vary much over time (e.g. Minnesota), while other state agencies report that because levels change over time annual testing is recommended (e.g. Wisconsin). There is some evidence that arsenic concentrations in wells remain relatively stable over time and thus annual or bi-annual testing may offer little value to the accuracy of health surveillance (Thundiyil *et al.* 2007). However, variation in arsenic release into groundwater has also been documented in some local situations where the lowering of the water table can allow oxidization of arsenic-rich aquifers, causing a chemical reaction that hastens release of arsenic into groundwater (Kreiss *et al.* 1983). Certain conditions, such as flushing of mains and pipes, may also

result in transient increase of arsenic levels at customers' taps, especially where systems contain iron pipes (USEPA 2007a). Arsenic concentrations are known to vary in relation to the type of well construction and depth, with water from deeper drilled wells generally having higher arsenic concentrations than that drawn from shallow or dug wells due to groundwater having prolonged contact with bedrock that allows for weathering and release of arsenic. Some jurisdictions also issue more detailed guidelines regarding the special times at which water should be tested but this is not common practice. For example, Alberta's public health agency advises testing for chemical contaminants after a long period of non-use, transfer to a new home, or when families are expecting a newborn.

Typical costs for arsenic testing in different jurisdictions are also reported in Table 2, with considerable variance indicated in the cost of single contaminant testing. Many testing laboratories offer a variety of different packages covering different parameters, which requires well owners to have some knowledge of prevalent water quality risks in their local area. Testing for multiple contaminants, as recommended by most drinking water authorities, can present a significant cost burden for households. For example, testing costs in Nova Scotia can range from CA\$15 for a single chemical parameter to \$230 for the more extensive suite of chemical parameters recommended by the provincial government. In relation to the AAP's recommendation that state governments should provide free or subsidized testing to low-income families (Rogan & Brady 2009), progress appears to be slow. Financial support for well water testing is already offered in some areas but this is an uncommon practice and testing for arsenic and other chemicals is often ineligible. For example, Ontario and Manitoba have free or subsidized bacteriological water testing services but do not offer support for chemical testing (Kreutzwiser *et al.* 2010; Manitoba Office of Drinking Water 2010). Alberta does have a free chemical testing service for homeowners using untreated groundwater as a drinking water source, but this is not offered at point of property transfer (Government of Alberta 2014).

It has been reported that many homeowners have difficulty in interpreting water quality test results returned from laboratories and that scientific results of water analysis are often presented without further explicit guidance on

Table 2 | Recommendations for frequency and cost of arsenic testing for selected Canadian and US jurisdictions

Country	Jurisdiction	Frequency of arsenic (As) testing recommendation ^a	Cost of arsenic (As) test
Canada	Alberta ^b	Every 2–5 years or after long period of non-use, transfer to a new home, or expecting a newborn	Free chemical testing of <i>untreated</i> groundwater for homeowners every two years; excludes at property transfer
	British Columbia ^c	Annually, or every 3–5 years depending on results	Not specified
	Manitoba ^d	Every 3–5 years in areas with elevated levels, more frequently if As is detected at or near drinking water guideline	Not specified; varies annually
	New Brunswick ^e	Every 2 years	From CA\$15
	Newfoundland & Labrador ^f	At least once/periodically	Not specified
	Nova Scotia ^g	Every 2 years	From \$15
	Ontario ^h	Not specified	CA\$25–50
	Quebec ⁱ	Required for new wells, otherwise at least once	Not specified
	Saskatchewan ^j	Depends on location	CA\$28
	Yukon ^k	Two consecutive years initially, then every 5 years (for chemicals)	CA\$43
United States	Maine ^l	Every 3–5 years, or when you are expecting a baby, annually on water treated for a problem	US\$20
	Minnesota ^m	At least once or twice	US\$30–40
	Michigan ⁿ	Related to changes in water use, e.g. lower well level or period of inactivity	US\$18
	New Hampshire ^o	Every 3–5 years and when moving into a new home	US\$15
	New Jersey ^p	Not specified, required for real estate transfer	<US\$50
Wisconsin ^q	Test at least once, or annually if arsenic is present	US\$16–24	

^aDetails from private well water websites and printed materials published by environment or public health authorities responsible for well water monitoring in selected jurisdictions.

^bAlberta Health Services (2009).

^cHealthLink BC (2013).

^dGovernment of Manitoba (2014).

^eGovernment of New Brunswick (2014).

^fGovernment of Newfoundland & Labrador (2013).

^gNova Scotia Environment (2008).

^hOntario Ministry of the Environment (2007).

ⁱGouvernement du Québec (2002).

^jGovernment of Saskatchewan (2012).

^kGovernment of Yukon (2014).

^lMaine CDC (2012).

^mMinnesota Department of Health (2013).

ⁿMichigan Department of Environmental Quality (2013).

^oNew Hampshire Department of Environmental Services (2011).

^pState of New Jersey Department of Environmental Protection (2010).

^qWisconsin Department of Natural Resources (2005).

actions to take in the case of contamination (Jones *et al.* 2006; Kreutzwiser *et al.* 2010). We found that most testing laboratories direct well owners to the relevant environmental or public health agency in their jurisdiction for further advice on test results and remediation options. The public health agency in New Brunswick was the only one we found to contact well owners directly with advice on appropriate corrective action in cases where contaminant results exceeded guideline levels, but whether homeowners actually apply treatment is not monitored.

Specific water testing requirements for newly constructed wells have been introduced in some jurisdictions. In New Brunswick, the Potable Water Regulation requires that all new wells must be tested for bacteriological and inorganic components, including arsenic, but such regulations do not cover existing wells (Government of New Brunswick 2012). Where a property is being transferred into new ownership it is common, although not universal, practice for mortgage and lending institutions to request a well water potability certificate before loan approval, which may

include a requirement for arsenic testing in areas where this is known to exist. Some US jurisdictions, including Oregon, New Jersey and Rhode Island, have taken the further step of enacting legislation that requires private well water testing at the point of real estate transaction to ensure that potential purchasers are aware of the quality of their drinking water source (Novakowski *et al.* 2006; Rogan & Brady 2009). Under the requirements of the New Jersey Private Wells Testing Act (PWTA), which became effective in 2002, sellers must test wells for a variety of regulated parameters (including arsenic in regions where this is a known problem) before a house can be sold and information must be disclosed to buyers (New Jersey Department of Environmental Protection 2009). When a parameter limit is exceeded, the testing laboratory must notify the NJDEP within 5 days and they must immediately notify the appropriate health authority so they may contact homeowners with advice on treatment. Whether this advice is followed is at the homeowners' discretion and public health authorities can only recommend corrective actions such as treatment installation, having no enforcement role to ensure that treatment is applied.

Well water treatment activities

Applying water treatment is a responsibility of well owners, but drinking water agencies provide advice on different options for arsenic removal. For example, in Wisconsin the state public health agency produces a comprehensive list of different methods to reduce exposure to arsenic, with advice on key advantages and disadvantages for homeowners. These options include using bottled water for drinking and cooking, installing a point of use (POU) treatment system at the kitchen faucet, installing a point of entry (POE) system to treat all water coming into the home, drilling a new well or connecting to a public water supply. Many treatment systems are available that can remove arsenic from drinking water including reverse osmosis (RO), steam distillation, iron oxide filters, anion exchange and activated alumina systems (Health Canada 2006). Suitability of treatment systems for a household depends on a number of site-specific considerations including the chemistry of drinking water, level of arsenic and other contaminants present, and the perceived need to treat all water entering a home or only selected taps (Health

Canada 2006). RO is commonly used for removal of arsenic from drinking water in small residential systems due to its relative affordability, effectiveness in treating multiple contaminants and low maintenance requirements (USEPA 2000). Laboratory and field-testing results have reported that RO filters can reduce arsenic concentrations by up to 99% (USEPA 2000), but this performance is only achievable for AsV removal. Where AsIII is present, pre-treatment with an oxidation unit is usually required for conversion of AsIII to the more easily removable form. Effectiveness of RO membranes can also be affected by the presence of chlorine and hardness, necessitating pH adjustment after installation. Competing ions in water are a limiting factor in the effectiveness of anion exchange systems, and this type of treatment is also not effective for As(III) removal. Activated alumina systems can be more expensive than other systems, but have proven more effective in removing both species of arsenic (Sargent-Michaud *et al.* 2007). Drilling a new well is another option available to homeowners but this can be expensive and there is no guarantee that the new well will remain arsenic free over time (Government of Wisconsin 2009). In Wisconsin, the Department of Natural Resources operates a Well Compensation program that offers financial assistance to eligible well owners for new well construction, connection to a community water supply or treatment system installation. Eligibility criteria include having a contaminated private water supply that serves a residence with arsenic concentrations above 50 µg/L, verified by the results of two water tests from a certified laboratory, and having a family income of less than US\$65,000 (Wisconsin Department of Natural Resources 2005). In response to very high arsenic concentrations found in wells in some parts of northeastern Wisconsin, special well construction standards were also established in 2004 for new wells in affected counties (Wisconsin Department of Natural Resources 2005).

Commercial treatment systems do not always guarantee safe drinking water, which may add to public uncertainty around their effective use. Since arsenic is tasteless and odorless, homeowners may be unaware when treatment devices are not removing arsenic from the water. A survey of 19 homes where RO filtration systems were used found that arsenic concentrations averaged 443 µg/L before installation and 87 µg/L after installation, with post-filtration

concentrations higher than 10 µg/L in ten homes and higher than 100 µg/L in four homes (George *et al.* 2006). Another study in rural Nevada found that out of 59 households with RO systems installed, 18 still exceeded the arsenic concentration of 10 µg/L (Walker *et al.* 2008). These studies suggest that the effectiveness of such systems can be variable due to poor maintenance practices, improper set-up and differences in water chemistry. Given the limitations of current treatment systems, Health Canada and most regional jurisdictions advise that once systems are operational, a sample of treated water should be tested at an accredited laboratory to ensure that the system is attaining the desired level of arsenic removal. Periodic testing at an accredited laboratory is also recommended by most regulatory agencies on both the water entering a treatment device and the water it produces to verify that the device is operating correctly. Compliance with this recommendation is almost certainly suboptimal given cost and convenience barriers, and as noted in the case of Alberta's free chemical testing, this does not apply to treated water.

As selection of an appropriate treatment system can be very complex, homeowners are usually advised by drinking water agencies to contact a reputable water treatment specialist for advice. They are also generally advised to use only systems that have been certified by an accredited body as meeting the appropriate drinking water treatment unit standards. However, finding a reputable supplier and the most appropriate system can present challenges for homeowners due to limited regulation of the treatment industry. Homeowners are cautioned to beware of unethical businesses that may try to sell unnecessary treatment equipment, perform unacceptable water tests or use improper construction methods for wells. Such concerns are not unfounded. In a Pennsylvania study it was found that 10% of well owners surveyed had purchased unnecessary treatment equipment (Clemens *et al.* 2007), and other well water survey results suggest that obtaining impartial advice on treatment options is a widespread problem.

Another limitation on selection and installation of treatment systems is cost. Data from the National Ground Water Association (NGWA) in the United States show that the capital cost for a whole house POE arsenic treatment system is ≥US\$3,000, while a single-tap POU system is generally ≤US\$500 (NGWA 2009). Treatment system operating

costs quoted by the NGWA are <US\$500 per annum (POE) and <US\$100 per annum (POU) (NGWA 2009). These costs relate to the three most popular types of arsenic treatment technology: RO (membrane technology), ion exchange technology and adsorption media. However, it has been reported that quotes from treatment specialists even for the same type of system can vary widely and there is little standardization of costs across the industry. Government financial assistance for water treatment for low-income homeowners is rare although a few agencies offer temporary solutions to assist homeowners. In New York, if a homeowner discovers contaminants in their well, the state will provide water on an emergency basis or put special filters on the tap. The New Jersey Housing and Mortgage Finance Agency's 'Potable Water Loan Fund' also offers zero interest loans up to \$10,000 to owners of single-family residences whose well water test fails to meet the primary drinking water standards.

Public education and outreach programs

Government environment and public health agencies across Canada and the USA incentivize and educate owners of private wells to take action to secure safe drinking water in various ways. At the federal level, Health Canada provides an arsenic factsheet, which gives information on toxicity, testing, and treatment. Several national organizations in the USA provide information on well water management via their websites, including the USEPA, Centre for Disease Control and Protection and NGWA (USEPA 2013a; CDC 2013; NGWA 2013). The NGWA also supports a National Ground Water Awareness Week to educate the public about the importance of well water stewardship. State and provincial environment and public health agencies provide well water information to the public through their websites including, at a minimum, an online fact sheet about arsenic in drinking water. A recent Canadian review found that arsenic information comes from multiple agencies rather than being compiled into one centralized source and that this can lead to confusion for well owners trying to access reliable and consistent information on drinking water quality and health risks (McGuigan *et al.* 2010).

In some areas well water quality awareness programs, incorporating community workshops or home visits, have been developed for rural residents. These programs include

the US 'Home*A*Syst' initiative, which has supported self-guided well assessments and workshops across 38 states since 1990, including promotion of well water testing. Another initiative is the Master Well Owner Network in rural Pennsylvania, a federally funded program providing water well management training to community volunteers and homeowners (Swistock *et al.* 2009). In Canada, similar workshop-based well water programs have been developed in Alberta (Government of Alberta 2012) and British Columbia (Regional District of Nanaimo 2013), with federal-level support from Agriculture and Agri-Food Canada. In New England, where 20% of the total population obtains water from a private well, the regional EPA has partnered with various State Drinking Water agencies and University-based Cooperative Extension Services to promote well testing, protection and maintenance through hosting community workshops and school-based activities (USEPA 2013b). Ontario's 'Well Aware' initiative, which has been operating since 2002, offers free home visits and community forums to educate well owners on local groundwater issues and to encourage testing for multiple contaminants (Novakowski *et al.* 2006; Green Communities Canada 2013). Although arsenic in drinking water is not the primary concern in this region, Well Aware has reportedly proven successful in encouraging more frequent well water testing. Dedicated well water awareness programs are limited in other Canadian provinces, including in the Atlantic region where arsenic in well water is a major concern. In Nova Scotia, the Environmental Home Assessment Program (EHAP) offers advice on well management and testing through home visits, but this reaches only a fraction of the 40% of households in the province on a private well water supply. It has also been reported that provincial well water programs, including Well Aware and EHAP, have been subject to erosion of funding capacity over time (Novakowski *et al.* 2006; Government of Nova Scotia 2013).

REPORTED EFFECTIVENESS OF WELL WATER PROGRAMS IN REDUCING ARSENIC RISK EXPOSURE

Information on water testing and treatment behaviors of private well owners is not routinely collected by drinking water

agencies in either the USA or Canada, such that there are limited national or local data regarding compliance with government guidelines. For example, in Nova Scotia, where arsenic levels above 25 µg/L have been reported in 9% of wells (Nova Scotia Department of Environment 1998), there are limited published data about homeowner arsenic testing or treatment application. Several independent well water surveys have found high confidence in well water quality even where routine testing for most drinking water contaminants is limited (Jones *et al.* 2006; Novakowski *et al.* 2006; Swistock *et al.* 2009; Kreutzwiser *et al.* 2010; Summers 2010), but none of these studies have addressed arsenic specifically. An investigation of private well water stewardship practices of 1,567 Ontario residents found that 90% had tested well water quality at least once, but that 65% had tested only once every two years or less frequently (Kreutzwiser *et al.* 2010, 2011). Notably, very few of these Ontario residents had tested their water for parameters other than bacteria and most had only taken action when there was a noticeable problem with their well water supply related to changes in taste, color or odor (Novakowski *et al.* 2006; Kreutzwiser *et al.* 2010). A survey of 1,014 well users in Alberta found that many well owners expressed confidence in the safety of their water supply even if they had no water test results or preventative measures in place (Summers 2010), underscoring the gap that exists between public and expert risk knowledge. Other survey findings underline another key point: that knowing about a water quality problem does not necessarily translate into action to avoid unsafe drinking water. As reported in the Alberta well water study, even when well users indicated they understood the need for regular testing or application of treatment, reported stewardship practices often fell short of recommended measures (Summers 2010). With respect to homeowner treatment practices, another survey conducted in Churchill County in Nevada, where there had been widespread media publicity about high levels of arsenic in drinking water, found that the majority of respondents (72%) consumed water from private wells but only a minority (38%) applied treatment. Of the 351 well water samples tested in this community, 74% were found to exceed arsenic levels of 10 µg/L (Walker *et al.* 2005). These findings demonstrate that not all households, even in a known arsenic cluster area, will necessarily invest in risk averting behavior.

Reasons why households do or do not comply with government recommendations for testing or for treatment application relate to a complex interplay of psychological, social and economic factors (Severtson *et al.* 2006). Commonly reported barriers that constrain good stewardship actions are inconvenience of water testing, lack of knowledge of testing guidelines, inability to identify contaminants of concern or to interpret test results, uncertainty over the reliability of treatment companies and the performance of treatment systems. A detailed discussion of these is available in the published literature (Jones *et al.* 2006; Novakowski *et al.* 2006; Swistock *et al.* 2009; Kreutzwiser *et al.* 2010; Summers 2010). Several studies have found that financial constraints are less of an impediment to regular testing than convenience factors (Kreutzwiser *et al.* 2010; Summers 2010). This has been demonstrated in situations where well users have not always selected the most rational economic option for risk aversion. For example, a study in an arsenic cluster area of Wisconsin found that many residents concerned about contaminant exposure chose to purchase bottled water for drinking (Jakus *et al.* 2012), while a home water treatment system would in most cases have been a more cost-effective remediation option (Sargent-Michaud *et al.* 2007). This is further supported by an evaluation of a range of different arsenic avoidance strategies for households in Maine, which reported that an RO POU system is the most cost-effective option for households of more than one person (US\$411 annually), compared to bottled water options which ranged from US\$650–4,700 annually dependent on bottled water type (e.g. haulage, coolers, containers) and household size (Sargent-Michaud *et al.* 2007).

Data from private well user surveys highlight deficiencies in water quality risk communication for private well users but there is evidence that some local awareness measures can be effective. With relation to evidence from both North American and international studies, intervention and outreach strategies to engage well owners in good management practice have been shown to influence risk aversion behavior, with more intensive and integrated strategies proving most effective. Evaluation of the Well Aware pilot project in Ontario has shown that people are up to five times more likely to take immediate action to fix problems with a private well if they are visited at home by a peer well owner rather

than receiving guidance through generic information dissemination or public awareness events. It is reported that 86% of Well Aware participants have followed the recommendations of home advisors and that the visit had a ripple effect with participants speaking to others regarding the visit and about what they had learned about wells (Federation of Canadian Municipalities 2009). In 2006, an expert panel commissioned to evaluate the Well Aware program, reported that participants are more likely to understand basic well stewardship principles than non-participants and that the initiative has 'created an empowering climate in which the well owner progresses far beyond regulatory requirements and approaches the maintenance of their well as a progressive, site specific and continual process' (p. 75) (Novakowski *et al.* 2006). While these results imply that integrated community intervention programs can significantly improve well water monitoring, still relatively few provinces or states in North America have introduced such initiatives for arsenic or other contaminants, and even successful programs, such as Well Aware, face difficulties in obtaining continuation funding.

In New Jersey an evaluation of the effectiveness of the PWTA in the period 2002–2007 found that 12% of more than 12,000 wells tested between September 2002 and April 2007 had arsenic above the New Jersey maximum contaminant level of 5 µg/L (NJDEP 2008). However, regulatory requirements for arsenic testing under the PWTA relate only to counties with a known regional occurrence and there is a possibility that regions outside these jurisdictions may also be contaminated but that well owners may be complacent about or unaware of the risk. As part of a comprehensive educational component, the PWTA has encouraged significant efforts to educate stakeholders in private wells management (e.g. buyers, sellers, landlords, renters, municipal officials, health agencies, realtors and certified laboratories), but a recent evaluation of the program suggests improvements can still be made with regard to stakeholder training and better health-related information regarding specific contaminants affecting communities, including arsenic (NJDEP 2008). Well water intervention programs can be costly to implement and this may act as a disincentive for regulatory agencies facing budgetary constraints. Programs to support well water testing at the point of well construction or at property transfer have

reported significant cost barriers. An assessment of the PWTA in New Jersey found the cumulative cost of acquiring well test data from 50,000 wells between 2002 and 2007 (as reflected in the expenses incurred by sellers, buyers, the NJDEP and the county and municipal health authorities) was approximately US\$40 million (Atherholt *et al.* 2009). Additional costs for health authorities to support the PWTA program, including notification, follow-up sampling, public outreach and education, have been estimated to be between US\$1.5 and US\$3 million per year (Atherholt *et al.* 2009).

Barriers related to enforcement of well water testing legislation present another problem. In Oregon, where legislation has been enacted that requires private well testing at the point of real estate transaction, there is currently no penalty for non-compliance. In this context, the need to make sales contingent on completion of testing and notification of results to all parties has been highlighted (Hoppe *et al.* 2011). In other areas, it has been remarked that home sellers may have little incentive to test their well water because of rules related to disclosure of test results to buyers (Boyle *et al.* 2010). For example, in Maine if a well water test is conducted, the results must be revealed to the buyer, but the law does not require the seller to have the water tested in the first place. Concerns have also been expressed that disclosure of information on arsenic contamination at a community level may lower property values. A study in two Maine towns where 14% of private wells were found to have arsenic concentrations exceeding the then EPA standard of 50 µg/L showed that there was a significant, but temporary, 2–3 year decrease in property prices (Boyle *et al.* 2010). It is noted, however, that this was a much shorter effect on property prices than has been observed for Superfund site areas where prices can be depressed for a decade, and that a property specific contamination incident that is treatable, such as arsenic contamination, may not have such a long-lasting effect on sale prices (Boyle *et al.* 2010).

DISCUSSION: ACTION AREAS TO ENHANCE PRIVATE WELL WATER MANAGEMENT

Limited regulation of private well drinking water systems presents a major challenge for the remediation of the

widespread and significant public health risk posed by arsenic in well water in North America. Our review indicates several key barriers that may limit the capacity of well owners to practice effective risk remediation, including inadequate understanding of testing requirements, inconsistency in testing guidelines, lack of follow-up monitoring of testing compliance or treatment application, difficulty in identifying trusted sources of impartial specialist treatment advice, ineffective enforcement of private wells testing legislation, and insufficient funding for subsidized testing, treatment and community-based stewardship programs. The complexity of private drinking water systems facing multiple and diverse contamination issues can further complicate risk communication challenges through the need for tailored testing and treatment advice. More positively, our review highlights several options that drinking water authorities and other stakeholders operating at a national, regional or local level can utilize to facilitate improved water quality monitoring and arsenic remediation activities practiced by households. The key capacity-building actions at a regulatory, community or individual level indicated from our review are summarized in Figure 1, and discussed below.

Monitoring compliance with guidelines

The need for improved monitoring of well user compliance with testing and treatment guidelines is highlighted in our review. Baseline data on testing and treatment practices of North American well owners are not centrally collected by state or provincial government agencies, and as a consequence stewardship behaviors with regard to arsenic and other contaminants are poorly understood. Effective arsenic risk remediation strategies need to be informed by a comprehensive quantitative and qualitative understanding of the personal, contextual and habitual factors that underpin testing and treatment practices. These baseline data deficits regarding well stewardship practices need to be urgently addressed for all areas where arsenic is a known contaminant of wells. Collecting such information is an important first step for informing the design of locally appropriate interventions targeted to different priority groups of risk-susceptible well users such as households with children or low-income rural residents.

- **Monitoring compliance with guidelines:** Collecting baseline data on compliance with testing and treatment recommendations among different population groups as the basis for targeted interventions
- **Enforcing action on exceedances:** Establishing integrated systems to ensure test results are acted upon and procedures for follow-up treatment are applied in cases of contamination
- **Facilitating risk communication:** Evaluating different risk communication challenges across population sub-groups, and developing support networks with relevant community-based knowledge brokers
- **Consistency in risk messaging:** Standardizing information on water testing parameters, processes and results reporting, to reduce complexity for well users
- **Forging cooperation:** Sharing knowledge around effective well water stewardship education and interventions through regional cooperation between jurisdictions experiencing common contaminant risks
- **Establishing credibility of experts:** Establishing a system for accreditation of well water treatment providers to ensure reliable and credible advice on appropriate systems and consistency in costs of treatment
- **Ensuring continuation of efforts:** Developing long-term strategies to ensure continuation of testing behaviors and treatment maintenance to achieve a continuous cycle of intervention
- **Making well water protection convenient:** Provision of infrastructure and financial support to assist well owners in access to testing and treatment options
- **Full cost-evaluation of protective measures:** Establishing feasibility studies to comprehensively assess the social, health and economic costs and benefits of different intervention packages within different local contexts and communities

Figure 1 | Capacity-building action areas to reduce arsenic exposure in private wells.

Connecting contaminant knowledge to remedial action

Few state or provincial drinking water agencies are directly notified by private or public health laboratories of water test results from individual wells and thus have no way of monitoring treatment application by homeowners. Even where public health agencies are directly notified of a contaminant exceedance, enforcement of remedial action is not supported by legislation. More integrative approaches, including stricter enforcement of testing disclosure rules and follow-up remediation practices, or an obligation for sellers to identify and correct serious water problems at point of property transfer, could prove effective risk management tools in this regard. Pediatric health advocates, professional societies such as the Canadian or American Pediatric Society and cancer care agencies should play a key role here in promoting legislative change for contaminant disclosure and treatment enforcement, especially

where children are potentially exposed to high levels of arsenic in drinking water.

Facilitating risk communication channels

Public perception studies have shown that providing health risk information does not necessarily prompt behavioral change (Krewski *et al.* 2002), such that access to online fact sheets alone may do little to allay public concerns or prompt action to avert risk. Risk communication studies further describe how the effectiveness of messaging techniques, including public relevance, local applicability and method of exchange, can define how receptive people are to risk information and whether they act upon this (USEPA 2007b). A key message from this literature is that effective risk communication for drinking water and other hazards requires interactive exchange between stakeholders. Home visits and engagement of community volunteers and

organizations have been shown to be very effective methods in the exchange of locally relevant contaminant risk information to well owners but these methods are underutilized and underfunded in many areas of elevated arsenic risk. Identifying and training key knowledge brokers that could assist well users in understanding testing requirements in a local area is one communication channel that could be better utilized. An example would be engaging real estate agents in awareness activities for newcomers to rural areas unfamiliar with managing private water supplies or to high-light specific local contaminant risks.

Multi-stakeholder coordination and cooperation

Well water survey respondents have reported uncertainties with relation to required frequency of testing, the selection of parameters for testing and how to interpret test results. National water quality experts, state and provincial drinking water agencies and local testing laboratories should collaborate in producing clearer and more consistent testing guidelines. These should be tailored to reflect specific regional and local contaminant risks and to ensure relevancy to different communities. Initiatives like Ontario's Well Aware program show how integrated community-based approaches to well water intervention, involving expert home visits and interactive workshops, generate an empowering climate for well owners to practice more effective risk remediation. Stewardship programs based on cooperation between multiple regulatory and community stakeholders, such as this, need to be part of a long-term, coordinated and strategic initiative with guaranteed federal as well as provincial funding to maintain intensity of program application. As arsenic occurrence is aligned to geology rather than jurisdictional boundaries, there is unrealized potential to develop cross-jurisdictional cooperation in well water education and stewardship programs. In New England, where university extension services have collaborated with state government agencies, such engagements have helped to produce more consistent well water recommendations and created opportunities to share experiences of successful forms of community intervention. While such efforts are not yet well coordinated and integrated elsewhere, there is significant scope for regional and cross-national cooperation between well water agencies and non-governmental stakeholders to coordinate

action for knowledge transfer and arsenic risk remediation in private wells.

Facilitating routine testing

Well water interventions such as point of property transfer legislation have proven effective in encouraging well owners to test their water at least once and should be explored by all jurisdictions, but other mechanisms are required to encourage regular testing behaviors. An example is the suggestion for a British Columbia by-law to make annual or semi-annual testing or treatment maintenance obligatory to ensure continued arsenic identification and removal (Mattu & Schrier 2000). Incentives such as tax credits for households that test water and apply remediation could provide another useful health promotion tool to encourage ongoing well water stewardship. Enrolling public health and safety agencies to promote annual or seasonal reminders to test drinking water, as with annual smoke alarm testing reminders or groundwater awareness months, are other possible route to establish new stewardship routines. Performance data should also be collected on whether or not households continue to monitor and maintain these systems over the long term in order to identify barriers to ongoing care of well water supplies.

Improving the credibility of well water remediation specialists

Previous studies have reported that homeowners are often unaware of their specific needs with regard to water treatment and that many have unnecessary treatment systems installed in their homes. Treatment systems can be especially complex for chemical contaminants like arsenic when compared to simpler measures such as shock chlorination for alleviating some bacterial problems. There are many different systems that can reduce arsenic concentrations but making an informed choice as regards the best fit for a household requires sound advice from remediation experts. Federal and provincial level agencies should provide an improved accreditation process to validate the expertise of water remediation specialists, to ensure consistency of advice for well owners and to allow for some standardization of treatment system costs and quality assurance across the industry.

Federal and provincial stakeholders that might play a key role in this process include government drinking water agencies, groundwater associations and trade associations representing remediation experts.

Improving access to well water testing and treatment

Noted barriers to regular testing of private wells include cost and inconvenience of laboratory facilities. Most jurisdictions in North America do not offer free or subsidized arsenic testing for low-income families or those that have difficulties accessing testing facilities (e.g. families with young children, those with disabilities or rural homeowners), even in areas where there is a known environmental health risk. This could be dealt with through a system of nonrefundable tax credits. Increasing pick-up locations, mobile laboratories and on-line ordering of bottles are other simple capacity-building measures to incentivize rural well owners to test drinking water that can be relatively easily implemented. Establishing such support systems has been proven to assist well users, as in a study in Ontario, where facilitating ease of sample collection and drop-off was shown to double sampling rates for bacterial and nitrate contaminants by private well users (Hexemer *et al.* 2008). Community-based non-governmental organizations (NGOs) or health clinics could be enrolled to coordinate such activities locally with government funding made available to support them. In a 2000 report, the US NRDC called for increased federal and state funds to assist households with treatment systems and upgrades to remove arsenic from tap water (NRDC 2000). Some financial assistance for on-site water treatment is available through the US Department of Agriculture (USDA) Rural Development's Home Improvement and Repair Loans and Grants Program for very low-income homeowners in qualifying communities (USDA 2013). The development of such programs for both Canadian and American rural well owners facing financial hardship represents another priority action area, as does dedicated allocation of federal and provincial funding for such initiatives.

Comprehensive cost-evaluation

Finally, we acknowledge that interventions in arsenic remediation require comprehensive evaluation in different local

and regional contexts to examine their social and economic feasibility. An initiative such as New Jersey's PWTA incurs significant expenditure and may not prove an easily transplantable model for other regions. However, this should not deter feasibility studies of similar programs for other areas but should underscore the importance of including a comprehensive cost-benefit analysis in well water intervention planning. A key priority is to ensure that such cost evaluations fully consider the averted costs to the health care and social welfare system of well water interventions to reduce arsenic and other drinking water contaminants, but to our knowledge such data are not currently available.

CONCLUSION

Arsenic is a naturally toxic element with carcinogenic and many other adverse health outcomes that is present in a significant proportion of drinking water wells worldwide. In some regions, major public health crises have raised the profile of this invisible contaminant, but the true extent of exposure risk is still not fully understood or recognized in North America. This has resulted in a misleading perception of low risk exposure and limited public health interventions. Frameworks for private well management are currently inadequate in supporting well owners in risk identification or remediation. Well monitoring is placed in the hands of individual well owners that have demonstrated variable capacity to avert risk. In recognition of this major public health concern, a number of health organizations in North America have begun to advocate for improved regulatory frameworks to manage the significant risk posed by arsenic and other contaminants in private wells. By reviewing the current status of cross-jurisdictional well water intervention programs in areas susceptible to natural arsenic occurrence, this paper has identified key barriers to arsenic risk remediation and highlighted examples of best practice in overcoming these. Government agencies and other key stakeholders involved in promoting improved well water stewardship practices should act to fully evaluate and enable the critical capacity-building action areas for arsenic risk remediation in private wells we have highlighted in this review. Our review indicates that as well as a need for regulatory enforcement there are many other underutilized

opportunities for assisting well users in undertaking self-protective well stewardship activities.

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