CONSUMPTION OF UNREGULATED DRINKING WATER AND HUMAN HEALTH RISK IN RURAL COMMUNTIES

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Abstract

Establishing safe drinking water for rural populations dependent on unregulated water is a global challenge. Despite initiatives to improve access to drinking water, hazards associated with unregulated sources pose a potential risk to human health for rural populations. In the absence of accurate information and monitoring of water quality, consumers form heuristic perceptions of risk associated with their drinking water. Risk perception affects water consumption contributing to uncertainty in risk exposure. Quantifying risk through human health risk assessments (HHRA) has been implemented since the 1940s and advances in risk assessment modeling have created an opportunity to improve HHRA by applying probabilistic Bayesian risk assessment methods. A holistic HHRA integrating risk perception, as it relates to exposure, can quantify uncertainty and provide feedback to improve risk communication and management. The literature lacks a review or summary that characterizes the type and frequency of HHRAs applied to rural populations dependent on unregulated drinking water. The purpose of this thesis is to: (1) summarize studies with HHRA methods applied to unregulated drinking water and rural communities, and describe the characteristics of methods, publications, and current literature gaps; and, (2) characterize and quantify risk perception as it relates to unregulated groundwater wells, and determine the impact of risk perception on human health risk using a holistic HHRA.

A systematic scoping review of peer-reviewed literature (Jan 2000 to May 2014) was used to identify studies with HHRAs applied to unregulated or unspecified drinking water. At least one drinking water source was identified as unregulated (21%) or unspecified (79%) in 100 studies, and 7% identified rural communities dependent on unregulated drinking water. No studies integrated non-traditional factors (e.g. risk perception) into a holistic HHRA. HHRAs applied to rural populations dependent on unregulated water are poorly represented in the literature even though almost half of the global population is rural. The scoping review confirmed a lack of HHRA studies addressing unregulated drinking water risks, and the absence of applied methods that facilitated the quantification and integration of non-traditional factors.

Based on the review findings, a community-based participatory observational case study and holistic HHRA was applied using arsenic concentrations and survey responses from two communities dependent on unregulated groundwater wells. Risk perception and human health risk was determined using probabilistic (Bayesian) risk assessment methods. Community tap water quality exceeded at least one health standard at a rate of 56% and 65%. Integration of risk perception did not change the overall risk status but lowered the cancer risk for arsenic by 3% for both communities. The probability of exposure to arsenic concentrations over 1:100,000 negligible cancer risk for the two communities was 23% and 22%. This study achieved a holistic Bayesian risk assessment through the integration of risk perception and provided a probability of risk that can be used to inform risk communication and management specific to the participating communities.

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1 Introduction and Literature Review

1.1 Introduction

Access to safe drinking water is not a universal human right; however, in 2010, the United Nations and their members adopted *The Human Right to Water and Sanitation - 64/292* resolution based on their concerns 'that approximately 884 million people lacked access to safe drinking water…' (UN 2010). The United Nations considers safe drinking water a component of their commitment to the promotion and protection of all human rights, and supports universal access to water through the Millennium Development Goals (MDG). From 2000 to 2015, the United Nations' Millennium Development Goal was to reduce, by half, the number of the world's population without 'sustainable access to safe drinking water (WHO/UNICEF 2015). However, reporting accuracy for this MDG has been challenging with respect to water quality. For example, establishing access does not guarantee the safety of the drinking water sources which may have poor quality due natural contamination or insufficient water management (Shaheed et al. 2014; Wescoat, Headington, and Theobald 2007). Water sources lacking oversight with regard to monitoring and management within a regulatory context are considered unregulated. Given the inability to provide timely and ongoing data on the water quality associated with the water sources identified in the MDG implies that even improved water sources are likely unregulated. In the absence of water regulations or effective management of unregulated water supplies, there exists a knowledge gap where consumption of water is subject to human risk perception (Shaheed et al. 2014; Martz 1983; Maxwell et al. 1998; Hynds, Misstear, and Gill 2013; Charrois 2010). This thesis summarizes the current research on applied human health risk assessment (HHRA) methods associated with unregulated drinking water in rural communities, and characterizes risk perception associated with drinking water to develop a community-based holistic HHRA.

1.2 Literature Review

This literature review details research in the areas of: rural populations and unregulated drinking water; the paradigm shift in applied human health risk assessment methods; the benefits of probabilistic Bayesian risk assessment; and, risk perception as it relates to drinking water. These areas of research have coalesced as the methods and approaches of risk assessment have changed over time, thus creating new opportunities to integrate and improve the analysis of risk. The theories and conclusions of researchers in risk assessment, mathematics, statistics, computer science, psychology, sociology, economics, and epidemiology, outside the discipline of human health toxicology, have much to contribute to the evolution of the methods and approaches of HHRA. Broadening the research in this area is necessary to develop a holistic HHRA approach through the integration of non-traditional factors (e.g. risk perception) to improve the determination of risk that better informs risk communication for the management of unregulated drinking water in rural communities globally. To accomplish this, it is imperative to determine the recent trends in HHRA approaches and methods, and explore human perception in an effort to understand how it influences exposure and risk.

1.2.1 Rural Populations and Unregulated Drinking Water

In 2015, the World Bank identified 46% (3.38 billion) of the world's population as rural, and determined that 15% of that population lacked adequate access to water (2015). The *25 Year Progress on Sanitation and Drinking Water* report on the Millennium Development Goal 7 reported that 84% of global rural populations had improved drinking water sources; however, 80% of those lacking adequate access to improved water sources were rural residents (WHO/UNICEF 2015). Highly variable by region, rural populations are more likely to be dependent on unimproved surface water sources (WHO/UNICEF 2015). Though rural populations have experienced a 15% increase in access to improved water sources since 1990, these sources are defined as improved only due to their resistance to contamination and not the quality of the water in comparison to the previously accessed source (WHO/UNICEF 2015). For example, a bored well would be considered an improved source when compared to surface water due to the decreased risk of bacterial contamination associated with groundwater wells; however, the well may be naturally contaminated with arsenic. Therefore, improved access through the use of groundwater wells may be an improvement; however, the quality of the water may still pose human health risks for rural populations (Shaheed et al. 2014).

Without sufficient water testing and mitigation of drinking water risks, rural populations are vulnerable to increased health risks associated with drinking water hazards (Shaheed et al. 2014; WHO/UNICEF 2012; WHO 2013). Recognizing the importance of water quality associated with improved drinking water for human health, the WHO/UNICEF *Joint Monitoring Programme (JMP) for Water Supply and Sanitation* initiated a water quality monitoring program in 2010 (WHO/UNICEF 2013). However, there are limitations to the JMP water quality monitoring program including a lack of epidemiological data to determine the health risks associated with water storage and intermittent end of pipe service, and water quality testing restricted to *E.coli*, arsenic, and fluoride (Shaheed et al. 2014; WHO/UNICEF 2013). In addition, inconsistent or 'one off' sampling of individual, private and unregulated water sources limits the temporal interpretation of risk.

For example, Canada is recognized as a developed country with 100% access to water for its citizens (WHO/UNICEF 2015); however, rural populations, including First Nations, are exposed to unregulated water sources that can pose a risk to human health when there is a lack of education, monitoring, and effective treatment of individual and private wells (Charrois 2010; Spence and Walters 2012; Corkal, Schutzman, and Hilliard 2004; Jones et al. 2005). Establishing safe drinking water for rural populations may also be hindered by a lack of resources (e.g. financial) and increased vulnerability (e.g. poverty, illness, minority status, etc.), making it difficult to cope with the responsibility of drinking water management (Nsiah-Kumi 2008; Wescoat, Headington, and Theobald 2007; Zheng and Ayotte 2015). Globally, rural populations face similar challenges when attempting to achieve access to safe drinking water regardless of how they are defined regionally (WHO/UNICEF 2015). Therefore, researching rural communities in specific regions (e.g. Canada) may provide insight and information that is transferrable to rural populations throughout the globe.

1.2.2 Paradigm Shift from Deterministic Risk Assessment

In 1999, Roger O. McClellan, a distinguished toxicologist in HHRA, provided a keynote speech which outlined the history and development of human health risk assessment starting with the earliest research on radiation conducted by Cantril and Parker in 1945. His historical summary of HHRA identifies a landmark decade, from 1960 to 1970, in which the US EPA and several national environmental, health, and toxicological institutes were developed. Organizations such as these throughout the world continue to provide the structure for the development and standardization of frameworks and guidelines on human health risk assessment that are applied by the public and academia (e.g. HC 2010; US EPA 2015; WHO/PCS 2001).

In 2001, the World Health Organization (WHO) and International Programme on Chemical Safety (IPCS) advanced the scope of human and environmental risk assessments by providing the *Framework for the Integration of Health and Ecological Risk Assessment*. This framework defined integrated risk assessment as 'a science-based approach that combines the processes of risk estimation for humans, biota, and natural resources in one assessment' but did not identify any particular method by which the risk assessment should be carried out. Following the introduction of the IRA framework, publications comparing traditional (deterministic) and IRA methods supported a need to shift towards an integrated approach often with the use of probabilistic methods (Bridges 2003; Sekizawa and Tanabe 2005; Suter II et al. 2005; Ryan 2003). Table 1.1 provides a comparison of the traditional deterministic approach of HHRA to a probabilistic approach as summarized by Richardson (1996) and US EPA (2014).

Table 1.1 Comparison of deterministic and probabilistic human health risk assessment methods.

Deterministic	Probabilistic
• Provides a single point estimate of individual risk (e.g. 90th percentile).	• Provides an estimate of the potential or probable risk for an individual or community.
• Commonly applies average or typical exposure values but has historically used 'worst-case' estimates of exposure contributing to over-estimation of risk.	• More likely to provide 'realistic' estimates of exposure and risk, and less prone to over-estimation.
• Typically applied and supported by regulatory agencies.	• Typically applied by the private sector; however, regulatory agencies have included it as an advanced or upper tiered method.
• Cannot integrate non-traditional data and requires quantitative data.	• Allows non-traditional or incomplete data to be characterized and integrated.
• Population exposure is only interpreted as above or below a threshold.	• Provides the proportion of the probability density function exceeding a threshold.
• Manipulation of parameters continues to yield results above or below a threshold.	• Manipulation of parameter inputs and re-running the model can be used to assess options for risk management or prioritize research.
• Limited to interpretation of risk relative to the average or worst-case estimates	• Possible to quantify uncertainty and measure model reliability.
• Use of inaccurate point estimate data (e.g. average, maximum) can yield inaccurate results.	• Use of uncertain and incomplete data or assigning inaccurate probability density functions can yield inaccurate results.
• Provides a cost effective and timely estimation of risk with minimal resources.	• May require additional resources and time to develop.

Support for integrated risk assessment was apparent and the academic research provided feedback on the costs and benefits of its implementation. In his research, Bridges (2003) concluded a paradigm shift from traditional risk assessment was necessary to meet the demand for the quantification of uncertainty and increased transparency. Almost 10 years later researchers were still discussing the implementation of probabilistic methods. For example, Liu et al. (2012) noted that integrated risk assessment can require higher initial resource investment than its traditional counterpart; however, the product may reduce future costs associated with poor decision-making and negative impacts on human health. With the benefits clear, one wonders if the lack skilled researchers in integrated risk assessment and probabilistic methods remains a limitation on the application as suggested by Bridges (2003).

Despite the benefits of integrated risk assessment acknowledged by a number of groups (Bridges 2003; Ryan 2003; Sekizawa and Tanabe 2005; Suter et al. 2003, 2005; Vermeire et al. 2007), there remains an ongoing need for consistency in the use of terminology and the application of integrated risk assessments (Wilks et al. 2015). The concepts of integrated risk assessment can be applied in the context of community-based risk assessments, taking integrated risk assessment in the direction of tailored assessments specifically responding to the needs of different communities (Wilks et al. 2015). Within the context of rural communities and unregulated drinking water addressed in this thesis, there has been no review and summary of the literature as it relates to community-based approaches and applied integrated risk assessment methods.

1.2.3 Probabilistic Bayesian Methods and Holistic Risk Assessment

Though limited, last decade in risk assessment has seen an increase in the application of probabilistic methods (US EPA 2015b), and a desire to integrate data from alternative sources to support holistic risk assessments that include non-traditional factors (e.g. economic, social, and human behaviour variables; Ryan 2003; Wilks et al. 2015). The traditional approach using deterministic methods of HHRA provide '…a single point estimate of "individual" risk', while probabilistic methods can estimate 'the range of probable risk across a population' (Richardson 1996). In 1996, Richardson used the Health Canada HHRA framework to compare deterministic and probabilistic methods and concluded that both methods can produce similar results except where the probabilistic methods allow for better characterization of exposure data.

Richardson (1996) also noted that the probability density function produced by probabilistic risk assessment could be used to estimate the proportion of the population exceeding a specified reference dose. This advantage of probabilistic methods provides an indication of how HHRA can be holistic through the inclusion of non-traditional variables that influence risk. For example, research by Doria (2010), Jones et al. (2006), and Spence and Walters (2012) suggests that perception of drinking water influences consumption and exposure which can improve the accuracy of risk when integrated in HHRA. Therefore, the development and standardization of probabilistic methods provides an opportunity to improve the determination of risk, quantify uncertainty, and provide feedback to support risk management.

In 2012, Liu et al. produced evidence that Bayesian belief networks, using conditional probabilities, could better describe mortality and morbidity rates while reducing the over-estimation of risk and additive uncertainty produced by traditional HHRA. Although studies have applied probabilistic Bayesian analysis in risk assessment (Serre et al. 2003; McCann, Marcot, and Ellis 2006; Uusitalo 2007; Sahmel et al. 2010b; Chowdhury, Champagne, and McLellan 2009; Liu et al. 2012; Schmidt et al. 2013), there remains challenges when putting it into practice. Table 1.2 provides the advantages and disadvantages of probabilistic Bayesian analysis in the context of environmental management or risk assessment as summarized by Liu et al. (2012), McCann et al. (2006), Sahmel et al. (2010), and Uusitalo (2007).

Table 1.2 Advantages and disadvantages of Bayesian risk assessment.

Advantages
• Can use historical data, expert judgement or a combination of data sources. • Produces graphical representation which is easy to create, revise and communicate knowledge. • Probability distributions over decision options can enable managers to make reasonable decisions. • Some software has ability to facilitate model construction. • Some software conducts sensitivity analysis. • Backwards inference can be made to determine the most causal conditions for a given outcome. • Characterizes variability inherent in the parameters used for the exposure reconstruction and uncertainty. • The range and likelihood of expected exposure decreases potential for exposure misclassification • Qualitative and quantitative data can be used in exposure reconstruction • Suitable for small and incomplete data sets
Disadvantages
• Model construction (e.g. conditional probability distribution tables) can be challenging to implement. • Temporal dynamics are not well represented. • Precision may be undermined if continuous variables are discretized. • Unable to handle feedback loops within the model. • Availability of relevant epidemiological studies can increase the number of assumptions that need to be made. • Development of appropriate distributions for exposure reconstruction can be a challenge. • Use of probabilistic techniques is common in the environmental and engineering fields but is still rare in specific areas of risk assessment.

Probabilistic methods, such as Monte Carlo techniques paired with Bayesian methods, are considered to be the next step to improving risk assessment (Sahmel et al. 2010). In their recommended framework for exposure reconstruction in occupational HHRA, Sahmel et al. (2010) provide examples where both techniques are used to address data gaps, and characterize uncertainty and variability. Zargar et al. (2014) highlight the importance of the information located at the tail-end of the probability distributions, and the need to characterize uncertainty in HHRA. This flexibility allows for a data fusion approach which requires a structure, described as 'architecture' by Zargar et al. (2014), and goals which suit the unique circumstances of the HHRA (Esteban et al. 2005). It is important to point out that Zargar et al. (2014) consider integrated HHRA to be the melding or fusion of data for the purpose of more informed risk assessment. For example, they point to the large volume and vast amount of data that require methods of HHRA that can integrate data from multiple sources to improve decision-making. To meet these needs, currently and in the future, data fusion combining multiple data sources can decrease variability and uncertainty in the data (Dasarathy 1997), and provide a mathematical way to simplify data from multiple sources (Zargar et al. 2014). For the purpose of this thesis the integration of data results in a 'holistic' HHRA, rather than simply integrated, because it supports the inclusion of a new data type that is not traditionally used in HHRA (i.e. non-traditional factors – risk perception).

Although Bayesian methods are applied more frequently in the field of environmental risk assessment (Liu et al. 2012), there are examples where probabilistic and Bayesian techniques have been applied to HHRA (Serre et al. 2003; Chowdhury, Champagne, and McLellan 2009; Liu et al. 2012; Schmidt et al. 2013; Ramachandran 2001). These methods can allow for the integration of uncertain or qualitative data that supports or compliments quantitative data. The integrated data can then contribute to a confidence interval that assists public health planning and policy (Serre et al. 2003). For this thesis, the use of Monte Carlo and Bayesian techniques in HHRA presents an opportunity to quantify uncertainty and integrate qualitative information (e.g. non-traditional factor - risk perception). In turn these methods will improve the accuracy of HHRA for a holistic view of risk that can be applied to inform risk communication and management for rural communities dependent on unregulated drinking water.

1.2.4 Drinking Water Risk Perception

Risk perception associated with drinking water affects water consumption but does not necessarily correlate with the safety of drinking water for human consumption (Martz 1983; Maxwell et al. 1998; Hynds, Misstear, and Gill 2013; Patrick 2011; Orgill et al. 2013; Chen et al. 2012). If perception of drinking water is inaccurate then the opportunity exists to over-use non-potable water and under-use potable water. Similarly, avoidance of drinking water may encourage consumption of higher risk water sources or sugary beverages (Onufrak et al. 2012; Onufrak et al. 2014; Dupont, Adamowicz, and Krupnick 2010). For example, Bogart et al. (2013) studied the perceptions of youth and their parents as it related to sugar sweetened beverages and tap water and found that 49% of parents and youth had similar perceptions about their tap water; however, 71% of those in agreement on their perceptions thought the water had negative effects on their health. In addition, they noted that tap water was perceived as unsafe concurrently with the high consumption of sugar drinks (Bogart et al. 2013). This study shows how a group of individuals may have similar perceptions of water and how that misinformation can negatively affect their health.

Most studies addressing perception of risk and water quality appear to be focused on tap water and customer satisfaction according to Doria (2010). This finding indicates that perception of risk as it relates to unregulated drinking water sources does not attract the attention of water treatment plants and commercial water providers. Doria (2010) states that direct organoleptic experiences with drinking water sources are the primary driver determining perception of drinking water risk, and that most studies in risk perception focus on hazards that the public know little about. In the Canadian context, Charrois (2010) points out that the majority of people with private drinking water wells are not sufficiently educated on the potential health risks associated with consumption of groundwater; therefore, people dependent on private water wells rely on their perception. Jones et al. (2006) uses Canada as an example of how the lack of regulation, testing, monitoring, and treatment associated with private water management may pose a risk to human health; however, under similar circumstances, drinking water risks can exist for any individual or global community dependent on unregulated water.

In the context of unregulated water and the dependence on perception, the many factors affecting drinking water risk perception clearly illustrates the difficulty, from a risk management perspective, in ensuring people's perception of risk is accurate. Doria (2010) provides a through discussion of the factors affecting perception of drinking water. For comparison, Figure 1.1 shows a list of factors that support risk management decisions for regulated and unregulated sources. Often based on defensible science and policy, regulated water sources have a multi-barrier approach to protecting human health. In contract, unregulated water is highly dependent on less quantitative factors as summarized by Doria (2010). Chowdhury et al. (2009) suggests the uncertainty associated with human behaviour may be reduced if behaviour can be integrated as a variable in HHRA.

Given there can be indirect health effects associated with human behaviour (i.e. consumption) in response to poor drinking water (Wescoat, Headington, and Theobald 2007), it is imperative that risk assessment captures individual's or communities' perception of risk. Furthermore, with an increased pressure for governments to include human perceptions/perspectives in water resource management (Jackson 2006), it would be beneficial to determine the impact those perceptions have on exposure and human health risk. Furthermore, understanding the effect of risk perception on human health risk could lead to improved risk management and communication (Markon and Lemyre 2013). As stated by Serre et al. (2003), "Uncertain knowledge obtained about important exposure parameters could be more valuable than the certain knowledge obtained about less important parameters". In other words, the inclusion of risk perception in HHRA may contribute uncertain knowledge for a more holistic and accurate determination of risk.

Doria (2010) provides two examples by Slovic (2000) and Hagerty (2003) that suggest that the public's perception of water quality may be decreasing over time due to "inter-temporal pessimism". If this is an accurate prediction, the perception of risk associated with drinking water quality and its importance in the determination of risk may be increasing. By studying the impact of risk perception on unregulated water consumption and human health risk we can provide insight on the exposure and risk outcomes that are required for risk communication and management to establish safe drinking water for rural populations that distrust their water.

1.3 Research Opportunity

This research contributes to a larger Saskatchewan Health Research Foundation (SHRF) grant objective to "Use community-based risk assessment to characterize challenges related to poor drinking water quality in Saskatchewan not included in current surveillance initiatives." To achieve the SHRF objective, this research conducts an observational case-study with two communities and assesses risk perception as it relates to the use of unregulated water wells in Saskatchewan. Bayesian HHRA methods provide an alternative approach to risk assessment that is not frequently used in Saskatchewan. In the global context, this research can provide valuable knowledge to rural populations dependent on unregulated drinking water by integrating qualitative data into HHRA to improve risk management in the absence of drinking water regulation. On a global scale, the research supports a global goal to increase access to safe drinking water sources for rural communities by showing the importance of integrating non-traditional variables impacting exposure and risk.

1.4 Research Purpose and Objectives

The purpose of this thesis is to determine the methods of HHRAs currently applied to rural communities that are dependent on unregulated drinking water and, using this information, integrating risk perception of drinking water into a holistic HHRA to support the improvement of risk communication and management. The objectives of the research are to:

1. Conduct a scoping review to characterize the methods and approaches of HHRA applied to rural communities dependent on unregulated drinking water sources.
2. Quantify risk perception, using probabilistic Bayesian HHRA, to determine its impact on human health risk.

1.4.1 Characterizing Methods and Approaches of Human Health Risk Assessment Applied to Rural Communities Dependent on Unregulated Drinking Water Sources

Chapter 2 provides a summary of the current literature characteristics that summarize the methods and approaches of human health risk assessment applied to rural communities dependent on unregulated drinking water sources. Eligible peer-reviewed literature identified those studies applying a drinking water HHRA to communities dependent on an unregulated or unspecified water source. Characteristics of studies were summarized and primary areas of interest included: the frequency of HHRA applied to rural communities; the application of deterministic and probabilistic methods; and the integration of non-traditional data into the quantitative risk assessment. The results of this study identified a lack of applied HHRA to rural communities dependent on unregulated water sources, and the limited use of methods that could facilitate the integration of non-traditional data. This scoping review provides a valuable summary of the literature to researchers, regulatory agencies, and organizations that can use the information to inform future HHRA application, approach, and reporting.

1.4.2 Using Probabilistic Bayesian Human Health Risk Assessment to Quantify and Determine the Impact of Risk Perception on Human Health Risk

Supported by the conclusions of the scoping review, Chapter 3 takes a holistic HHRA approach to determine the impact of drinking water risk perception on the lifetime incremental cancer risk due to the presence of arsenic in the drinking water of two rural communities in Saskatchewan, Canada. The need to explore new approaches and tools (i.e. holistic HHRA, and Bayesian risk assessment methods) support the desire to include data of different types and quality in risk assessment. Demonstrated for the first time in the context of unregulated drinking water, this study allows for qualitative risk perception data to be quantified and integrated into a quantitative risk assessment to decrease uncertainty associated with exposure and risk. In addition, the results of the risk assessment provide the communities with a better understanding of the discrepancy between their perception and the safety of their drinking water.

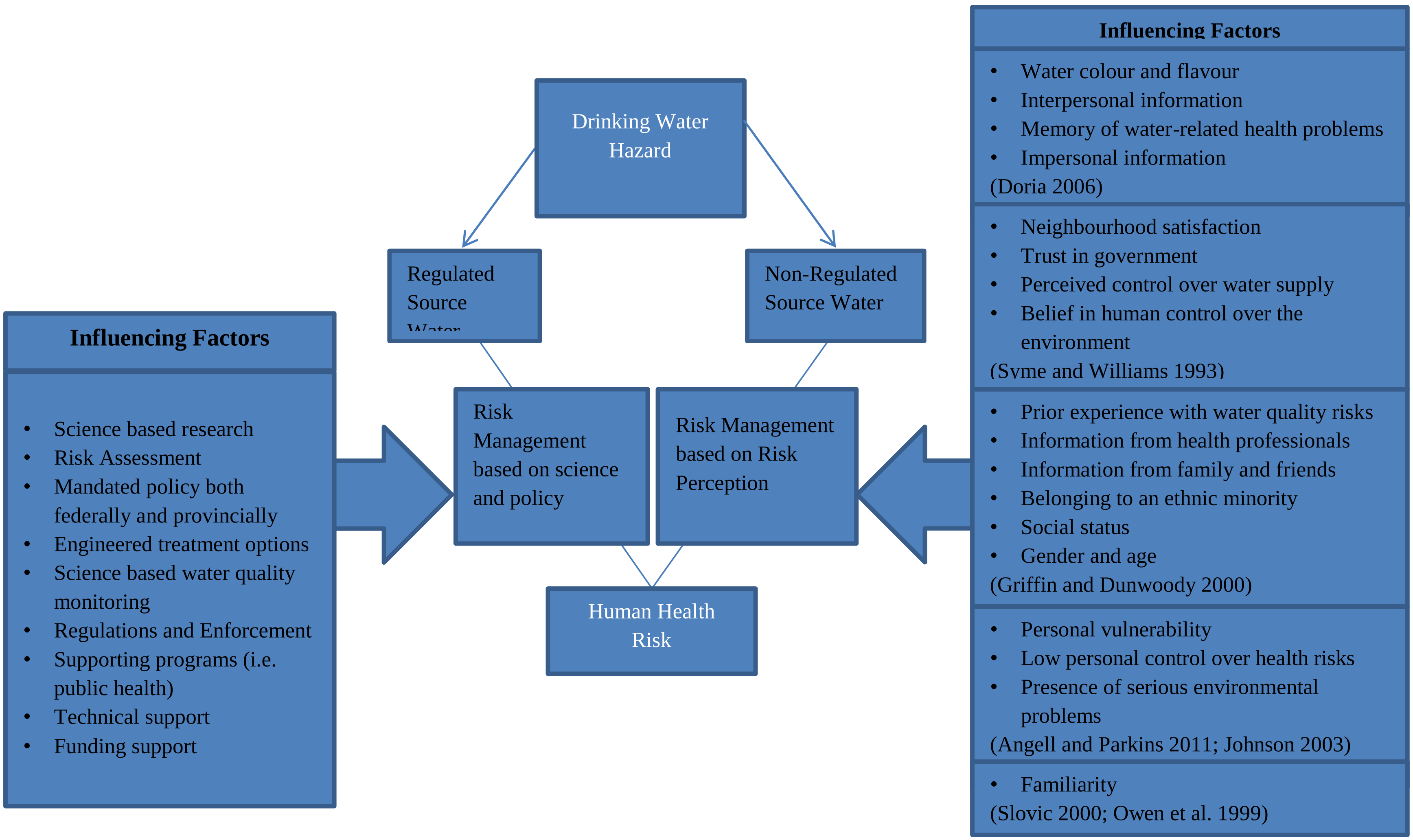

Figure 1.1 Diagram of potential factors affecting risk management of regulated and unregulated drinking water.

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2 Human Health Risk Assessment Applied to Unregulated Drinking Water Sources: A Scoping Review

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 Author contributions are as follows: Lorelei Ford participated in the entire process of the research including: design, search, screening, full text review, data extraction, data analysis, interpretation of results, writing, and editing the manuscript. Lianne McLeod participated in the design, search and screening and contributed to editing. Cheryl Waldner and Lalita Bharadwaj participated in the design of research, full text review, data extraction, interpretation of results, and writing/editing of the manuscript. Proportion of full text review for Lorelei Ford, Lalita Bharadwaj, and Cheryl Waldner was 44%, 46%, and 10%, respectively.

2.1 Abstract

Safe drinking water is a global challenge for rural populations dependent on unregulated water. A scoping review of research on human health risk assessments (HHRA) applied to this vulnerable population may be used to improve assessments applied by government and researchers. This review aims to summarize and describe the characteristics of HHRA methods, publications, and current literature gaps of HHRA studies on rural populations dependent on unregulated or unspecified drinking water. Peer-reviewed literature was systematically searched (January 2000 to May 2014) and identified at least one drinking water source as unregulated (21%) or unspecified (79%) in 100 studies. Only 7% of reviewed studies identified a rural community dependent on unregulated drinking water. Source water and hazards most frequently cited included groundwater (67%) and chemical water hazards (82%). Most HHRAs (86%) applied deterministic methods with 14% reporting probabilistic and stochastic methods. Publications increased over time with 57% set in Asia, and 47% of studies identified at least one literature gap in the areas of research, risk management, and community exposure. HHRAs applied to rural populations dependent on unregulated water are poorly represented in the literature even though almost half of the global population is rural.

2.2 Introduction

In 2015, the World Bank identified 46% (3.38 billion) of the world's population as rural, and determined that 15% of that population lacks adequate access to water (World Bank 2015). In 2000, the Millennium Declaration was signed by the United Nations to establish the Millennium Development Goal (MDG) to reduce, by half, the number of the world's population without 'sustainable access to safe drinking water' (WHO/UNICEF 2015). However, increased access to water does not guarantee water sources are safe for consumption, and without sufficient water testing and mitigation of drinking water risks, rural populations are vulnerable to increased health risks associated with drinking water hazards (Shaheed et al. 2014; WHO/UNICEF 2012; WHO 2013). Global rural populations remain an 'at risk' priority due to: exposure to unknown drinking water hazards; a lack of oversight associated with the use of unregulated water sources; a failure to mitigate known drinking water risks (e.g. avoidance or non-regulated treatment); and, their vulnerability and inequality as it relates to education and financial resources to establish safe water in comparison to urban populations (Fawell and Nieuwenhuijsen 2003; Nsiah-Kumi 2008; WHO/UNICEF 2015). To support the management of the risks to rural communities and to further the field of human health risk assessment (HHRA) it is imperative to understand the research undertaken in this area. To this point, there has not been a review or summary of the research literature that provides the type and frequency of applied HHRA methods to determine the drinking water risks to rural communities dependent on unregulated source water.

Human health risk assessment has been used to quantify risk as it relates to human exposure to potential hazards since the late 1940s. With its origins in environmental risk assessment, HHRA has since evolved independently from the environmental discipline (Suter II et al. 2005). The fields of human health and environmental risk assessment have not paralleled one another in their development of integrated risk assessment despite similarities in the traditional application of methods (Bridges 2003). In 2003, Bridges hypothesized that the departmental separation of human health and environment by governments; the lack of integrated risk assessment training in universities; and, the requirement for communication and collaboration between disciplines are sources of resistance to the integration of human health and environmental risk assessment. Bridges (2003), Munns et al. (2003), Suter et al. (2005), and Vermeire et al. (2007) have acknowledged the need for guidelines and frameworks to facilitate integrated assessment, and there are examples that have been suggested or developed (Briggs 2008; Sexton and Linder 2014; Suter et al. 2005; WHO/IPCS 2001). However, a recent publication by Wilks et al. (2015) suggests the integration of environment and health risk assessments remains a challenge due to lack of agreement between '…terminology, models and methodologies across chemical categories and regulatory agencies…'. In addition to concerns regarding the implementation of integrated risk assessment, Wilks et al. (2015) acknowledge that non-traditional factors such as behaviour, socio-economics, perceptions, and values could improve the determination and management of risk through a more holistic approach.

The terms *integrated* and *holistic* are inconsistently defined as noted by Bridges in 2003. Integrated risk assessment, generally, refers to the inclusion of both human health and environmental risk in one assessment (Bridges 2003; Hart and Pollino 2009; Sekizawa and Tanabe 2005; WHO/IPCS) 2001), while the term *holistic* suggests a systems approach where different data types and sources influencing risk can be utilized (e.g. social, economic, perception, etc.; Arquette et al. 2002; Serre et al. 2003). Adopting a holistic approach using probabilistic and stochastic methods can benefit HHRA by allowing for the use of alternative data sources and types (Bridges 2003; Serre et al. 2003; Zargar et al. 2014) which can increase the accuracy through the quantification of uncertainty (Liu et al. 2012). As mentioned previously, Wilks et al. (2015) suggests that a holistic approach would consider economic, social, cultural, and political factors; however, they do not describe the inclusion of these factors as a data source per se. For the purpose of this scoping review, we define integrated risk assessment according to the WHO/IPCS (2001) as '…a science-based approach that combines the processes of risk estimation for humans, biota, and natural resources in one assessment.' Alternatively, we suggest that a holistic risk assessment would be similar to that described by Arquette et al. (2002) and include non-traditional factors, that may be gathered from qualitative data sources or multiple disciplines, in the determination of risk that is specific and relevant to the humans or environment of concern. A holistic human health risk assessment would be inherently integrated; however, an integrated risk assessment is not necessarily holistic.

Deterministic methods of HHRA have been applied to comply with structured national and international guidance documents and frameworks. Despite studies that identify the benefits of integrated risk assessment (Bridges 2003; Ryan 2003; Sekizawa and Tanabe 2005; Suter II et al. 2005; Liu et al. 2012; Briggs 2008), there has not been a systematic review of application frequency of deterministic, integrated or holistic methods. A scoping review of recent HHRA practices may be used to inform and support the adoption and use of holistic frameworks by government and researchers. This could improve methods and quantify uncertainty, which would support effective risk communication and management (Markon and Lemyre 2013). This paper summarizes HHRA methods used to assess human health risks associated with unregulated drinking water and describes the frequency of HHRAs applied to rural communities, the characteristics of methods and publications, and current literature gaps.

2.3 Methods

This scoping review involved a multi-disciplinary team of four researchers in the fields of water quality, human health, epidemiology, and toxicology. Analysis and writing remained the responsibility of the lead (Lorelei Ford) with all team members participating in the review process, meetings, and editing. A health sciences research librarian was consulted on the selection of databases and search terms to ensure the identification of relevant studies. The framework chosen for the review was that presented by Pham et al. (2014) which is based on the works of Arksey and O'Malley (2005), and Levac et al. (2010). This review utilized the first five steps of the Arksey and O'Malley (2005) framework, including: identification of the research question; identification of relevant studies; study selection; charting the data; and, collating, summarizing and reporting results.

2.3.1 Research Question

The research question had two parts and asked, 'What methods of HHRA have been used to determine the health risks associated with consumption of unregulated drinking water, and how often are they applied within the context of rural communities?'

2.3.2 Data Sources and Search Strategy

In January 2014, two researchers (Lorelei Ford and Lianne McLeod), with the assistance of a research librarian at the University of Saskatchewan Health Sciences Library, identified the databases, search terms, and limitations that would define the review. Search databases included ProQuest - Public Health (multidisciplinary), EMBASE – Embase + Embase Classic (biomedical, broad), MEDLINE – Ovid (biomedical, specific), Global Health (global), and Scopus (multidisciplinary, broad). These databases provided comprehensive coverage of a wide range of disciplines as they relate to human health risk assessment. Search terms included: 'risk', 'risk assessment*' or 'analys*, 'water', 'groundwater', and 'health'. The search terms 'risk assessment', 'water' and 'groundwater' were expanded to ensure inclusion given the diverse range of terminology for HHRA. The concatenated term 'groundwater' was specifically included because search terms for 'ground' and 'water' returned fewer results. Search terms did not include 'drinking water' because studies using the term were included using the search term 'water'. Searches were restricted to English language publications between January 1st, 2000 and May 8th, 2014. The Scopus search excluded newspaper articles due to the otherwise high number of non-peer reviewed articles. Detailed search strategies are provided in Supplemental Materials – 5.1 Database Search Terms.

2.3.3 Citation Management

Search results were exported to Microsoft Excel and imported to Microsoft Access (Microsoft Corporation, Redmond, WA) for title and abstract relevance screening. Citation fields included: author, reference, journal, title, and abstract. Each database was independently de-duplicated and then combined. Duplicates were identified and eliminated independently by two researchers (Lorelei Ford and Lianne McLeod) and agreement confirmed.

2.3.4 Eligibility Criteria

Study selection was a two-step screening process involving a title and abstract screen. In addition to title and abstract screening methods identified by Arksey and O'Malley (2005) and Pham et al. (2014), abstracts were categorized, according to the inclusion criteria in Table 2.1, by two researchers (Lorelei Ford and Lianne McLeod) during screening to enable reliable sorting for full-text review.

Scoping review inclusion criteria to identify human health risk assessments applied to unregulated or unspecified drinking water.

Table 2.1 Scoping review inclusion criteria to identify human health risk assessments applied to unregulated or unspecified drinking water.

Inclusion Criteria
English language
Published between January 1st, 2000 to May 8th, 2014
Peer-reviewed
Identified applied HHRA
Identified water use for human consumption
Identified the water source as unregulated or unspecified [a]

[a] Professional judgement and consensus was used to categorize studies that did not identify the water source as unregulated but provided evidence that the source water was not regulated.

Titles were included if it was clear they *were* or *could* be about risk assessment and drinking water, to minimize the potential for exclusion of relevant articles. For this scoping review, regulated water sources (e.g. municipal treatment, community treatment, or centralized water sources for cities and towns) were excluded to focus the review on unregulated water sources (e.g. private drinking water wells, raw water sources, etc.). Unspecified water sources represent a category of studies that failed to confirm the water source as unregulated and did not describe the site, hazards tested, or circumstances to suggest water was regulated. Unspecified water sources, likely unregulated, were included in analysis to identify shortfalls in reporting but excluded from descriptive statistics when specifically addressing unregulated water sources.

2.3.5 Title and Abstract Relevance Screening

Titles and abstracts were scanned independently by two researchers (Lorelei Ford and Lianne McLeod) to prevent exclusion of valid citations. Disagreements between reviewers during this scan resulted in the article's inclusion for full-text review. A form was created in Microsoft Access to categorize the abstracts to reach consensus on meeting inclusion criteria. The title and abstract scans were completed November 6th and November 20th, 2014, respectively.

2.3.6 Data Characterization

Articles meeting inclusion criteria were eligible for full-text review. Themes and categories were developed and defined based on specific references and terms to ensure characterization of data was consistent. Three broad themes were developed to include HHRA characteristics, literature characteristics; and literature gaps. Categories within the human health risk assessment characteristics theme included the exposure population, exposure pathway, hazard identification, applied methods, framework used, HHRA terminology, factors and uncertainty, and outcomes specific to the application of risk assessment. Literature characteristics related to the world region in which the studies took place, publication dates, and publication sector (or field). Literature gaps, defined as any gap identified in the study by authors, general fit into three categories including gaps in HHRA research, risk management, and community exposure. Except for a few cases, in which researchers contacted authors by email via ResearchGate (ResearchGate GmbH, Berlin, Germany), full-text articles were accessed through the University of Saskatchewan online library. Non-peer reviewed literature was eliminated from the review. If studies did not provide sufficient evidence for exclusion they were retained for analysis and identified as 'unspecified'. Prior to full-text review, all researchers independently reviewed one randomly selected article (i.e. Kavcar et al. 2009) and discussed themes, categories, and definitions as suggested by Levac et al. (2010). Full-text review was conducted by three researchers (Lorelei Ford, Lalita Bharadwaj and Cheryl Waldner) and studies which failed to meet requirements of inclusion criteria for abstract scan and full-text review were removed from further analysis. Individual reviews were summarized and discrepancies or questionable categorizations were re-examined prior to combining results. Final categorization was completed on June 30th, 2015. A detailed list of the themes and categories, including examples, and references for the full-text review, are summarized in Supplemental Materials – 5.2 Full-Text Review Categorizations.

2.3.7 Data Summary and Synthesis

Screening and full-text review were compiled using Microsoft Excel 2010 (Microsoft Corporation, Redmond, WA). All data entries were reviewed and scanned for manual errors or incomplete entries prior to analysis. Calculation of descriptive statistics, frequencies, and percentages on nominal data was performed using Microsoft Excel 2010. Charts were designed using Tableau 9.1 (Tableau Software Inc., Seattle, WA).

2.4 Results

2.4.1 Search and Selection

One-hundred papers met the inclusion criteria for data extraction and scoping review. A total of 7,838 unique articles were found after database results were de-duplicated (Figure 2.1). Further title and abstract screening resulted in the selection of 158 studies for full text review; however, three articles could not be located (i.e. Maqsood 2011; Titilayo et al. 2012; Zhao et al. 2012) and the remaining 55 did not meet inclusion criteria.

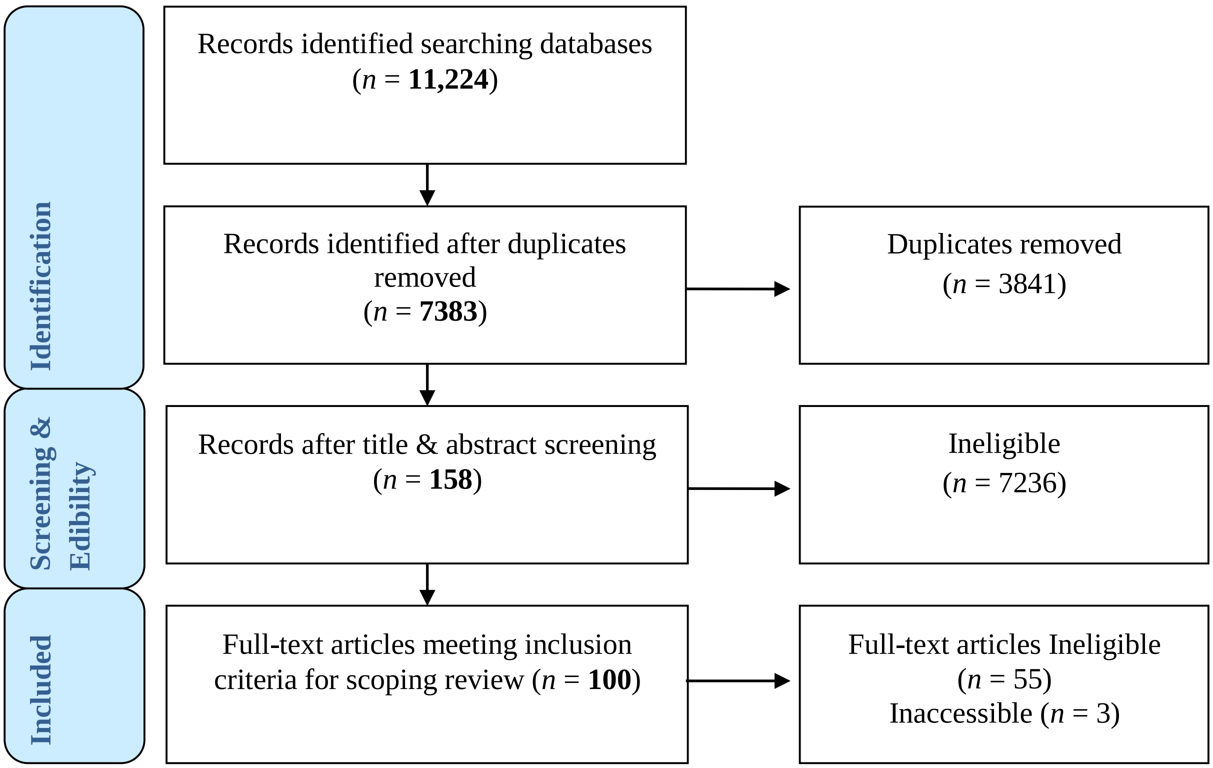

Figure 2.1 PRISMA flowchart of scoping review process. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis.

2.4.2 Human Health Risk Assessment Characteristics

Table 2.2 provides a summary of the characteristics of applied HHRAs and categorized into exposure population, exposure pathway, hazard identification (including status of drinking water), applied method, scope, framework used, HHRA terminology, factors and uncertainty, and outcomes.

Table 2.2 Human health risk assessment characteristics from scoping review literature (*n* = 100).

Characteristic	**Number (*n* = 100)**	**Percentage (%)**
Exposure Population		
Geographic Area of Population		
Rural (rural and unregulated)	28 (7)	28 (7)
Urban (urban and rural)	16 (4)	16 (4)
Remote (remote and rural)	2 (0)	2 (0)
Unspecified	54	54
Community [a]		
Geography	86	86
Topography	27	27
Cultural/Spiritual	2	2
Unspecified	20	20
Receptors [a]		
Adults	66	66
Local Residents	41	41
Child	31	31
Toddler	15	15
Teen	15	15
Responsible for source water	13	13
Seniors	11	11
General Public	10	10
Infants	10	10
Local Farmers and Families	5	5
Employees	2	2
First Nation/Indigenous	0	0
Age categories not defined	39	39
Other (e.g., gender, visitors, etc.)	6	6
Unspecified	8	8
Exposure Pathway [a]		
Oral	100	100
Dermal	23	23
Inhalation	4	4
Hazard Identification		
Status of drinking water		
Unregulated (unregulated and untreated)	21 (14)	21 (14)
Unspecified (unspecified and untreated)	79 (51)	79 (51)
Source of drinking water [a]		
Groundwater (unregulated groundwater)	67 (14)	67 (14)
Surface water (unregulated surface water)	39 (7)	39 (7)
Other (e.g., bottled, rain, cistern, etc.)	21	21
Unspecified	5	5
Type of drinking water		
Untreated	56	56
Untreated and Treated	9	9

Unspecified	35	35
Hazard in drinking water		
Anthropogenic chemical	35	35
Natural chemical	22	22
Anthropogenic and natural chemical	25	25
Microbiological/Pathogen (microbiological/pathogen and chemical)	10 (2)	10 (2)
Radiological (radiological and chemical)	1 (3)	1 (3)
Unspecified	7	7
At least two hazards identified	5	5
Data source [a]		
Source water sampled	96	96
Historical data	13	13
Predicted/Extrapolated	11	11
Biomarkers (i.e., hair samples)	3	3
Unspecified	2	2
Applied Method		
Deterministic	86	86
Probabilistic/Stochastic	9	9
Deterministic and Probabilistic/Stochastic	5	5
Scope [a]		
Human Health Risk Assessment	100	100
Integrated (human and environmental)	4	4
Holistic (integration of non-traditional data)	0	0
Framework Used [a]		
US EPA	75	75
World Health Organization	6	6
Other (i.e., studies, government)	15	15
Unspecified	12	12
HHRA Terminology		
Health (risk) Assessment	47	47
Human Health Risk Assessment	25	25
Risk Assessment	24	24
Other (e.g., cancer risk, risk estimate, etc.)	14	14
Factors and Uncertainty		
Non-Traditional Factors acknowledged [a]		
At least one non-traditional factor	90	90
Geography	76	76
Social	23	23
Economic	13	13
Risk Perception	3	3
Cultural/Spiritual	2	2
Other (e.g., behaviours, additional risks, temporal effects, etc.)	22	22
Non-Traditional Factors applied [a]		
At least one non-traditional factor	69	69

Geography	56	56
Social	4	4
Economic	2	2
Risk Perception	1	1
Cultural/Spiritual	1	1
Other (e.g., behaviours, additional risks, temporal effects, etc.)	16	16
Uncertainty acknowledged [a]		
At least one uncertainty acknowledged	83	83
Dedicated section to uncertainty	20	20
Quality Assurance/Quality Control	47	47
Analytical detection limits	38	38
Seasonal/Environment	38	38
Data gaps	30	30
Sufficiency of sampling	28	28
Quality of historical data	10	10
Other (e.g., exposures, toxicological factors, effects of unknown variables, etc.)	18	18
Outcomes		
Result [a]		
Exposure Assessment	96	96
Hazard Assessment	95	95
Hazard Quotient/Index	81	81
Epidemiological Assessment	4	4
Other (i.e., quantitative microbial risk assessment and cancer risk)	27	27
Conclusion by Authors		
Quantitative	94	94
Quantitative and Qualitative	4	4
Qualitative	2	2

[a] not mutually exclusive.

Human health risk assessments were applied to rural populations dependent on unregulated source water was found in only 7% (7/100) of the scoped studies (Table 2.2). Overall unregulated water sources were identified in only 21% (21/100) of the studies, while the remaining (79%, 79/100) failed to specify the regulatory status but did not provide enough information to be excluded as regulated. Over half (54%, 54/100) of the geographic areas for the population were insufficiently described and could not be categorized as rural, urban, or remote.

Source water categories including ground and surface water were, not exclusively, identified in 67% (67/100) and 39% (39/100) of the reviewed studies, respectively (Table 2.2). Groundwater was categorized as unregulated in 14% (14/100) of the studies, which doubled the percentage of surface water sources found to be unregulated (7%, 7/100). Regardless of the source water's regulatory status, groundwater was identified as untreated in 64% (43/67) of the articles (e.g. Çelebi et al. 2014; Phan et al. 2013; Su et al. 2013; Sultana et al. 2014; Wu et al. 2014) versus only 10% (4/39) surface water. Only three studies identified a rural population dependent on unregulated and untreated groundwater (i.e. Jamaludin 2013; Papić et al. 2012; Peplow and Edmonds 2004).

Drinking water hazards were identified as natural or anthropogenic chemicals in 82% (82/100) of articles reviewed (Table 2.2). Risks associated with bacteria, viruses, parasites, and radiological parameters were studied in 11% (11/100) of the HHRAs, exclusive of chemicals; with a small proportion (5%, 5/100) including a chemical hazard in addition to microbes, pathogens, or radiological parameters.

Receptors, defined as the specific group of people exposed to potential risk, were inconsistently described throughout the reviewed literature. Not mutually exclusive, the literature identified adult or local residents as receptors in 66% (66/100) and 41% (41/100) of the studies, respectively (Table 2.2). A specific age category for receptor descriptions was not defined in 39% (39/100) of the studies. Other receptor categories identified (Table 2.2) included: children, toddlers, teens, '(people) responsible for source water', the 'general public', infants, 'local farmers and families', or 'employees'. No studies identified receptors as First Nations, or indigenous communities. When the exposure population was described as a community, the population was delineated by a geographic area (86%, 86/100), topography (27%, 27/100), cultural or spiritual characteristics (2%, 2/100), or were unspecified (20%, 20/100) due to their vague descriptions they were in proximity to sources of pollution, source water, or hydro-geological influences.

Table 2.2 shows that 86% (86/100) of HHRAs applied to unregulated or unspecified drinking water were deterministic with 14% (14/100) utilizing probabilistic and/or stochastic methods in their analysis (i.e. Busset et al. 2010; Deng et al. 2012; Donovan et al. 2008; Hunter et al. 2011; Kavcar et al. 2009; Kumar et al. 2010; Li et al. 2007; Marara et al. 2013a; Mondal et al. 2010; Nzihou et al. 2013; Razzolini et al. 2011; Wang et al. 2009; Williams et al. 2000). Only four studies had an integrated environmental risk in addition to human health (i.e. Buczyńska and Szadkowska-Stańczyk 2005; Genthe et al. 2013; Liu et al. 2011; Yu et al. 2010). The USEPA risk assessment framework was applied in 75% (75/100) of the studies, while 6% (6/100) of the studies utilized the standardized international methods of the World Health Organization. Peer-reviewed, other government or non-government methods of HHRA were applied in 15% (15/100) of the studies while 12% (12/100) had no clear methodological framework.
Use of terminology describing HHRAs was inconsistent within and between studies. The term 'health risk' or 'health risk assessment' was used in 47% (47/100) of the scoped articles. Less frequently the terms 'human risk assessment' or 'human health risk assessment', and 'risk assessment' described the assessment in 25% (25/100) and 24% (24/100), respectively. Other articles (14%, 14/100) specifically described the assessments as quantitative microbial (or health) risk assessment, cancer risk, risk estimates, and hazard evaluations.

Non-traditional factors were acknowledged or applied qualitatively, by lending to the interpretation of risk, but were not quantified variables within the risk assessment. Non-traditional factors were acknowledged in 90% (90/100) of the studies, however, their qualitative application to the interpretation of risk was only 69% (69/100; Table 2.2). Geographical (76%, 76/100), social (23%, 23/100) and economic (13%, 13/100) factors were acknowledged most frequently. Only 5% (5/100) of studies recognized risk perception, or cultural/spiritual non-traditional factors. The 'other' categories included: health variables (e.g. Giri and Singh 2014; Singh and Ghosh 2012), temporal influences (e.g. Giri and Singh 2014; Jamaludin 2013; Sultana et al. 2014; Yacoub et al. 2013), differences in water sources (e.g. Çelebi et al. 2014; de Jongh et al. 2012; Hynds et al. 2014), effectiveness of risk management (i.e. Machdar et al. 2013), and human behaviors or proximity to human activities (i.e. Ahmed et al. 2010; Armah et al. 2012; Buczyńska and Szadkowska-Stańczyk 2005; Lee et al. 2005, 2006; Ramirez-Andreotta et al. 2013; Santos et al. 2013; Zheng et al. 2013).

Uncertainty was acknowledged at least once in 83% (83/100) of the articles, but only 20% (20/100) provided a section specifically dedicated to the discussion of uncertainty (Table 2.2). Quality assurance and quality control, and analytical detection limits were mentioned in 47% (47/100) and 38% (38/100) of the articles, respectively. Seasonal or environmental influences, such as changes in hazard concentrations over time, were identified in 38% (38/100) of studies. Data gaps (30%, 30/100) and sufficiency of sampling (28%, 28/100) were more frequently mentioned than the quality of historical data for use in the calculation of risk (10%, 10/100). Other sources of uncertainty were disclosed in 18% (18/100) of the articles and included: uncertainty associated with reference to supplementary material or methods (i.e. Kim et al. 2004; Törnqvist et al. 2011); variation in exposure (i.e. Ahmed et al. 2010; Kavcar et al. 2009; Kelepertzis 2014; Lee et al. 2007; Ni et al. 2009; Steyn et al. 2004; Zheng et al. 2013); insufficient toxicological data or guidelines (i.e. Lee et al. 2007; Li et al. 2007; Ramirez-Andreotta et al. 2013; Rapant and Krcmová 2007); error in methods or their application (i.e. Ahmed et al. 2010; Hynds et al. 2014; Kavcar et al. 2009; Kazama et al. 2012; Lee et al. 2010; Li et al. 2007; Steyn et al. 2004); unknown immunity, virulence, reporting and diagnosis (i.e. Hunter et al. 2011); and, failure to consider secondary effects or multiple sources of risk (i.e. Addo et al. 2013; Lee et al. 2010; Papić et al. 2012; Santos et al. 2013).

2.4.3 Literature Characteristics

Table 2.3 provides a summary of the literature characteristics including: the region(s) in which the research was conducted; the number of studies published; and, the sector or discipline the studies were published in.

Most (57.4%, 58/100) of the studies were conducted in Asia and included the countries of China, Pakistan, India, and Bangladesh. All studies reported one region in which the research took place with exception of Hunter et al. (2011) research conducted in France and the United Kingdom;

therefore, there were 101 study regions identified in the scoped literature. Figure 2.2 provides a visual summary of the number of studies by world region.

Table 2.3 Literature characteristics from scoping review (*n* = 100).

Characteristic		
World Region	**Number (*n* = 101 [a])**	**Percentage (%)**
Asia	58	57.4
West Africa	9	8.9
Europe	7	6.9
European Union	8	7.9
North America	7	6.9
South America	4	4.0
South Africa	3	3.0
Middle East	2	2.0
Caribbean	1	1.0
East Africa	1	1.0
Oceania	1	1.0
Publication Year	**Number (*n* = 100)**	**Percentage (%)**
January 2010–May 2014	75	75
January 2005–December 2009	20	20
January 2000–December 2004	5	5

[a] not mutually exclusive, one study took place in two regions.

The number of articles published annually increased during the review period from January 2000 to May 2014. Twenty-five percent (25/100) of the articles were published from 2000 to 2009, while the remaining 75% (75/100) were published in less than half that period from January 2010 to May 2014. The highest number of publications per year (19%, 19/100) occurred in 2013. From January 2000 to 2013 is the average publishing rate is 6.6% per year excluding studies from January to May 2014. Figure 2.3 provides the number of publications by sector and year where sectors are not mutually exclusive. Articles were predominately published in journals indicating a focus on human health (94%, 94/100), toxicology (81%, 81/100), and environment/resource management (79%, 79/100).

Figure 2.2 Number of scoping review studies by world region.

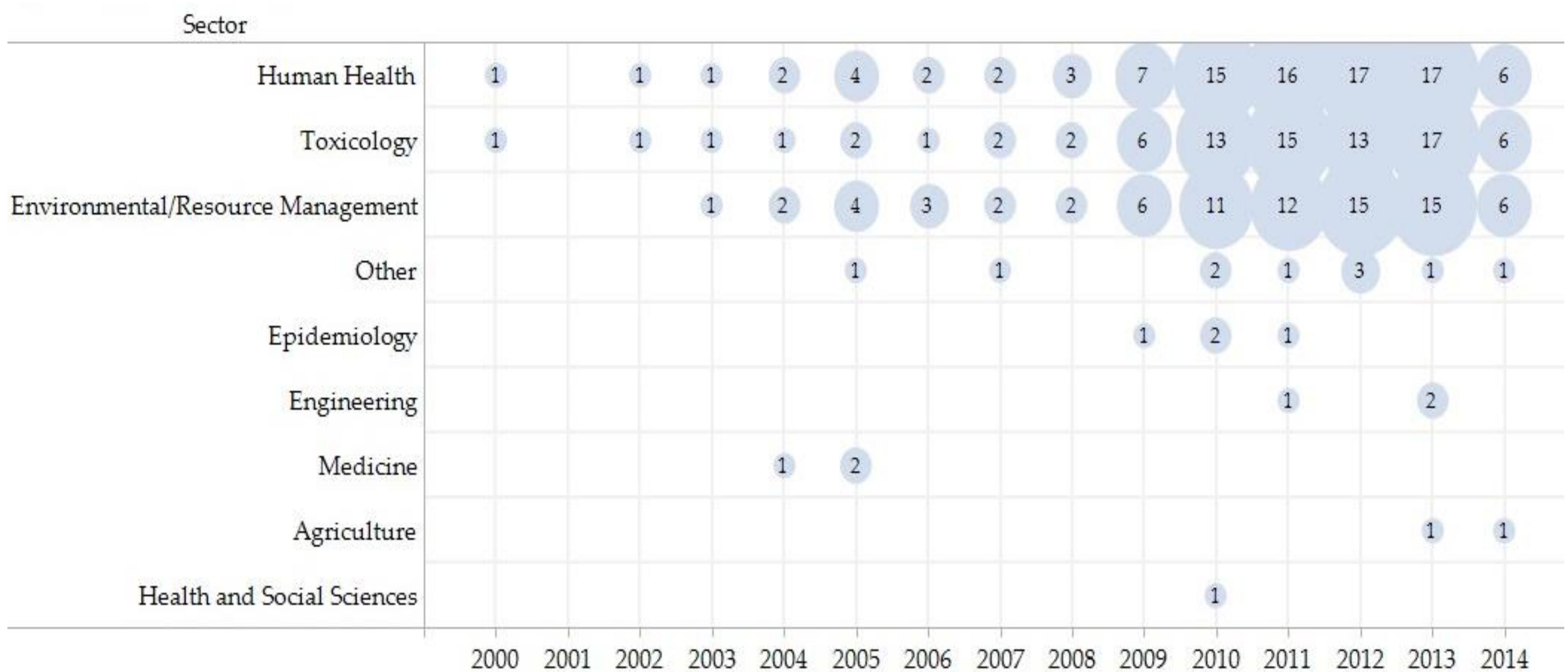

Figure 2.3 Scoping review studies by sector and year. Sectors are not mutually exclusive.

2.4.4 Literature Gaps

At least one gap in the literature was identified in 47% (47/100) of the studies. Literature gaps were not mutually exclusive and were summarized into three main categories including: the research field of HHRA research (35%, 35/100), risk management gaps associated with mitigations to reduce risk (22%, 22/100), and community exposure (10%, 10/100). Table 2.4 provides detailed descriptions of the gaps identified in the literature and relevant studies.

Table 2.4 Description and references for research, management, and community gaps identified in the scoping review literature (*n* = 67).

Gap Description	References
Research in HHRA	
Use of biomonitoring	(Obiri et al. 2010)
Improved methods or application	(B. Wu et al. 2010; Hunter et al. 2011; Ahmed et al. 2010; Steyn, Jagals, and Genthe 2004; Howard, Pedley, and Tibatemwa 2006)
Sources of uncertainty	(Peplow and Edmonds 2004; B. Wang et al. 2009)
Determining temporal exposures	(Momot and Synzynys 2005)
Determining future exposures	(Rapant and Krčmová 2007; P. R. D. Williams et al. 2000)
Considering all pathways of exposure	(Busset et al. 2010; Buchhamer et al. 2012; Qiao et al. 2010; Chai et al. 2010; Ujević Bošnjak et al. 2012; Mondal et al. 2010)
Exposure to additional hazard sources	(Busset et al. 2010; P. Williams et al. 2002; Kelepertzis 2014; Zheng et al. 2013)
Exposure to mixtures	(Phan et al. 2013; Qiao et al. 2010; de Jongh et al. 2012; B. Wang et al. 2009; Ma et al. 2014; Genthe et al. 2013)
Guides to direct researchers	(Caylak 2012a)
Gather more epidemiological evidence and toxicological data	(Marara, Palamuleni, and Ebenso 2013; Emmanuel, Pierre, and Perrodin 2009; Wu et al. 2010; Peplow and Edmonds 2004; Kelepertzis 2014; Ramirez-Andreotta et al. 2013; Lee et al. 2006; Razzolini et al. 2011)
Risk Management	
Collect data to inform management	(Ni et al. 2009; Machdar et al. 2013; Razzolini et al. 2011; Ramirez-Andreotta et al. 2013)
Knowledge of geochemistry and aquifers	(Singh et al. 2014; Emmanuel, Pierre, and Perrodin 2009)
Monitoring	(Wu et al. 2010; de Jongh et al. 2012)
Evaluation of exposures	(Williams et al. 2002; Hynds, Gill, and Misstear 2014; Buczyńska and Szadkowska-Stańczyk 2005)
Establish national/regional HHRAs	(Kumar et al. 2010; Addo et al. 2013; Etchie, Etchie, and Adewuyi 2012; Ahmed et al. 2010)
Standardize methods for mixtures	(Wang et al. 2009)
Standardize regulations	(Yacoub et al. 2013; Leung et al. 2013)

Improved communication, response and determination of risk	(Santos et al. 2013; Genthe et al. 2013; Steyn, Jagals, and Genthe 2004; Ramirez-Andreotta et al. 2013)
Community Exposure	
Inclusion of specific community (i.e., sensitive community members)	(Williams et al. 2000)
Isolate risks specific to communities	(Caylak 2012b; Hunter et al. 2011; Giri and Singh 2014)
Consider quality of life, socioeconomic, and political factors	(Lee et al. 2010; Singh et al. 2014; Z. Wang et al. 2011)
Improve community involvement, engagement, education, and risk management	(Karim 2010; Genthe et al. 2013; Razzolini et al. 2011)

2.5 Discussion

This paper provides an overview of HHRAs applied to unregulated drinking water in peer-reviewed literature and describes the frequency of their application to rural communities, the characteristics of their methodology, and gaps identified in the literature. Most of the scoped publications (79%) failed to specify the regulatory status of source water. The inclusion of literature with water sources of unknown regulatory status reveals the need to improve characterization of source water hazards in HHRA. Although 28% of applied HHRAs were identified as taking place rural communities, only 7% clearly identified both a rural population and unregulated water source. Similarly, in a third of the articles the source water was not specifically described as raw or treated. This lack of transparency in identifying the population of concern has been previously described in a review by Pons et al. (2015) of waterborne disease outbreaks in Canada and the United States, and appears to be an ongoing oversight by authors reporting on risk associated with drinking water. It is essential to describe the population of concern and the regulatory status of source water utilized for drinking purposes to effectively assess the potential drinking water risks to global rural communities; to support development of appropriate risk management options; and, to further research in the discipline of human health risk assessment.

The water source (i.e. ground, surface, and other) was highly reported in the studies which suggest that groundwater (67%) was the most frequent source of drinking water; however, only 14 of the studies identified the groundwater source as unregulated. Although only 21 studies identified an unregulated drinking water status, it is possible that 51 of the studies that did not specify the regulatory status but identified untreated water could be identified as unregulated. A high proportion of unregulated groundwater use would be expected given the global effort to meet the needs of increasing populations and improve accessibility of drinking water in rural and remote locations (Kundzewicz and Döll 2009; WHO/UNICEF 2015; Pons et al. 2015; Famiglietti

2014). Information on source, treatment and regulatory status of drinking water is essential for effective use of reported data. The potential for risk is very different between treated and untreated sources. For example, treated water may pose risks associated with disinfection by-products while raw groundwater sources may focus on naturally occurring heavy metals. The very nature of unregulated source water implies a lack of management options such as regular maintenance and monitoring. Without clear identification of drinking water supplies, and reliable information, data, and reporting, it is difficult to gauge risk and provide risk management options to rural communities.

The application of HHRA methods was largely deterministic with approximately 1 in 7 reporting the use of probabilistic or stochastic methods. Though these methods are not being utilized to *integrate* non-traditional factors into a *holistic* HHRA, more than half of the papers mentioned or qualitatively applied non-traditional factors to the interpretation of risk. For example, the most frequently acknowledged non-traditional factor was geography which was often used to define the area associated with the hazard or to compare risk between specific areas. A shift from deterministic to probabilistic methods (which can utilize stochastic distributions) has benefits including: the quantification of uncertainty (Bridges 2003; Burns et al. 2014); less dependence on animal based studies (Bridges 2003); increased transparency in the process of risk assessment (Burns et al. 2014); the potential inclusion of qualitative information (Serre et al. 2003); and, the use of vast and multiple data types (Zargar et al. 2014). In the context of this review only 4 studies carried out what the WHO/IPCS (2001) defined as an integrated risk assessment; however, only (Genthe et al. 2013) further met the scoping review criteria addressing rural population consuming unregulated source water.

Holistic approaches using probabilistic risk assessment methods and decision-type networks (e.g. Bayesian Risk Assessment) that can utilize qualitative and quantitative data were not applied in the literature despite frequent acknowledgement and use of non-traditional factors to interpret risk (e.g. comparison of risk between geographical areas). The integration of qualitative data, such as behavior, can improve risk management due to its influence on water use and exposure for rural communities (Chowdhury, Champagne, and McLellan 2009; Hertwich, McKone, and Pease 1999). Researchers could explore the benefits of probabilistic and stochastic methods in holistic HHRA to integrate non-traditional factors potentially influencing risk and to better characterize uncertainty (Serre et al. 2003). For example, effective education or government programming to alter human behaviour can be used decrease exposure to hazards, rather than treating illness outcomes. Therefore, by determining how the behaviour changes the overall risk, the strategy for risk communication and management can be tailored to the receptors. Researchers continue to rely on traditional methods of HHRA despite the advances in software and data processing capability; the ongoing need to improve the use of data and accuracy of risk assessment; and, encouragement to use probabilistic methods by governments (i.e. US EPA 2015). Probabilistic methods in HHRA can enable more holistic risk assessments (e.g. Zargar et al. 2014), similar to the environmental field (e.g. Hooten and Hobbs 2015), to assess not only multiple hazards but to include non-traditional factors that may influence risk.

The potential influence of non-traditional factors is related to uncertainty if they have an influence on the overall measure of risk (Slovic 1999; Boholm 2010; Renn 1998). Uncertainty is an important part of any risk assessment because it provides the caveats that may affect the interpretation of the risk measure. Fewer than half of the papers reported quality assurance and control within their studies. Declaration of uncertainty is fundamental to risk assessment (Burns et al. 2014) and well-established frameworks provide checklists to ensure users disclose uncertainty (IPCS 2014; US EPA 1989). Twenty percent (20%) of the reviewed research papers addressed uncertainty and limitations under a specific sub-heading in the article. Without full disclosure of uncertainty, it is difficult compare or assesses risk evaluations.

A significant short-coming identified in the literature was a lack of defined at risk exposure populations. This can be improved when thorough descriptions of receptors are provided (Kavlock et al. 1996). For example, age groupings for receptors and terms such as ‘rural’ and ‘urban’ should be defined with geographic area for better characterization of risk. Adult receptors were frequently chosen to represent communities while sub-groups or sensitive populations were less frequently identified. The scoped studies had limited demographic representation of the receptors and considered only a single route of exposure. Despite the perceived need for inclusion of all exposure pathways as identified in the literature (Buchhamer et al. 2012; Chai et al. 2010; Qiao et al. 2010), the oral pathway of exposure was most frequently assessed.

Communities were often defined by a geographic or topographic area, implying a natural link between groundwater hazards and the physical environment, notably the geology or land-use. However, a geological approach including the interpretation of hydro-geology could be more relevant when associations between geology and hazards are required (e.g. Rajagopal and Talcott 1983). Typically, receptors in studies were vaguely identified as ‘local residents’, ‘general public’; ‘local farmers and their families’; and, ‘individuals responsible for their source water’. Related to the need to better describe the receptors, researchers identified gaps in community exposure including the necessity to address additional receptor groups or communities to improve aspects of risk assessment or management options. Clearly defining the receptors and communities in the human health risk assessment further improves the research, allowing future research to build on the knowledge associated with the characteristics of similar receptors.

Studies most frequently identified natural and anthropogenic chemicals as potential hazards. The focus of the studies on chemicals, versus bacteriological water quality parameters, suggests that the unspecified and untreated (51%) water sources in the studies may largely be unregulated groundwater; however, we are unable to confirm this. Interestingly, bacteria, pathogens, and radiological parameters were infrequently included in studies despite their presence in surface and groundwater (Ritter et al. 2002 and Villanueva et al. 2014). Thus, future research considering risk associated with chemical, radiological, and microbiological parameters may provide a more comprehensive measure of risk for communities dependent on unregulated source water. Source water and specific hazards were generally well defined in the scoped studies; however, risk management or mitigation would benefit from comprehensive characterization of hazards and receptors including: mixed chemical or hazard exposures; geographical/geological influences; social/societal factors; and limitations and uncertainties associated with all aspects of HHRA.

The relative frequency of HHRA research on unregulated or unspecified drinking water is variable globally and is primarily focused in Asia. Since 2000, the majority of HHRA studies have taken place in countries with large numbers of rural residents without improved drinking water sources and high exposures to natural and anthropogenic water quality hazards (e.g. China and India; UNICEF/WHO 2012; Zhang et al. 2010). Conversely, there is an absence of HHRA studies conducted in more developed regions with known drinking water hazards (e.g. North America). Villanueva et al. (2014) suggest that assessing drinking water exposure is a challenge due to insufficient information on hazards and exposure. Therefore, global rural populations reliant on unregulated drinking water, regardless of regional socio-economic status, may be at increased health risk due to a mistaken perception that hazards are low. Alternatively, underutilization of safe unregulated drinking water is a missed opportunity to provide sustainable water to rural populations. Considering the development status of countries, a developed region (e.g. North America) would have the resources required to drastically reduce the risks to their population reliant on unregulated drinking water, and the research and risk management strategies carried out may provide insight into the larger global challenge of improving access to safe drinking water.

Research publications focusing on unregulated or unspecified drinking water increased from 2000 to 2014. For the scope of this review, publications prior to 2000 were not included because the literature is dated and data analysis methods have since advanced with mainstream use of computers for analysis (USEPA 2001; Hooten & Hobbs 2015). Regardless, this review determined an approximate 7% annual publication rate which is similar to the global exponentially increasing annual publication rate of approximately 8% from 1980 to 2012 (Bornmann and Mutz 2015). In addition to increased publishing, the Millennium Declaration was established in 2000 by the Member States of the United Nations leading to the Millennium Development Goals and United Nations initiatives which have focused on improving access to safe drinking water and sanitation internationally (WHO/UNICEF 2015). These programs ‘gained momentum in the 2000s’, (Bartram et al. 2014) which may have created increased funding opportunities for drinking water research in countries with large rural populations lacking access to safe and sustainable drinking water. If these global initiatives are influencing publications, drinking water research, particularly in undeveloped countries and vulnerable communities, should continue to increase in the wake of international initiatives such as the World Health Organization’s *Water Quality and Health Strategy 2013-2020* (WHO 2013).

Publications on drinking water quality and human health best fit into journals addressing the interrelationship between disciplines focused on human health, risk assessment, and the environment. Researchers conducting *risk assessments* on *human health* should use the full description *human health risk assessment* instead of variations that introduce ambiguity. Human health risk assessments are defined by the USEPA (2015a) as '…the process to estimate the nature and probability of adverse health effects in humans who may be exposed to chemicals in contaminated environmental media, now or in the future'. Use of standardized terminology in title and abstract would ensure risk assessments with human subjects are easily identified during literature searches. Increased consistency in use of terminology, in addition to improvements already discussed (i.e. need to better characterize the hazards and receptors), would improve the clarity and transparency of applied HHRAs.

Fewer than 50% of studies identified gaps in the literature. Risk assessment short-comings were identified more frequently than gaps in risk management or community exposure. Risk assessment gaps often included the need for increased epidemiological and toxicological data, in an effort to understand the toxicological effects when exposed to chemical mixtures through multiple pathways. Risk management gaps, identified by researchers, expressed a similar need for increased data and monitoring, and improved evaluations of exposure. In addition, risk management gaps highlighted the desire by researchers to have specific national or regional HHRAs. We can summarize the gaps identified by researchers in the field of HHRA to say that overall they require: increased data collection and monitoring as well as strong integration with research fields that support HHRA (e.g. toxicology and epidemiology); the determination of risk by way of standardized methods and guides that improve accuracy and account for uncertainty; community-based research approaches that consider how the data and results can be used to support ongoing drinking water management; and, improved communication and involvement with communities to ensure the outcome of HHRA studies are specific and relevant as it relates to the receptors and their exposure.

In addition to risk assessment and management gaps identified in the scoped studies, the need for risk characterization specific to communities has been recognized by researchers. Consideration of non-traditional factors (e.g. quality of life, socioeconomic, and political) have been suggested and supports the need to determine how these factors may influence risk. The importance of HHRA to protect community health requires transparency and diligent data collection, analysis, and reporting. This could be achieved through equal partnerships with communities and would be beneficial, ethical and in practice with a community based participatory research approach where both the researchers and community would benefit (O'Toole et al. 2003; Slovic 1999). In the context of HHRA it is ideal to meet the goals of research and management for applied research that benefits both academia and communities.

2.5.1 Strengths and Limitations

This scoping review was carried out with a systematic approach. Inclusion of five databases, each varied in breadth and depth, ensured the necessary coverage required for this review. The multidisciplinary team and frequent communication provided a balanced process and facilitated consensus through screening and full-text review, thus, eliminating the need for reliability statistics. A professional librarian guided initial database searches decreasing the likelihood of bias or error associated with attaining citations relevant for review. Abstract categorization assisted in development of inclusion or exclusion criteria for full-text review while allowing the team to become familiar with the literature as recommended by Daudt, van Mossel, and Scott (2013). Consistent with Pham et al. (2014), full-text reviews did not include qualitative or quantitative assessment of research quality. Research team meetings at each step through the scoping process were necessary to integrate advice from the team, and maintain effective communication (Daudt, van Mossel, and Scott 2013).

The possibility exists that relevant articles were excluded. Ending the search in May 2014 limited interpretations of publication trends up to publication. Despite mutually established and well-defined definitions for charting, the full-text review between researchers is subject to interpretation error. Exclusion of regulated water sources limited our ability to compare the characteristics of the scoped studies to regulated sources; however, the focus of this scoping review was to determine the characteristics associated with HHRA studies focused on unregulated source water.

2.6 Conclusion

A summary of the HHRA literature and methods applied to populations dependent on unregulated or unspecified drinking water sources is provided. This review reveals a lack of HHRA research dedicated to rural populations dependent on unregulated source waters in spite of the global concern regarding access to safe drinking water. The majority of the scoped HHRAs were applied in countries of proportionally high rural populations globally, of which a large proportion of water is unregulated and untreated. Insufficiently defined and poorly disclosed risk assessments decrease the usefulness of the research when attempting to gather vital information on exposure populations, water sources, and hazards to further this area of study or manage risk. The field of HHRA may be delayed in the adoption of methods that allow for the inclusion of various data types and the quantification of uncertainty for a holistic approach. It is essential that literature gaps identified by researchers and summarized herein, are used to inform the future direction of research and management on unregulated drinking water for the world's rural populations. Furthermore, the adoption of community-based participatory approaches, where possible, will provide the information necessary to support risk management decision-making and improve the health of communities.

2.7 Recommendations

Global rural populations face potential health risks related to water quality hazards associated with unregulated source water. Evolution and improvement in the approach and application of HHRA methods are necessary for a better understanding of the human health risks, and improved risk communication and management in rural populations. Recommendations for researchers, based on a summary of studies in the field of HHRA on unregulated and unspecified source waters, are as follows:

- Components of the HHRA (e.g. exposure population, source water, hazards, etc.) should be adequately described to improve the detection of potential relevant literature upon title and abstract searches, and the quality of research reporting. Consistent use of terminology and reporting associated with standardized HHRA frameworks is essential. Uncertainty and limitations should be clearly presented to allow for appropriate interpretation of the research.
- A holistic approach to HHRA should be considered when non-traditional factors are suspected of influencing the human health risk. This can be accomplished with alternative methods of risk assessment (e.g. Bayesian risk assessment) to characterize non-traditional factors and their influence on the human health risks. Gaps in the literature also identify the need to consider the effects and uncertainty non-traditional factors have with respect to multiple hazards, exposures and pathways.
- Identification of gaps in research, management, community, and risk assessments is a necessary component of HHRA. Recognition of gaps in these areas drives research forward, paving the way for new research to better inform future approaches, frameworks, and decision-making.

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3 Consumption of Unregulated Well Water in Rural Communities: Impact of Perception and Use on Human Health Risk

3.1 Abstract

Hazards in unregulated drinking water pose a potential health risk to rural populations. In the absence of drinking water regulations, rural populations rely on experience to inform their perception of drinking water risk. Determining the impact of risk perception on drinking water use can better inform assessments of exposure and health risk. A community-based participatory observational case study provided risk perception data to integrate in a holistic human health risk assessment completed using probabilistic Bayesian risk assessment methods. Tap water and household surveys were collected from two communities in Saskatchewan, Canada. At least one drinking water health standard was exceeded by 65% (49/76) of households in the Rural Municipality #184 (RM184) and 56% (25/45) in Beardy's and Okemasis First Nation (BOFN). Most households in RM184 (66%) and BOFN (59%) perceived their water as safe to drink. Households in the RM184 showed an association between risk perception and the presence of a drinking water health exceedance when compared to drinking water guidelines ($p = 0.012$); however, households in BOFN showed no significant association between risk perception and the presence of a drinking water exceedance. The probability of drinking tap water when water was perceived as safe (0.92) or not safe (0.00) suggests households in RM184 were unlikely to drink water perceived as not safe. In BOFN, the probability of drinking tap water when perceived as safe (0.77) or as not safe (0.11) suggested there were factors that lead participants to contradict their perceptions. Using arsenic as an example, accounting for risk perception lowered the adult Incremental Lifetime Cancer Risk by 3% for both communities. The probability of exposure to arsenic concentrations greater than the 1:100,000 considered as negligible cancer risk was 23% for RM184 and 22% for BOFN. This novel approach provides a probability of risk specific to communities that can inform risk communication and management.

3.2 Introduction

Rural populations with access to water are often dependent on unregulated drinking water sources (WHO/UNICEF 2015). Representing 46% (3.38 billion) of the global population, the large majority (96%) access water that has not been verified as safe (World Bank 2015; WHO/UNICEF 2015; Shaheed et al. 2014). Unregulated drinking water sources (e.g. groundwater, surface water, bottled water, or rain water) lack regulatory oversight includes regular water quality testing and monitoring to ensure drinking water quality meets standards for human consumption. In the absence of effective water regulation, consumers, including private well owners, are responsible for the protection of the water source and human health. Individuals responsible for managing unregulated water sources often lack the knowledge and resources required to effectively manage drinking water and reduce risks to human health (Shaheed et al. 2014; Martz 1983; Maxwell et al. 1998; Hynds, Misstear, and Gill 2013; Charrois 2010). In addition, the frequency of chemical or biological hazards exceeding drinking water quality guidelines in unregulated drinking water sources can have serious health consequences (Hynds, Misstear, and Gill 2013; Fox et al. 2016; Charrois 2010; Rogan and Brady 2009a; Pons et al. 2015; Simpson 2010; Schuster et al. 2005; Villanueva et al. 2013; Fawell and Nieuwenhuijsen 2003).

In 2010, the United Nations developed the Millennium Development Goals (MDG), which committed to reduce, by half, the global population without sustainable access to safe drinking water by 2015 (WHO/UNICEF 2015). Over that period, the MDG initiative successfully increased global access to improved drinking water sources by 15% (2.6 billion people), but the safety of water from these sources was not a measurable outcome (Shaheed et al. 2014). To address this issue the WHO and UNICEF Joint Monitoring Program (JMP) included water quality monitoring in their Sustainable Development Goals (SDG) going forward from 2016-2020 (WHO/UNICEF 2016). Despite these global efforts, the quality of drinking water for the 15% that have recently gained access and the percentage of the global population that already has access to water of unknown quality is a gap in our understanding of the potential human health risks to these rural populations.

In North America, Canada and the US report that they reached their MDG for 100% improved access to drinking water; however, the safety of many unregulated drinking water sources remains unknown to consumers. Approximately 43 million Americans and 6 million Canadians access unregulated groundwater (Fox et al. 2016; Statistics Canada 1996) from private sources and there may be considerable health risks associated with exposure to groundwater contaminants. In Canada, rural populations, including First Nations, rely on unregulated groundwater sources that can pose a risk to human health due to the lack of education, monitoring, and effective treatment of individual and private wells (Charrois 2010; Spence and Walters 2012; Corkal, Schutzman, and Hilliard 2004; Jones et al. 2005). Similar problems exist globally, where rural populations depend on unregulated drinking water sources, but lack the capacity to manage them (WHO/UNICEF 2015; Schwarzenbach et al. 2010). Establishing safe drinking water for these rural populations may also be hindered by a lack of resources (e.g. financial) and increased vulnerability (e.g. poverty, illness, minority status, etc.), making it difficult for individuals or communities to cope with the responsibility of drinking water management (Nsiah-Kumi 2008; Wescoat, Headington, and Theobald 2007; Zheng and Ayotte 2015).

In the absence of effective monitoring and management of unregulated water supplies, drinking water consumption is often dependent on risk perception or how safe people feel the water is to consume (Shaheed et al. 2014; Martz 1983; Maxwell et al. 1998; Hynds, Misstear, and Gill 2013; Charrois 2010). People's perception of the safety of their drinking water has not been found to correlate with the safety of water for human consumption which can lead to the overuse of unsafe water sources (Martz 1983; Maxwell et al. 1998; Hynds, Misstear, and Gill 2013; Patrick 2011; Orgill et al. 2013; Chen et al. 2012; Turgeon et al. 2004). Conversely, the avoidance of safe drinking water, perceived as unsafe, may encourage consumption of alternative unsafe water sources or sugary beverages (Onufrak et al. 2012; Onufrak et al. 2014; Dupont, Adamowicz, and Krupnick 2010). The factors contributing to drinking water risk perception are complex (Doria 2010); however, drinking water risk perception characterizes an uncertainty associated with human behaviour (i.e. consumption of water) that influences consumption and exposure (Chowdhury, Champagne, and McLellan 2009).

Perception of risk associated with unregulated drinking water is a 'non-traditional' variable as it relates to exposure and human health risks. The integration of non-traditional variables, similar to risk perception (e.g. economic, social, and human behaviour), into risk assessment has been suggested by Ryan (2003) and Wilks et al. (2015) but has not been accomplished as it relates to health risks associated with unregulated drinking water (Ford et al. 2017). Fortunately, Bayesian risk assessment methods have become more accessible and allow for the integration of uncertain or qualitative data. Bayesian risk models can enhance traditional quantitative assessments by including community knowledge and providing a measure of uncertainty around the estimates of risk necessary to assist public health planning and policy (Serre et al. 2003; Ritter et al. 2002). The literature provides examples of probabilistic and Bayesian techniques that can be applied to HHRA to facilitate integration of different data types and sources such as non-traditional variables (Serre et al. 2003; Chowdhury, Champagne, and McLellan 2009; Liu et al. 2012; Schmidt et al. 2013; Ramachandran 2001).

With increased pressure on governments to include human perceptions/perspectives in sustainable water resource management (Jackson 2006; Jackson et al. 2012), it would be beneficial to determine the impact perceptions have on human health risk given the indirect health effects associated with human behaviour in response to poor drinking water (Wescoat, Headington, and Theobald 2007). In 2005, Suter II et al. predicted future risk assessments would require an integrative approach defined by collaborative, place-based risk assessments that could integrate additional data to inform direct and indirect risks. In addition, more informed risk assessment supports risk management by providing scalable assessments relevant to communities or populations (Suter II et al. 2005). Understanding the effect of risk perception on human health risk could improve drinking water risk management and communication (Markon and Lemyre 2013), and as stated by Serre et al. (2003), “Uncertain knowledge obtained about important exposure parameters could be more valuable than the certain knowledge obtained about less important parameters”. Therefore, the inclusion of risk perception in HHRA, as it relates to unregulated drinking water, may contribute uncertain knowledge for a holistic and accurate interpretation of risk.

3.2.1 Purpose and Objectives

The purpose of this research is to integrate risk perception associated with unregulated drinking water into a holistic human health risk assessment to support the improvement of risk communication and management for communities. The objectives include characterizing and quantifying risk perception as it relates to unregulated drinking water wells, and determining the impact of risk perception on human health risk using Bayesian risk assessment to improve accuracy and quantify uncertainty.

3.3 Methods

3.3.1 Research Approach

A community-based participatory observational case study and probabilistic Bayesian risk assessment methods were used to integrate drinking water risk perception into a holistic human health risk assessment. The collection of risk perception and water quality data specific to these case communities enabled the integration of risk perception for the development of holistic human health risk assessment while providing the information necessary for communities or individuals to mitigate drinking water risks.

3.3.2 Study Area

Participating rural communities included private well owners in the Rural Municipality of Grayson #184 (RM184; 50°38′05″N 102°37′01″W) and residents with access to wells on Beardy’s and Okemasis First Nation (BOFN; 52°49'56"N 106°17'43"W), Saskatchewan, Canada (Figure 3.1). Communities were selected because the density of unregulated well users, known groundwater hazards, and the willingness of communities and individuals to partner and participate. The southern three quarters of the province is geologically located within the Western Canada Sedimentary Basin which is comprised of Precambrian rocks, layered under ‘flat-lying sedimentary strata’ as described by Maathuis (2008). He describes the flow within aquifers or aquitards as mostly horizontal and in response to gravity; however, under certain circumstances flow can be vertical as well (Maathuis 2008). With Saskatchewan water found within the sedimentary layers, most of the potable groundwater is within the upper aquitard but is of poor aesthetic quality due to exceedances in sulphate, sodium, chloride, hardness, iron, manganese, and total dissolved solids (Maathuis 2000; Maathuis 2008).

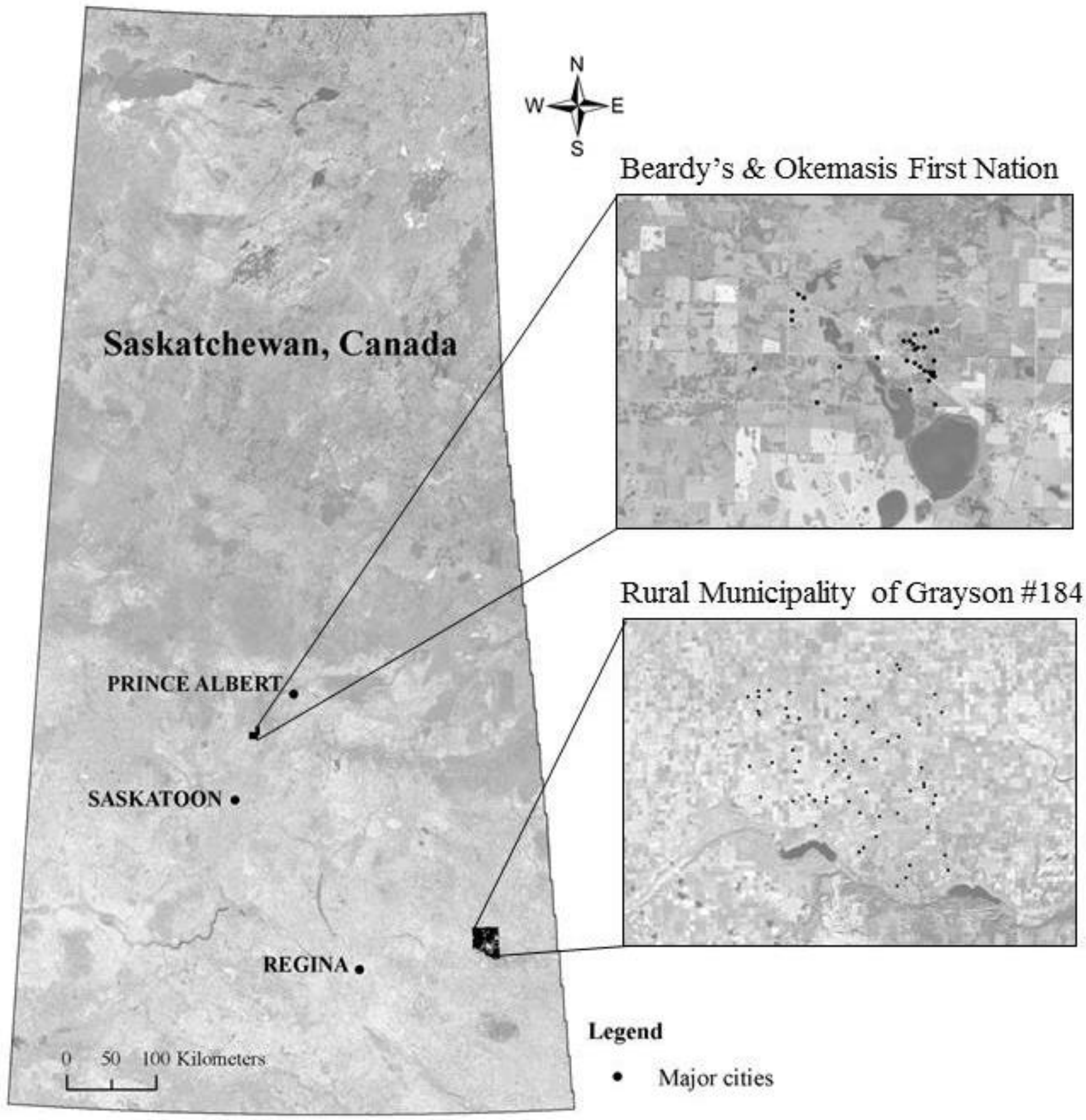


Figure 3.1 Study communities in rural Saskatchewan, Canada.

3.3.3 Community Partnership and Participant Recruitment

Primary recruitment for the pilot survey took place in partnership with a local stewardship group located in the Lower Qu'Appelle River valley, Saskatchewan. Individuals participating in the pilot survey were volunteers outside the study areas but within the same watershed as RM184. A total of 45 volunteers with private drinking water wells were contacted by a research assistant to complete the pilot survey.

Recruitment of participants for the primary study was initiated through partnerships with the municipal government and the Chief and Council. Community leaders were approached and consent at the community level was established prior to garnering the participation and consent of individual household participants. Individual participants received a letter of invitation either by mail or in-person and completed a consent form which identified the purpose, risks and benefits of the study. For the purpose of this study the population of interest included adults aged 20 to 59 in households with: a well plumbed to the house, a working well pump, the ability to bypass treatment and water storage, primary residence in the community, and a signed consent form.

The total population, community characteristics, the number of households with access to wells, and the number of adults was gathered from three sources including: *eHealth Saskatchewan*, the community representatives (i.e. Rural Municipality Council and Band Office), and the study survey. Each community provided the contact information, location, and the estimated total number of households with access to wells. The number of eligible households includes those households that met the inclusion criteria and non-respondents for which the status of eligibility could not be determined. The required minimum sample size of adults to represent community risk perception was determined using a proportion of 0.5 with a 95% confidence interval and lowest possible marginal error.

3.3.4 Ethical Considerations

All individual households participating in the pilot survey or main study were provided with a clear description of the research, including its purpose, risks, benefits, and contacts. To ensure local support, following the collection of data and follow-up with individual household participants, provincial and municipal health authorities were made aware the research was taking place. Survey and water quality data was confidential with exception of its disclosure to individual household participants. Only a generalized summary of the data was used for presentation and publication purposes. The study was approved by Behavioral Ethics Board at the University of Saskatchewan Research Ethics Office, Saskatchewan, Canada (#Beh14-108, April 14th, 2014).

3.3.5 Outreach and Education

Pilot survey participants received educational materials on well management, testing, and disinfection. Individuals participating in the pilot survey also received a letter of thanks and a voucher for free nitrate and bacteria analysis at an accredited laboratory. For study participants, results of water sampling were immediately reported by phone to each well owner upon receipt from the laboratory. Following a phone call, the original water quality results and a letter explaining excursions from the *Saskatchewan Drinking Water Quality Standards and Objectives* (WSA 2015) for tap water (post distribution and treatment) and raw water (purged well water), was sent to each well owner in RM184. Water quality results from individual wells on BOFN were provided to the Band on behalf of community members as requested. Follow-up with the communities included presentations, summarized data, and posters at their request.

3.3.6 Survey Data Collection

Well user characteristics and questions to determine the association between drinking water risk perception and well water use (exposure) were collected with a close-ended household interview survey (Table 3.1). Categorical and dichotomous questions were designed to determine: eligibility, household use and perceived safety of well water for drinking, well-user characteristics (i.e. age of adults, household highest education and income, residence time, and water consumption), and water treatment. For ease of interpretation, water treatment included equipment and technology that conditions or treats drinking water.

Each pilot survey participant completed two telephone interviews separated by a minimum of 30 days. Cohen's kappa (κ) was used to determine inter-rater agreement between the two interviews for each pilot survey participant (Cohen 1960). Interviews to administer the survey for the primary study were conducted by telephone or in-person to households in RM184, and in-person for households on BOFN. Interviews took place from July to October 2014.

Table 3.1 Interview questions to determine perception of risk, and well-user characteristics.

Category	Question	Answer
Well User Information	How many adults aged 20 to 59?	Number of adults
	What is your household income?	< \$24,999 \$25,000 - \$49,999 \$50,000 - \$99,999 > \$100,000 Prefer not to say
	What is the highest level of education in the household?	< Grade 12 (no diploma) High school diploma Some college (no degree) Associate/technical degree Bachelor's degree Graduate/professional degree Prefer not to say
	How long have you lived here?	Years
Water Consumption	How much water do you drink per day?	L/day
Well Use	Do you use your well water for drinking?	Y/N
Well Safety	Do you think your well water is safe to drink?	Y/N
Water Treatment	Do you operate or own any water treatment equipment? (i.e. softener, filters or reverse osmosis)	Y/N

3.3.6.1 Characterization of Risk Perception

Risk perception associated with drinking water was quantified by determining the probability of well use given the water was perceived as safe or not safe. Due to the high level of agreement between well use and safety, the maximum likelihood and Wald statistic could not accurately be calculated due to quasi separation. A contingency table was used to summarize the relationship between the binomial survey questions and the Clopper-Person exact-binomial estimate method was applied to determine the probability and 95% confidence interval representing the probability of occurrence (Clopper and Pearson 1934). The beta distribution, identified by Thulin (2014), was then selected to define the probability of drinking the water when it was perceived, safe or not, for integration with the exposure variable in the risk assessment. The basic equation to develop the probability that well water would be consumed based on the perception the well was safe was as follows (Equation 3.1):

$$p.risk = \left((prop.s * prob.s) + (prop.ns * prob.ns)\right) \qquad 3.1$$

Where:

p.risk is the probability the water was used if it was perceived as safe and if was perceived as not safe.
prop.s is the proportion of people that perceived the well water was safe.
prob.s is the probability the water was used if it was perceived as safe.
prop.ns is the proportion of people that perceived the well water as not safe.
prob.ns is the probability the well water was used if it was perceived as not safe.

3.3.7 Hazard Data Collection

While arsenic was the metal of interest in this study, the full suite of drinking water parameters (i.e. major ions, *Escherichia coli* and total coliform bacteria), and metals were analyzed to provide communities and individuals with a comprehensive understanding of the raw well water, and post treatment and distribution in-house tap water. For the purpose of this study unregulated tap water from a groundwater source was collected to establish the arsenic concentrations (hazard variable) for the HHRA as it pertains to each community.

3.3.7.1 Water Quality Materials and Methods

Sample bottles for water collection included a sealed plastic 250 mL sterile bottle containing sodium thiosulfate for bacteriological analysis, and a plastic 500 mL bottle for chemical analysis including major ions and metals. Bacteriological samples were collected using nitrile gloves with care taken not to contaminate the sample. Chemical samples were taken after triple-rinsing with sample water and nitric acid was added if required by the laboratory. Field measurements were collected using the YSI Pro 1030 and Analite NEP160 turbidity meter or LaMotte 2020wi turbidity meter ISO kit. Field measurements included: temperature (°C), specific conductivity (µS/cm), pH, and turbidity (NTU). Meters were calibrated on a weekly basis.

3.3.7.2 Water Quality Sampling

An in-house tap and raw well water sample were collected for each household participating in the study. Tap water samples were collected from the kitchen as first-flush grab samples. Tap samples were intended to be representative of the water quality if an individual filled a glass for drinking and constituted the arsenic data used in this study. The in-house tap sample for bacteriological and chemical analysis was not disinfected prior to sampling. Raw water was collected from an outside tap or hydrant close to the well and prior to water treatment or storage.

The raw well was purged prior to sampling to ensure the sample was representative of the current state of groundwater quality. Purging was achieved when the temperature and specific conductivity had stabilized (Knobel 2006). Chemical raw water samples were collected prior to disinfecting the tap with 1 part bleach to 2 parts water in preparation for bacteriological sampling. Hydrants were disinfected, prior to sampling, using a propane torch prior to bacteriological sampling. Each sample was assigned a sample number that corresponded to the household(s) connected to the well. Water samples were placed in an ice-filled cooler and transported by bus to the laboratory within 48 hours.

3.3.7.3 Water Quality Analysis

All water samples were submitted to the Provincial Disease Control Laboratory (PDCL) and approximately 1 in 10 samples were duplicated and sent to the Saskatchewan Research Council (SRC) to determine inter-laboratory variability for arsenic due to methodological differences between labs. Both laboratories are accredited by the Canadian Association for Laboratory Accreditation Inc. and conform to ISO/IEC 17025:2005 international standard. Laboratory analytical methods were conducted according to the *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA, and WEF 2012) with exception of the PDCLs use of a modified ICP-MS method for metals (EPA 1994). Water quality results, both raw and at the tap, were compared to *Saskatchewan's Drinking Water Quality Standards and Objectives* (2015) to determine the percent excursions for both Maximum Acceptable Concentrations (MAC) and Aesthetic Objectives (AO). These results were used to inform individual participants of the status of their drinking water, and provide a general characterization of groundwater in the study areas. A Chi-squared test for independence was used to determine if there was a significant association between risk perception and the presence of at least one exceedance of a drinking water guideline (SPSS Version 24, IBM Corp., Armonk, NY).

3.3.8 Data Management and Analysis

Water quality and survey data were entered by a research assistant into a Microsoft Access (Microsoft Corporation, Redmond, WA) and verified by the lead researcher. Descriptive statistics for arsenic and survey data were conducted using SPSS Version 24 (IBM Corp., Armonk, NY). Distributions for arsenic were determined using R package 'fitdistrplus' for fitting parametric distributions to non-censored or censored data (Delignette-Muller et al. 2016). One-half the detection limit was applied to left censored data for deterministic statistics.

3.3.9 Human Health Risk Assessment

A probabilistic risk assessment using Bayesian inference with Gibbs sampling was performed based on Health Canada guidance and methods (2010a, 2010b, 2010c). The procedure for the risk assessment followed Health Canada's framework and includes: background and objectives, problem formulation, exposure assessment, toxicity assessment, and risk characterization (Health Canada 2010b). Potential limitations and uncertainty will be addressed; however, aspects of risk management in response to risk characterization were to be determined by the communities or individuals participating in the study. The human health risk assessment model was informed by a conceptual diagram integrating risk perception with water intake and exposure (Figure 3.2). The following methods outline the frameworks, deterministic equations used, and the parameters and Bayesian model.

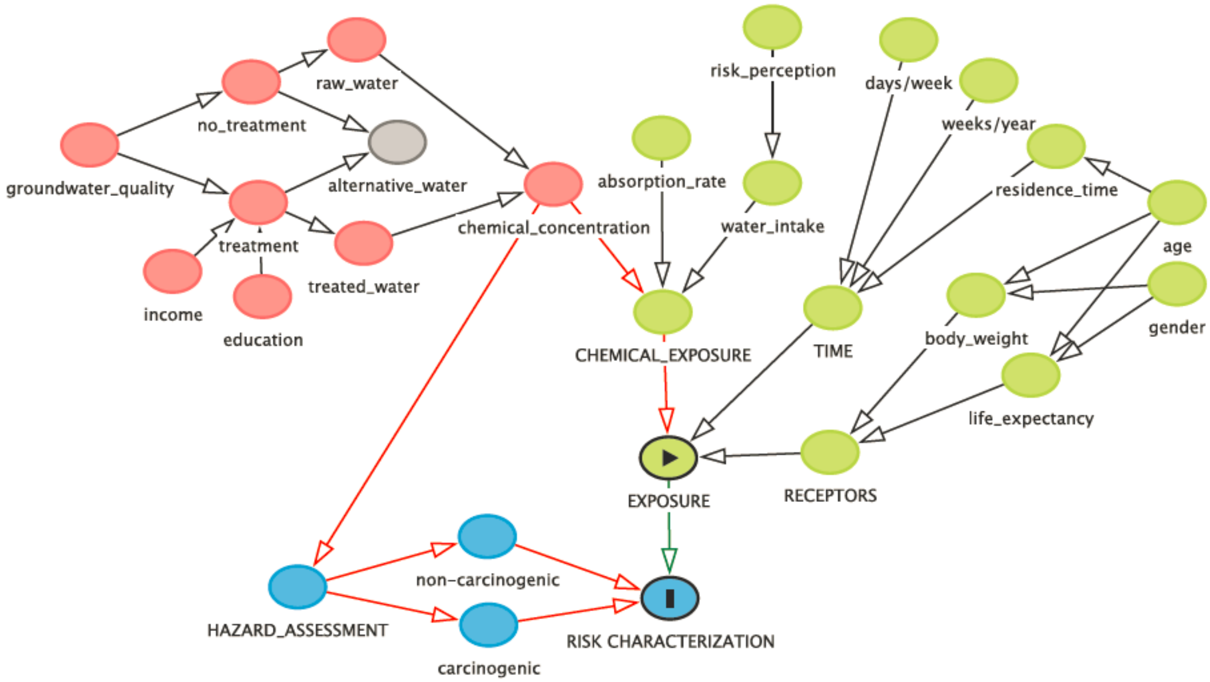


Figure 3.2 Conceptual diagram integrating perception of risk associated with drinking water and human health.

3.3.9.1 Problem Formulation

Arsenic was identified as a chemical of concern due to its natural presence in Saskatchewan groundwater (Thompson et al. 1999; Maathuis 2008; Sketchell and Shaheen, 2001). Arsenic in drinking water is a known health risk and concern within Canada and globally (Chappells et al. 2015; Normandin et al. 2014; McGuigan et al. 2010; Kumar et al. 2010; Chakraborti et al. 2015; Liu et al. 2009). Water quality testing took place from July to October 2014. The assumption of potential risk was made prior to testing and was based on Maathuis (2008) who identified 14.9% of Saskatchewan wells exceeded arsenic concentrations of 10 μg/L. The percentage of wells with arsenic concentrations greater than the *Saskatchewan's Drinking Water Quality Standards and Objectives* (2015) of 10 μg/L, and descriptive statistics were calculated for both communities.

All age categories represent potential human receptors in these communities; however, this HHRA focused on rural adults aged 20 to 59 with access to unregulated water wells. Household interviews were conducted with homeowners and it was assumed that their perception generally represented other adults in the home. For the purpose of this study we consider oral exposure to arsenic through ingestion of drinking water as the only pathway of exposure. Oral exposure through drinking water is considered a primary potential source when drinking-water is at least 10 μg/L (WHO 2011). For arsenic concentrations below 10 μg/L, Health Canada (2006) acknowledges the potential for increased estimated lifetime cancer risks associated with oral exposure to arsenic concentrations greater than 0.3 µg/L.

3.3.9.2 Exposure Assessment

The drinking water intake rate for adults in the Canadian population is estimated by Health Canada to be 1.5 mg/L; however, this study applies Richardson's (1997a) probability density function describing daily tap water consumption rate for both sexes in the Canadian population. The intake rate (IR_W) was multiplied by the probability of use given well water perceived as safe or not safe to better reflect exposure. Lifetime average daily dose ($LADD$) was calculated according to Health Canada's *Guidance on Human Health Preliminary quantitative Risk Assessment* (2010b) for ingestion of contaminated drinking water (Equation 3.2).

$$LADD\ (\mu g/kg\ bw/day) = \left(\frac{C_W \times IR_W \times RAF_{Oral} \times D_2 \times D_3 \times D_4}{BW \times LE}\right) \qquad 3.2$$

Where:

C_W = concentration of arsenic in drinking water (µg/L)
IR_W= adult water intake rate (L/day)
RAF_{Oral}= relative absorption factor
D_2= days per week exposed/7days
D_3= weeks per year exposed/52 weeks
D_4= total years exposed to site
BW= body weight (kg)
LE= life expectancy (years)

3.3.9.3 Toxicity Assessment and Risk Characterization

The incremental lifetime cancer risk (ILCR), as a result of unregulated well water consumption in RM184 and BOFN, was calculated using the LADD and cancer slope factor (CSF) of 1800 µg/kg/day (HC 2010a; Equation 3.3). Arsenic is categorized as a Group 1 carcinogen to humans causing increased risk of bladder, lung and liver cancers (HC 2010a; WHO 2011). A ILCR of ≤ 1 in 100,000 (1×10^{-5}), deemed by Health Canada as 'essentially negligible', was used as the threshold of acceptability for ILCR (2010b).

$$ILCR = LADD\ (\mu g/kg\ bw/day) \times CSF\ (\mu g/kg/day)^{-1} \qquad 3.3$$

3.3.9.4 Holistic Bayesian Human Health Risk Assessment

A probabilistic holistic Bayesian HHRA (i.e. ILCR for arsenic) was used to allow for the integration of risk perception as a variable and to quantify uncertainty when determining the probability of increased incremental lifetime cancer risk to two rural communities with access to unregulated well water. The lifetime cancer risk represents the number of additional cancer cases per 100,000 people over their lifetime. A value greater than 1.0 x 10^{-5} suggests a risk greater than that considered negligible by Health Canada (HC 2010). Bayesian inference was selected for modeling the HHRA because of its flexibility to integrate multiple data types, allowance for updated or future information in the model, and quantification of uncertainty through the use of Markov chain Monte Caro (MCMC) sample simulations (Zargar et al. 2014; Tighe, Pollino, and Wilson 2013). The model was developed using OpenBUGS version 3.2.3 rev 1012 (Lunn et al. 2009). Using water management as an example, Ames et al. (2005) provides a simple framework for building a Bayesian network involving: problem identification, model inference and model validation as three major steps. Having identified the purpose of this study, the following sections will focus on model inference and validation. Uncertainty associated with probabilistic risk assessment was identified using the USEPA (2001) guidance document on conducting probabilistic risk assessment.

3.3.9.5 Model Inference

Model convergence was qualitatively determined by visually monitoring the Brook-Gelman-Rubin (BGR) diagram, history, quantiles, and trace plot convergence for 3 chains according to Spiegelhalter et al. (2012). Burn-in period was determined to be 30,000 followed by 90,000 iterations per chain for a total of 270,000 iterations. Sample iterations were confirmed sufficient with an MC error less than 5% of the standard deviation as stated in Spiegelhalter et al. (2012). Quantitative model convergence was confirmed with R-CODA package to confirm the upper 97.5% of the scale reduction factor was less than 1.05 (Plummber et al. 2016; RStudio Team 2016).

The exposure assessment and ILCR equations identified previously provide the basis for the calculation of risk in this model; however, the parameters in the model were, when appropriate, characterized as stochastic nodes represented by probability density distributions. Model parameters and their sources are listed in Table 2. The model outcome ILCR represents the adult population and the probability of increased cancer incidence for each community. A step-function was used to determine the probability of the cancer risk exceeding 1 in 100,000 (Spiegelhalter et al. 2012). For the purpose of this study the step-function was used to determine the ‘probability of community risk’ which similarly represents the probability that the incremental lifetime cancer risk is greater than the 1:100,000 for individuals in the community. Figure 3 provides the Doodle graph of the model.

Table 3.2 Parameters and data sources for holistic Bayesian HHRA[a].

Deterministic Parameters	Probabilistic Parameters	Unit	Data Type	Likelihood Distribution	Reference
C_W	chem.c	µg/L	Continuous	N(-0.207, 1.24)† BOFN N(-0.436, 1.64)† RM184	Study
IR_W	h2o.in	L/day	Continuous	N(0.28, 0.50)	Richardson, 1997a
Risk Perception	prob.s	No units	Binomial	B(21, 7) BOFN B(47, 5) RM184	Study
	prob.ns	No units	Binomial	B(3, 17) BOFN B(1, 27) RM184	Study
	prop.s	No units	Binomial	B(27, 19) BOFN B(51, 27) RM184	Study
	prop.ns	No units	Binomial	B(19, 27) BOFN B(27, 51) RM 184	Study
RAF_{Oral}	Not included	No units	Discrete	Assumed a constant of 1	Health Canada 2010a
$D_2 \times D_3$	exp.f	days/year	Discrete	U(0.93, 0.96) between 340 to 350 days per year	Deng et al., 2012; Kentel and Aral, 2004
D_4	res.t	years	Discrete	U(20, 59)	Health Canada adult age category
BW	recp.t	kg	Continuous	LN(4.24, 0.20)	Richardson, 1997a
LE	lif.exp	years	Constant	N(80, 10)	Health Canada 2010b
CSF	SF.As	µg/kg/day	Constant	1800	Health Canada 2010a
$LADD$	exp	µg/kg bw/day	Logical Calculation	Determined by model	Health Canada 2010b
$ILCR$	risk.adu	Chance of cancer risk	Logical Calculation	Determined by model	Health Canada 2010b

[a] N, B, LN, and U means normal, beta, lognormal and uniform distribution; †Mean and precision logged to facilitate the use of the normal distribution

Semi and non-informative priors were applied to parameterize the data distributions that characterize mean and precision (tau). Precision was defined by 1/sigma^2 where sigma was the standard deviation. The semi-informative prior on the likelihood life expectancy (lif.exp) with a standard deviation of 10 and a normal distribution around the Canadian life expectancy of 80 years was developed using Parameter Solver, Version 3.0 (MD Anderson Cancer Centre, Houston, TX; Table 3.3). Non-informative Jeffery's priors were used on the likelihood of chemical concentration (chem.c), water intake (h2o.in), and receptor weight (rep.t; Lunn et al. 2013). Table 3.3 lists the probabilistic parameter and priors used in the model. Figure 3.3 provides the Doodle graph of the model. The full model in OpenBUGS can be referenced in Supplementary Materials – 5.3 Example of Model Code for Bayesian Human Health Risk Assessment.

Table 3.3 Priors on HHRA model parameters[a].

Probabilistic Parameters	**Prior Type**[†]	**Prior Description**	**Prior Distribution**
lif.exp	Semi-informative	SD = 10	sigma = G(125, 12.5) tau = 1/sigma^2
chem.c	Uninformative (Jeffery's)	μ = LNAs.ugl	LNAs.ugl = N(0, 0.00001)
		SD = sigma2	sigma2 = G(0.0001, 0.0001) tau2 = 1/sigma2^2
h2o.in	Uninformative (Jeffery's)	μ = intake	Intake = N(0, 0.00001)
		SD = sigma3	sigma3 = G(0.0001, 0.0001) tau3 = 1/sigma3^2
recp.t	Uninformative (Jeffery's)	μ = adu.wt	adu.wt = N(0, 0.00001)
		SD = sigma4	sigma4 = G(0.0001, 0.0001) tau4 = 1/sigma4^2

[a]G and N means gamma, and normal distribution; [†]Lunn et al. 2013 used to select priors

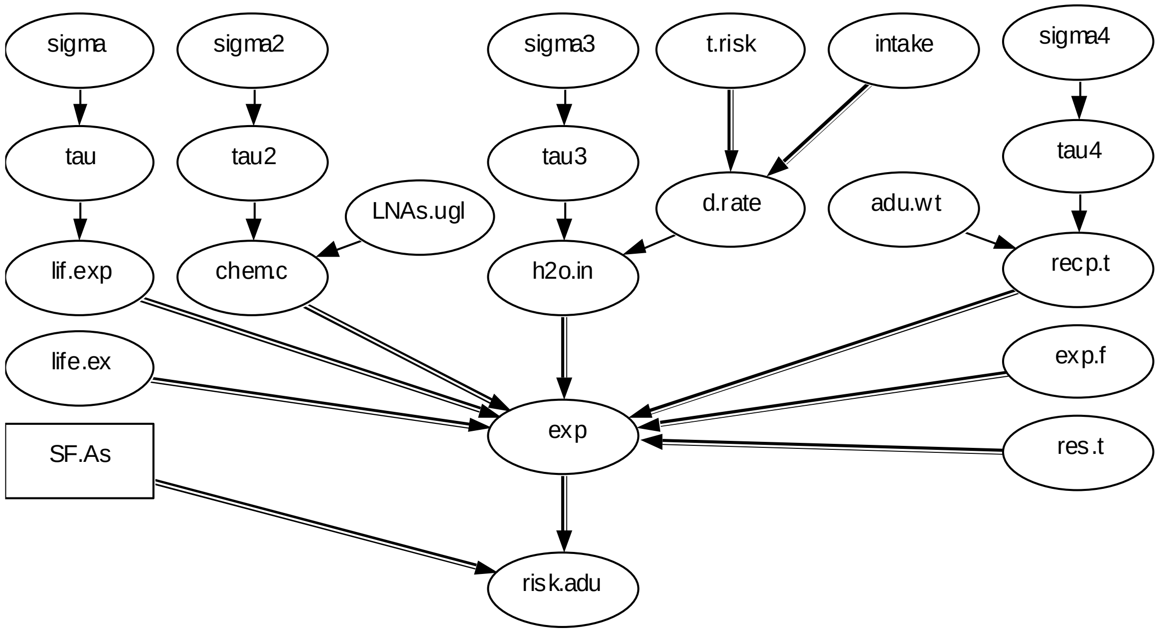


Figure 3.3 Doodle graph for holistic Bayesian HHRA model to determine ILCR for adults consuming unregulated well water.

3.3.10 Uncertainty

Uncertainty in stochastic probabilistic models, such as a Bayesian human health risk assessment, accounts for uncertainty through quantitative characterization of both variability and uncertainty through the use of probability distributions. The USEPA (2001) provides guidance on the process for conducting probabilistic risk assessment and outlines the potential for uncertainty in three areas including parameter uncertainty, model uncertainty, and scenario uncertainty.

3.3.10.1 Parameter Uncertainty

The USEPA (2001) identifies sources of parameter uncertainty including: systematic errors or bias in collection of data, analytical measurements, inference from unrepresentative data, or extrapolation or use of surrogate data. Selection bias may be present due to the number of non-respondent households in RM184 resulting in data uncertainty for both water quality (i.e. arsenic concentration) and survey data because their reason for not participating could not be determined. Systematic error in data collection was minimized by following standard methods of water quality sampling, and piloting the survey. Duplication and analysis of at least 10% of water quality samples was used to confirm lab agreement. Error associated with analytical methods was minimized as a result of the standard operating procedures associated with the use of accredited laboratories for water quality analysis. Other standard parameters used in the HHRA were sourced from Health Canada (2010a, 2010b) and Richardson (1997) which are representative of the Canadian population but not necessarily specific to the two communities participating in this study.

3.3.10.2 Model Uncertainty

Model uncertainty is associated with the accuracy of the model for its desired application. The USEPA (2001) states that model uncertainty is characterized by inappropriate characterization of variables or the system being modeled and unknown interactions between variables. A standardized HHRA equation to determine the ILCR to decrease model uncertainty (Health Canada 2010a).

Standard and widely accepted values for model variables were applied and non-informative priors were used to ensure the posterior distribution was not influenced by the prior and representative of the data. Life expectancy values may be biased due to the assignment of a normally distributed probability density function when it is known to be a non-symmetric distribution with highly variable shapes dependent on the population (Román et al. 2007); however, Canadian specific data could not be obtained from Health Canada or Statistics Canada. Exposure frequency between 340 to 350 days per year is conservative to reduce bias of over-estimation of risk given individuals may consume alternative water sources on occasion. The model was built using the data from the RM184 community and then modified for BOFN. Model sensitivity was evaluated by comparing the cumulative distribution function for both communities with and without perception in the model, and the model was validated by comparing the probabilistic outputs to the deterministic calculations using average values for each parameter.

3.3.10.3 Scenario Uncertainty

Lack of or incomplete information to define exposure is how the USEPA defines scenario uncertainty (2001). The intention of this research was to better inform exposure through the inclusion or risk perception as defined by the relationship between perceived water safety, and water use for drinking. Study participants were asked to estimate their water consumption per day; however, it was not verified quantitatively. It was determined that the community average fell within the range of the Canadian drinking water rates so Richardson's (1997) probability density function for Canadian drinking water rates was applied. This study also limited the pathways of exposure to oral exposure, and excluded all age categories of exposure with exception of adults aged 20 to 59. Exclusion of the additional drinking water hazards (e.g. nitrate, bacteria, uranium, selenium, lead, etc.) introduces uncertainty regarding the overall drinking water risk and health effects as a result of exposure to mixtures of multiple carcinogen and non-carcinogens.

3.4 Results

3.4.1 Pilot Survey

The pilot survey was completed by 25 households with a 56% response rate achieving the minimum requirement of 10% of the sample population for reliability statistics (*n* = 76 RM184; Connelly 2008). Kappa values for the questions on well use (0.65) and well safety (0.75) were in ‘substantial agreement’ according to the benchmarks provided by Landis and Koch (1977).

3.4.2 Community Profile and Study Survey

A total of 121 individuals participated in the study with 76 households from RM184 and 44 households from BOFN (Table 3.4). Participation rate relative to the number of eligible households with wells was 62% (76/123) for RM184 and 94% (44/47) for BOFN. Eligible houses in RM184 included all respondents that were eligible (n = 93) and non-respondents (n = 30). The responses, though not all eligible, in RM184 was 117 resulting in a response rate of 80% (117/147). One household from BOFN did not complete a survey which resulted in a survey response rate of 94% (44/47).

Table 3.4 provides community and household characteristics identified by *eHealth Saskatchewan* (2014), the participating communities, and the study. The total population for each community includes all age groups registered with the provincial health care program.

Table 3.4 Characteristics of the community and study population.

Characteristic	**RM184**	**BOFN**
Saskatchewan Health (2014)		
Total population	197	1821
Total adult population (incl. those not accessing wells)	101	79
Communities		
Households with access to wells	147	50
Study		
Eligible households with wells (incl. non-responses)	123	47
Total households participating	76	44†
Total study population	190	185
Total study adult population	80	79
Households with income ≥ $50,000	38 (50%)	4 (9%)
Households with highest education ≥ high school	58 (76%)	24 (55%)
Mean±SD of residence time (years)	28±17 (n = 73)	19±13 (n = 43)
Mean±SD of water consumption rate (L/day)	1.0±1.2 (n = 54)	1.5±1.5 (n = 44)
Well Use (for drinking)	46 (61%)	22 (50%)
Well Safety (for drinking)	50 (66%)	26 (59%)
Water Treatment	67 (88%)	8 (18%)
Previous Water Testing	64 (84%)	41 (93%)
Previous Water Testing for Metals	18 (24%)	3 (7%)

†arsenic concentration was determined for 45 households; however, one participant did not complete the survey

Minimum sample size of adults required to represent adult community (population) perception of risk with a confidence interval of 95% and proportion of 0.5 was n = 81 with 5% margin of error for RM184, and n = 77 with 2% margin of error for BOFN. The study identified a total of n = 80 adults in RM184 and n = 79 adults in BOFN surveyed households. Non-participating respondents from RM184 were not eligible primarily due to a lack of plumbing to the well or a lack of interest in being a study participant. There were no non-respondent households from BOFN.

Comparison of the Saskatchewan Health adult population (2014) to the total number of adult study participants indicates that the study accounted for 79% and 100% of the adult population in RM184 and BOFN, respectively. The provincial and study total adult population on BOFN was identical suggesting that not all adults living on BOFN were registered to receive provincial health benefits.

Household income ≥ $50,000 applied to 50% (38/76) and 9% (4/44) for RM184 and BOFN, respectively. The highest level of education ≥ high school achieved by an adult in each household was 76% (58/76) in RM184 and 55% (24/44) in BOFN. The average residence time for individuals, representing households, in the survey was 28 years and 19 years for RM184 and BOFN, respectively. The estimated average water consumption rate of 1.0 L/day (RM184) and 1.5 L/day (BOFN) were within the expected range of water consumption when compared to the Canadian average of 1.5 L/day (Richardson 1997).

Household well use and perceived safety were similar within each community and indicates that approximately half of the residents were dependent on unregulated groundwater for drinking (Table 3.4). The majority of households in the RM184 had water treatment (88%, 67/76)) with a high percentage having previously tested their water source (84%, 64/76). Almost all households (93%, 41/44) on BOFN were aware of previous water testing; however, in-house water treatment was only present in 18% (8/44) homes. Households in RM184 (24%, 18/76) and BOFN (7%, 3/44) were aware of water quality testing for metals.

3.4.3 Water Quality and Hazard Identification

Tap water samples were collected from RM184 (n = 76) and BOFN (n = 45). Fourteen percent of the samples were duplicates for which the Lin's Concordance Correlation Coefficient for arsenic had almost perfect agreement (0.98 CI 0.97-0.99; Lin 2000; 1989). The number and percent of tap water quality excursion(s) from the *Saskatchewan's Drinking Water Quality Standards and Objectives* (2015) are provided in Table 3.5. The percentage of households in RM184 and BOFN with at least one health related exceedance of a Maximum Acceptable Concentration (MAC) was approximately 65% (49/76) and 56% (25/45), respectively. Tap water, post treatment if present, in RM184 exceeded MACs for arsenic, boron, total coliform bacteria, *E.coli*, nitrate, lead, selenium, and uranium. The aesthetic water quality parameter excursions were frequent and included chloride, iron, hardness, magnesium, manganese, sodium, pH, sulphate, total alkalinity, and total dissolved solids. Tap water in BOFN households exceeded MACs for total coliform bacteria, *E.coli*, and nitrate. Aesthetic Objectives exceeded on BOFN include copper, iron, manganese, sodium, total alkalinity, and total dissolved solids.

Table 3.5 Number and percent excursions of tap water quality compared to *Saskatchewan's Drinking Water Quality Standards and Objectives* (2015).

Tap Water Quality	**Drinking Water Guideline**	**Number (Percent) Excursions RM184 (*n* = 76)**	**Number (Percent) Excursions BOFN (*n* = 45)**
Maximum Acceptable Concentration			
Aluminum	200 µg/L	0 (0)	0 (0)
Arsenic	10 µg/L	6 (8)	0 (0)
Boron	5000 µg/L	1 (1)	0 (0)
Barium	1000 µg/L	0 (0)	0 (0)
Cadmium	5 µg/L	0 (0)	0 (0)
Total Coliform Bacteria	0 organisms/100 mL	36 (47)	23 (51)
Chromium	50 µg/L	0 (0)	0 (0)
E. coli	0 organisms/100 mL	7 (9)	1 (2)
Florine	1500 µg/L	0 (0)	0 (0)
Nitrate	45000 µg/L	15 (20)	7 (16)
Lead	10 µg/L	2 (3)	0 (0)
Selenium	10 µg/L	8 (11)	0 (0)
Uranium	20 µg/L	12 (16)	0 (0)
Aesthetic Objectives			
Chloride	250,000 µg/L	4 (5)	0 (0)
Copper	1000 µg/L	0 (0)	1 (2)
Iron	300 µg/L	16 (21)	15 (33)
Hardness	800,000 µg/L	27 (36)	0 (0)
Magnesium	200,000 µg/L	6 (8)	0 (0)
Manganese	50 µg/L	32 (42)	25 (56)
Sodium	300,000 µg/L	15 (20)	1 (2)
pH	6.5-9.0 pH Units	24 (32)	0 (0)
Sulphate	500,000 µg/L	34 (45)	0 (0)
Total Alkalinity	500,000 µg/L	18 (24)	1 (2)
Total Dissolved Solids	500,000 µg/L	48 (63)	32 (71)
Zinc	5000 µg/L	0 (0)	0 (0)

Descriptive statistics for arsenic concentration at the tap for RM184 and BOFN are provided in Table 3.6. Arsenic distributions were right-skewed and followed a lognormal distribution.

Table 3.6 Descriptive statistics for arsenic concentrations (µg/L) in tap water.

Community	Mean	Standard Deviation	Median	Min	Max
RM184 (*n* = 76)	2.58	5.38	0.65	0.12†	36.3
BOFN (*n* = 45)	1.57	1.79	0.70	0.12†	8.30

†one-half of detection limit

3.4.4 Characterization of Risk Perception

The probability of drinking the tap water in RM184 when water was perceived as safe was 0.92 and not safe was 0.00 (Table 3.7). Tap water used for drinking when perceived unsafe was verbally expressed as infrequent and circumstantial (e.g. drinking from the hydrant while working in the yard) in the RM184. The probability of drinking tap water in BOFN when water was perceived as safe was 0.77, and 0.11 when perceived as unsafe (Table 3.7). The relative frequency of bottled water use in households was 38.2% (29/76) and 72.7% (32/44) in RM184 and BOFN, respectively. At the 0.05% level of significance there is enough evidence to conclude that risk perception and water safety are associated in RM184 ($p = 0.012$); however, there was no association between risk perception and water safety in BOFN ($p = 0.39$).

Table 3.7 The probability of water use for drinking given it was perceived as safe or not safe.

Community	Conditions†	Total Number	Prevalence Estimate	Exact-Binomial (Clopper-Pearson) 95% Confidence Interval
RM184 Drinking water (*n* = 76)	P (not safe|used)	0	0.00	0.00, 0.13
	P (not safe|not used)	26	1.00	0.87, 1.00
	P (safe|used)	46	0.92	0.81, 0.98
	P (safe|not used)	4	0.08	0.02, 0.19
BOFN Drinking Water (*n* = 44)‡	P (not safe|used)	2	0.11	0.01, 0.35
	P (not safe|not used)	16	0.89	0.65, 0.99
	P (safe|used)	20	0.77	0.56, 0.91
	P (safe|not used)	6	0.23	0.09, 0.44

†The probability the water was not used for drinking given it was perceived as safe or not safe is included for completeness but was not used in the characterization of risk perception. ‡Note: one survey was not completed

3.4.5 Risk Characterization

The integration of risk perception modified exposure to drinking water risk due to arsenic for both case studied communities (Table 3.8). As a result of the decreased drinking water rates, there was a decrease in the overall ILCR and probability of community risk for RM184 and BOFN (Table 3.9). Regardless of the integration of risk perception RM184 had a mean ILCR exceeding Health Canada's negligible risk of 1.0×10^{-5}. RM184 had a 23% and 26% chance of being over the acceptable risk for the community whether or not perception was included.

Although BOFN did not have a mean ILCR greater than the negligible risk, the uncertainty (represented by the upper credible interval) indicated the mean ILCR for the community may be greater than a 1:100,000 ILCR. For BOFN, there was a 22% and 25% chance that the ILCR was over the acceptable risk for the community whether or not perception was included. Figure 3.4 shows the cumulative distribution of incremental lifetime cancer risk for both communities and the model's sensitivity to the inclusion of risk perception.

Table 3.8 Model results showing the influence of risk perception on drinking water rate using Bayesian human health risk assessment.

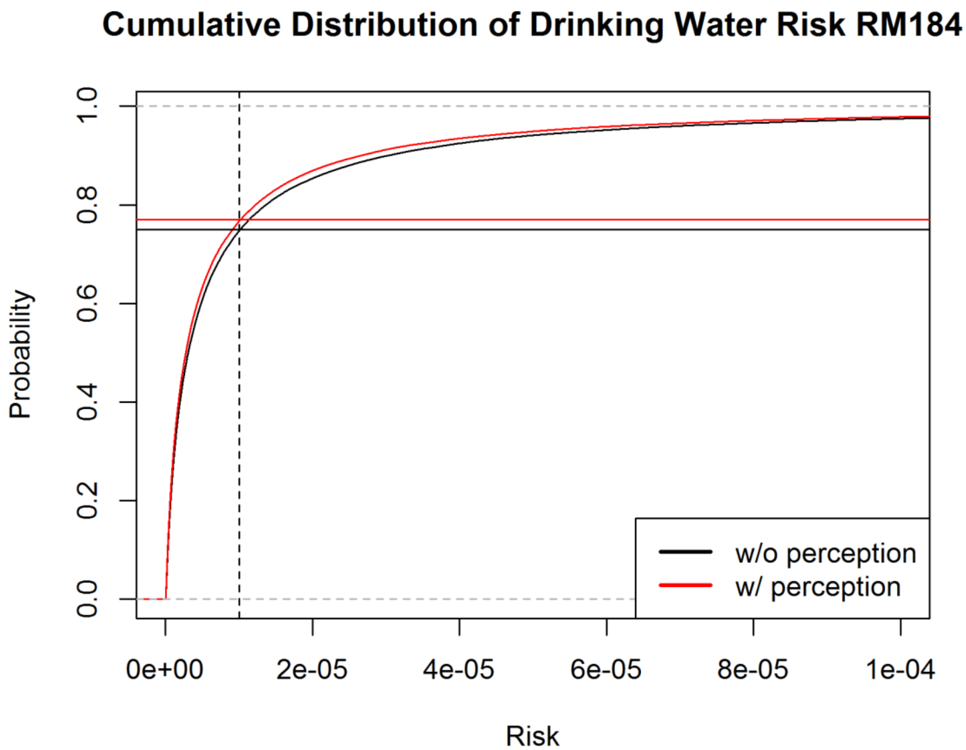
Source	Mean Drinking Water Rate L/day (Credible Interval)
Health Canada†	1.5 (0.50, 3.52)
RM184	1.3 (0.44, 3.16)
BOFN	1.3 (0.43, 3.06)

†Probabilistic density function provided by Richardson (1997)

Table 3.9 Incremental lifetime cancer risk and probability of community risk for adults consuming tap water from wells in the communities of RM184 and BOFN.

Community	Perception	Incremental Lifetime Cancer Risk (Mean)†	95% Credible Interval†	Probability of Community Risk
RM184	No	**1.5×10^{-5}**	9.5×10^{-8}, **1.0×10^{-4}**	0.26
	Yes	**1.3×10^{-5}**	8.4×10^{-8}, **9.0×10^{-5}**	0.23
BOFN	No	1.0×10^{-5}	2.5×10^{-7}, **5.1×10^{-5}**	0.25
	Yes	8.9×10^{-6}	2.2×10^{-7}, **5.9×10^{-5}**	0.22

†ILCR over HC negligible cancer risk in bold



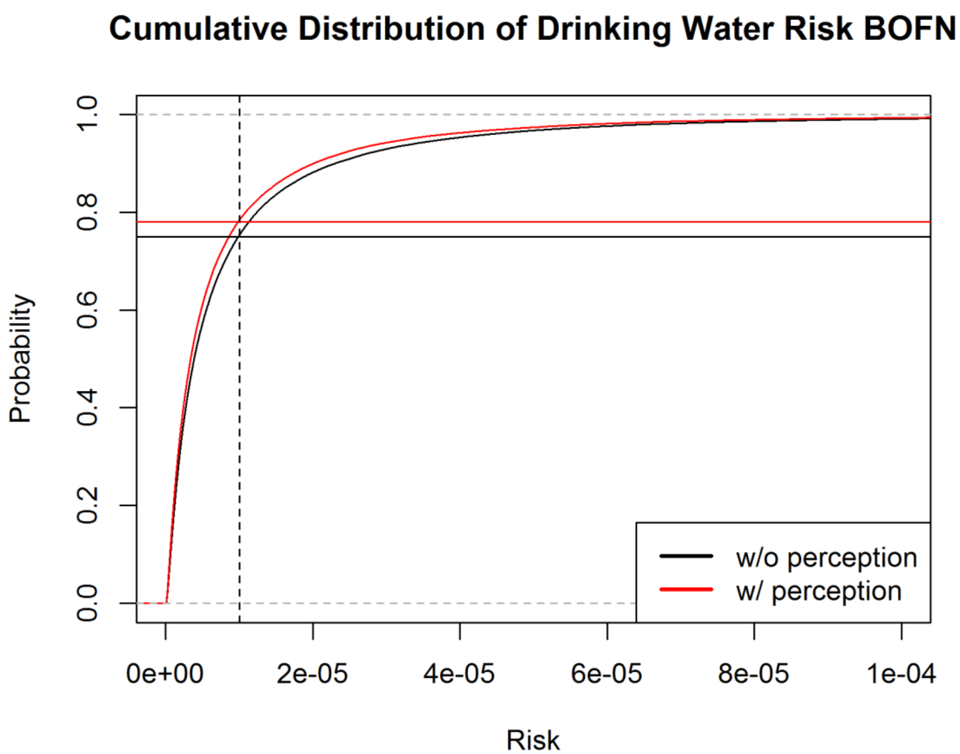


Figure 3.4 Cumulative distribution of drinking water risk for RM184 and BOFN. Vertical dashed line denotes Health Canada's negligible cancer risk threshold of 1:100,000.

3.5 Discussion

This research advances the field of risk assessment and supports the application of community-based holistic human health risk assessments that reflect the perception of risk associated with unregulated drinking water. Specifically, the integration of a qualitative variable, not traditional to risk assessment, can inform the characterization of risk. This discussion frames the importance of a holistic approach to human health risk assessment by acknowledging significant drinking water risks to unregulated water users, the importance of how their perception of risk is relevant to their exposure, and how the improvement to risk characterization may inform risk communication and management.

3.5.1 Unregulated Drinking Water Risks

Households participating in this study were exposed to increased health risks associated with the consumption of their unregulated drinking water sources. The majority of households' tap water exceeded at least one health related Maximum Acceptable Concentration (MAC) when compared to *Saskatchewan's Drinking Water Quality Standards and Objectives* (WSA 2015) for bacteria (e.g. total coliform bacteria and *E.coli*), nitrate, uranium, selenium, arsenic, and lead. The presence of drinking water hazards, including arsenic, from private wells throughout the world, Canada, and Saskatchewan are not unusual and have been identified and summarized in many studies (e.g. Rogan and Brady 2009b; Fitzgerald et al. 2001; Jones et al. 2005; Kreutzwiser et al. 2011; Charrois 2010; Flanagan, Johnston, and Zheng 2012; Singh et al. 2014; Corkal, Schutzman, and Hilliard 2004; Thompson et al. 1999; Maathuis 2008; Maathuis 2000; Hynds, Gill, and Misstear 2014). Not directly a drinking water hazard, it is worth noting that 32% of households in RM184 had pH below 6.5 which may facilitate the release of metals from filter media used for treatment or the distribution system (Federal-Provincial-Territorial Committee on Drinking Water 2015). The presence of drinking water hazards and potential for health risks for the study communities is not unexpected or unusual for unregulated drinking water sources though the specific drinking water risks would vary.

Most households in both study communities had conducted, or were aware of, previous water testing; however, few households could recall the results of their water quality analysis. When asked if their drinking water had been tested for metals, 24% of the households in the RM184 said they had tested in the past. Despite reporting metals testing, household respondents could not name which metal(s) the water was tested for or the results. In addition to testing wells for nitrate and bacteria when they had babies or small children in the home, many households had previous testing done by industry (e.g. potash mining) but were not aware of the results and how they may have related to their health. Unexpectedly, only 7% of households on BOFN were aware of previous metal testing despite years of routine testing for metals conducted by the Band and Health Canada (Health Canada 2013). Overall, the history of water quality testing and communication of results in both communities was insufficient to properly inform residents of the potential health risks associated with their drinking water.

Despite the limited awareness of the specifics of drinking water quality, 88% households in the RM184 had water treatment installed. For these households, the decision to treat their water may be motivated by the aesthetic water quality which frequently deviated from drinking water objectives (Doria 2010). In RM184 the high percentage of households with income greater than $50,000 and education greater than high school might have influenced the frequency of water treatment use. However, studies conflict on the existence of a relationship between income or education and water treatment (Doria 2010). For example, Jones et al. (2007) found no correlation between household income and the use of in-home water treatment. In addition to lower income and average education, households on BOFN may have fewer households with water treatment due to fewer exceedances in aesthetic parameters, and reliance on the Band for water testing, well maintenance, and water treatment. The lack of an association between risk perception and the presence of a drinking water exceedance in BOFN, and the lack of control and management for individuals on BOFN may contribute to decreased motivation to allocate household income to water treatment or to acquire knowledge that supports drinking water management. Given the ambiguity of previous studies associating income, education, and treatment it is likely the motivating factors vary among specific households and communities. Overall, the limited use of treatment to mitigate drinking water risks and the lack of knowledge around well water testing found in this study is not unexpected for users of unregulated source water and has been previously identified and studied (e.g. Fitzgerald et al. 2001; Corkal, Schutzman, and Hilliard 2004; Charrois 2010; Jones et al. 2006; Hynds, Misstear, and Gill 2013).

3.5.2 Exposure and Risk Perception

The influence of risk perception on exposure was likely a result of multiple factors influencing risk perception associated with drinking water (Doria 2010). For example, households in the RM184 showed a high probability of water consumption when they perceived the water as safe (0.92) but were unlikely, if at all, to consume the water if it was perceived unsafe (0.00). Although households on BOFN were motivated to drink their water if it was perceived as safe (0.77) the probability they would drink the water when they did not think it was safe (0.11) was still apparent. Doria (2010) outlines multiple factors that influence perception of drinking water risk (e.g. organoleptic properties, trust, control, experience, gender, age, vulnerability, etc.) which manifest themselves differently between individuals and communities. Perception of risk may also be influenced by other non-traditional factors such as culture (Doria 2010; Spence and Walters 2012). Understanding probability of use based on perception of risk, which is influenced by a variable number of factors (e.g. aesthetics, trust, control, etc.), is important as it relates specifically to drinking water exposure and risk for a community.

Similar to findings by Doria (2010) and Owen et al. (1999) there was no association found between the presence of a drinking water hazard and perceived risk in BOFN; however, RM184 demonstrated a significant relationship that might have contributed to the higher percentage of water treatment to correct aesthetic characteristics of the water (e.g. high iron and manganese). These results support the theory that perceptions are heuristically based in the absence of quantitative information. The inability of drinking water consumers to accurately determine drinking water risk in the absence of quantitative water quality information is not unusual (Doria 2010; Syme and Williams 1993; Turgeon et al. 2004; Orgill et al. 2013). Therefore, a community-based risk assessment determines the community-specific perception of risk based on their unique experiences with their water source (Martz 1983; Maxwell et al. 1998; Hynds, Misstear, and Gill 2013). The inaccuracy of their perceived risk may result in increased consumption of unsafe drinking water or decreased consumption of relatively safe drinking water. The lack of hazard information coupled with an unreliable dependence on risk perception presents human health risks of unknown proportion for consumers of unregulated well water.

This research provides an example of currently available methods that allow for a non-traditional factor (i.e. risk perception, as it relates to drinking water safety and use) to be integrated in a holistic human health risk assessment. In this study, binomial data was converted to a probability and described by a beta distribution using probabilistic Bayesian inference with Gibbs (Markov chain Monte Carlo) sampling methods. These methods facilitate a holistic human health risk assessment and can be expanded to integrate additional non-traditional factors to better inform risk, and risk communication and management. Wilks et al. (2015) acknowledges the need to include behaviours, socio-economics, perceptions, and values to improve risk characterization and management through a holistic approach. Researchers such as Bridges (2003), Liu et al. (2012), Serre et al. (2003), and Zargar et al. (2014) have explored the use of probabilistic methods to facilitate the integration of different data types and sources to improve risk assessment and quantify uncertainty. It is this perspective of 'integrating' a non-traditional factor (i.e. risk perception) to achieve a holistic understanding of risk and uncertainty associated with consumption of unregulated drinking water, that provides an example of what can be accomplished. Specifically, as suggested by Wilks et al. (2015), how non-traditional factors such as perception, can improve the approach to human health risk assessment and benefit communities' risk management, or help prioritize resources to improve drinking water management.

3.5.3 Risk Perception and Management

Integration of community perception of risk decreased the estimated mean exposure and overall assessment of human health risk; however, this change was likely insignificant due to overlapping credible intervals. The effect of risk perception on consumption reduced the mean consumption rate for both communities by 0.2 L/day assuming Health Canada's mean drinking water rate (1.5 L/day) accurately describes these communities. The mean daily drinking water rate for the study communities was estimated, based on the household response for an individual, and was found to be within the range determined by Richardson (1997). This result suggests that assuming the national average drinking water rate would have over estimated exposure and human health risk for the study communities, especially if deterministic methods were applied (Liu et al. 2012).

In response to the reduction in unregulated water consumption the mean ILCR decreased but did not change in overall risk status (i.e. the mean ILCR did not move either community from their status of risk or no risk). However, the probabilistic Bayesian risk assessment method used in this study provides a posterior probability distribution and credible interval that describes the potential range of the mean ILCR which informs the interpretation of risk. This quantification of uncertainty, represented by the credible interval, around the mean is the non-additive accumulation of the uncertainty associated with the variables in the model (Liu et al. 2012). To determine the probability that the mean ILCR exceeds negligible risk, a simple step-function can be calculated from the posterior probability distribution. For example, the mean ILCR for BOFN indicates 'no risk' but yet there is a 22% probability it exceeds negligible risk based on the distribution function describing the ILCR for BOFN. Probabilistic Bayesian risk assessment methods provide the context of risk calculations which is easy to comprehend and can aid risk communication and management.

Awareness of uncertainty is beneficial and welcome information to consumers which can assist them in making safe, sustainable drinking water choices. Markon and Lemyre (2013) studied public reactions to the communication of risk and uncertainty and suggest that authorities be cautious on how they communicate uncertainty but to do so precisely. Providing complete information on risk and uncertainty to the public will decrease the chance that information is not misinterpreted especially when a behavioural change is required by the public to decrease health risk (Markon and Lemyre 2013). Many consumers are capable of making decisions, maintain trust in authorities and understand the meaning of the message when uncertainty is disclosed (Markon and Lemyre 2013). In fact, when the public feel they are not well informed or there is disagreement in the message from authorities they are less likely to follow risk management instruction provided and will trust their own heuristic experiences. Therefore, in the absence of drinking water regulations, which provide the framework to monitor, interpret and mitigate drinking water risks, knowledge of consumer risk perception provides insight on drinking water use (exposure). This understanding can be used to correct misconceptions or inaccuracies in perceived risk by communicating the discrepancies and uncertainty with communities.

A risk communication and management strategy specific to each community in the study can be developed by local health authorities, government or individuals based on the rate of drinking water use, hazards present, and risk calculation for each community. For example, what motivated individual households on BOFN to consume water they perceived as unsafe? Given that a large number (73%) of households on BOFN also consume bottled water, and they are notified when well water is not safe to drink it would seem they have alternatives, however, they still consume the water. Understanding this discrepancy in relation to the hazards present is vital to the strategy for risk communication and management. For example, the community of RM184, is less likely to consume water they believe is unsafe. Therefore, providing them with accurate information and an understanding of their drinking water risks may be all that is required to decrease exposure to drinking water hazards. Applying the same strategy for BOFN may not be sufficient due to lack of individual household control over the water source, which may be contributing to a lack of trust and acceptability in the water (Syme and Williams 1993). Most importantly, communities' culture may need to be considered when managing health risks to ensure communication is relevant and effective (Doria 2010). Ultimately, each community must take the results of this risk assessment and communicate and manage the health risks specific to their community members. This approach to holistic human health risk assessment provides a deeper understanding of the behaviour associated with community perception of drinking water risk, the probability of consumption, and the potential for human health risk associated with hazard(s).

3.5.4 Limitations and Significance

This research has limitations associated with the parameters, model, and scenario as outlined in *3.3.6.3 Uncertainty*. The community-based approach introduces community-specific risk perception data that might not be transferred to another community. However, this model offers informed priors that can complement another data set using the probabilistic Bayesian approach in a manner similar to that suggested by Hooten and Hobbs (2015). Tighe et al. (2013) provide an example of how a limited data set can be informed by a Bayesian network approach to inform an exposure assessment to antimony in the New South Wales floodplain in Australia.

3.6 Conclusions

This research provides a measure of the contribution and influence that risk perception has on the assessment of exposure and human health risk associated with consumption of unregulated groundwater. Quantification of a community risk perception can be characterized as the probability of drinking water use based on the belief the water is safe to drink. Then through the application of probabilistic Bayesian risk assessment methods and risk perception specific to the community, the resulting holistic HHRA included alternative data types and quantified uncertainty. This approach to HHRA integrates behaviour in relation to the characterization of risk which can be used to inform risk communication and management specific to the community. The model developed in this study can be used to conduct future HHRA addressing multiple hazards and all age groups, or to prioritize communities when directing support or funding.

In addition, the community-based research approach and integration of risk perception in HHRA lends to increased participation, cooperation, and value for the opinions of community members that may improve trust and minimize health risks as suggested by Doria (2010). This approach makes it easier to show community members the discrepancies between their heuristically developed perceptions of risk and the actual risk associated with their drinking water source. Understanding the risk and uncertainty, individuals or communities will have the information required to take responsibility and improve decision-making as suggested by (Markon and Lemyre 2013).

3.7 References

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4 Conclusion

4.1 Introduction

Almost half of the world's population is geographically rural with limited access to regulated water sources that provide safe drinking water through monitoring and treatment (WHO/UNICEF 2015). Initiated by the United Nations, the Millennium Development Goals (MDGs) were created to address this gap in access to safe drinking water and initiate increased access to improved sources increased global access by 15% (WHO/UNICEF 2015). However, access to improved water sources does not guarantee safe drinking water due to the lack of monitoring and reporting of water quality (Shaheed et al. 2014). For example, despite achieving 100% access to improved drinking water in North America there remains exposure to drinking water hazards associated with unregulated water including private wells (Charrois 2010; Spence and Walters 2012; Corkal, Schutzman, and Hilliard 2004; Fox et al. 2016; Jones et al. 2006).

In addition to the hazards present, rural populations are vulnerable due to their distance from services associated with urban centers, and the subsequent potential for lack of education and resources to manage drinking water (Nsiah-Kumi 2008; Wescoat, Headington, and Theobald 2007; Zheng and Ayotte 2015). The absence of regulatory water monitoring and treatment increases the likelihood that water-use decisions will be formed heuristically based on their perceived risk (Chen et al. 2012; Hynds, Misstear, and Gill 2013; Martz 1983; Maxwell et al. 1998; Orgill et al. 2013; Patrick 2011).

Therefore, characterizing risk perception can inform exposure associated with consumption of unregulated drinking water, quantify uncertainty associated with human health risk, and better inform risk management and communication (Chowdhury, Champagne, and McLellan 2009). Understanding the perceptions and risks of rural populations dependent on unregulated water sources supports community-based drinking water management decisions to ensure safe and sustainable drinking water. Lastly, it is essential to advance research in the field of holistic human health risk assessment by integrating non-traditional factors to determine their influence on the measure and interpretation of risk.

This thesis contributes knowledge to the field of human health risk assessment by identifying the lack of research addressing the human health risks associated with consumption of unregulated drinking water, and a failure of the field to explore new methods of determining risk. This thesis advanced the field of HHRA and drinking water management by showing how risk perception influences consumption (exposure), and human health risks. In addition to the research, the findings of this thesis supports communities and provides an example of how their perceptions can influence our qualitative understanding of risk, and provide them with an improved perspective from which to manage and communicate risk. This was accomplished by conducting a scoping review of recent human health risk assessment methods applied in the literature, and developing a holistic human health risk assessment that integrated risk perception case studied on two rural communities dependent on unregulated drinking water in Saskatchewan, Canada.

Based on the scoping review and applied HHRA case studies, this thesis set out to:

1. review the literature and characterize the methods of HHRA applied to rural communities dependent on unregulated drinking water, and to use this information to inform the field of HHRA and the second objective of this research; and

2. conduct a community-based participatory observational case study using Bayesian risk assessment methods to develop a holistic human health risk assessment that integrates a non-traditional factor such as risk perception to improve accuracy, and support risk communication and management.

The field of HHRA lacks a current review of the literature that summarizes the applied methods of human health risk assessment as it pertains to rural populations dependent on unregulated drinking water. This thesis exposes a lack of HHRA research dedicated to rural populations dependent on unregulated water in spite of the global concern regarding access to safe drinking water. Contributing to this apparent lack of dedicated research and in agreement with Pons et al. (2015), this thesis suggests studies are often deficient in effectively identifying and defining the population and receptors of concern. In addition, studies failed to specify if water sources were regulated or not, and were not transparent regarding uncertainty and limitations. The absence of this critical information inhibits research by not allowing researchers to source relevant studies and build on existing research.

Despite the benefits associated with Bayesian and probabilistic methods (Bridges 2003a; Burns et al. 2014; Serre et al. 2003; Zargar et al. 2014), the findings from this thesis indicate the majority of HHRAs on unregulated and unspecified drinking water apply deterministic methods. These results suggest that the field of HHRA may be delayed in the adoption of methods that allow for the inclusion of various data types and the quantification of uncertainty to support the integration of non-traditional factors (e.g. behaviour) and holistic HHRA. The use of probabilistic and Bayesian methods of risk assessment can move the field of HHRA forward by: 1) characterizing risk with probability density functions, 2) quantifying uncertainty, 3) identifying gaps in the data where additional data is required, and 3) integrating non-traditional factors influencing risk (Bridges 2003b; Serre et al. 2003; Zargar et al. 2014; Liu et al. 2012; Wilks et al. 2015).

This research provides a measure of the contribution and influence that risk perception has on exposure and human health risk associated with consumption of unregulated groundwater. Furthermore, it provides an example of how a non-traditional factor, which influences behaviour, can be quantified to characterize risk specific to the characteristics of a community. Communities lacking resources, education, and access to regulated water it is important to understand their perception of risk to ensure effective risk communication and management strategies that support the use of safe and sustainable drinking water.

The community-based research approach and integration of risk perception in HHRA lends to increased participation, cooperation, and value for the opinions of community members that may improve trust and minimize health risks as suggested by Doria (2010). This approach also made it easier to show community members and leaders the discrepancies between their heuristically developed perceptions of risk and the actual risk associated with their drinking water source. Understanding the risk and uncertainty, individuals or communities will have the information required to take responsibility and improve decision-making as suggested by (Markon and Lemyre 2013).

4.2 Future Research

Global rural populations face potential health risks related to water quality hazards associated with unregulated source water. Evolution and improvement in the approach and application of HHRA methods are necessary for a better understanding of the human health risks, and improved risk communication and management in rural populations. Based on conclusions of this thesis future research should:

- Ensure HHRA and drinking water research adequately describes the exposure population and source water to improve the detection of relevant literature to support future research and support the development and application of new approaches and methods.
- Use a holistic approach to HHRA by integrating data from different sources and types when non-traditional factors are suspected of influencing the human health risk.
- Determine the relationship between risk perception and water consumption to attempt to verify and quantify the exposure as it relates to the national average used by Health Canada.
- Determine the effectiveness of risk communication and management strategies based on a holistic and integrated HHRA.

4.3 Limitations

It is possible that literature relevant to rural communities dependent on unregulated drinking water sources was missed in the scoping review process. Screening and full-text review stages could be subject to interpretation error, and the exclusion of the regulated water sources limited our ability to compare characteristics of unregulated vs. regulated water sources; however, this comparison was not the focus of the scoping review.

Characterization of risk perception and calculated exposure and human health risk associated with arsenic and consumption of unregulated drinking water for the case-studied communities cannot be assumed for other communities, however, the opportunity exists to apply the model and the probability density functions associated with the model variables to other communities.

A detailed list of limitations specific to each manuscript can be referenced in Chapter 2 and Chapter 3.

4.4 Conclusion

Human health risk assessments applied to rural populations dependent on unregulated drinking water are poorly represented in the literature despite almost half of the global population being rural. For these vulnerable communities, taking a holistic approach to human health risk assessment necessitates the use of probabilistic or Bayesian methods to integrate non-traditional factors influencing risk. Using these methods, risk perception can be quantified to determine its influence on exposure and human health risk associated with consumption of unregulated drinking water. This approach can be used to improve risk communication and management specific to the needs of communities and support the exploration of non-traditional factors and their influence on the characterization of risk.

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5 Supplementary Materials

5.1 Database Search Terms and Results

Search History – May 8, 2014
Database: **Ovid MEDLINE**(R) <1946 to April Week 5 2014>
Search Strategy:

----

1 (risk adj2 (assessment* or analys*)).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier] (199988)
2 exp Risk Assessment/ or risk assessment.mp. (189599)
3 1 or 2 (201925)
4 water.mp. or exp Water/ (562529)
5 groundwater.mp. or exp Groundwater/ (10264)
6 4 or 5 (564267)
7 exp Health/ or health.mp. (1835151)
8 3 and 6 and 7 (2603)
9 limit 8 to (english language and yr="2000 -Current") (2218)
****

Database: Ovid MEDLINE(R) <1946 to April Week 5 2014>
Search Strategy:

----

1 (risk adj2 (assessment* or analys*)).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier] (199988)
2 exp Risk Assessment/ or risk assesment.mp. (175843)
3 1 or 2 (201926)
4 water.mp. or exp Water/ (562529)
5 groundwater.mp. or exp Groundwater/ (10264)
6 4 or 5 (564267)
7 exp Health/ or health.mp. (1835151)
8 3 and 6 and 7 (2603)
9 limit 8 to (english language and yr="2000 -Current") (2218)
****

Database: **Embase Classic+Embase** <1947 to 2014 May 07>
Search Strategy:

----

1 (risk adj2 (assessment* or analys*)).mp. [mp=title, abstract, subject headings, heading word, drug trade name, original title, device manufacturer, drug manufacturer, device trade name, keyword] (394871)
2 risk assessment.mp. or exp risk assessment/ (343254)
3 1 or 2 (394871)
4 water.mp. or exp water/ (823914)
5 groundwater.mp. or exp ground water/ (21259)
6 4 or 5 (825148)

7 health.mp. or exp health/ (2676374)
8 3 and 6 and 7 (4358)
9 limit 8 to (english language and yr="2000 -Current") (3509)
****
Database: **Global Health**
Search Strategy:
----
1 (risk adj2 (assessment* or analys*)).mp. [mp=abstract, title, original title, broad terms, heading words] (26366)
2 risk assessment.mp. or exp risk assessment/ (22755)
3 1 or 2 (26366)
4 exp water/ or water.mp. (81998)
5 groundwater.mp. or exp groundwater/ (3695)
6 4 or 5 (82096)
7 health.mp. or exp health/ (276768)
8 3 and 6 and 7 (1811)
9 limit 8 to (english language and yr="2000 -Current") (1631)
****
Scopus
Search Strategy from ProQuest
May 08 2014 15:11
Set#
Searched for
Databases
Results
S1
all(risk NEAR/2 assessment* OR risk NEAR/2 analys*) AND all((water OR groundwater)) AND all(health)
ProQuest Public Health
2590°
S2
(all(risk NEAR/2 assessment* OR risk NEAR/2 analys*) AND all((water OR groundwater)) AND all(health)) AND la.exact("English") AND pd(>20000101)
ProQuest Public Health
2538°
S3
((all(risk NEAR/2 assessment* OR risk NEAR/2 analys*) AND all((water OR groundwater)) AND all(health)) AND la.exact("English")) NOT stype.exact("Newspapers") AND pd(>20000101)
ProQuest Public Health
2105°
° Duplicates are removed from your search and from your result count.

NOTE: When proquest search run, the numbers come out differently. However, once the last page of results is loaded, the final numbers to change to those above and the export contains 2105 records. The initial results are shown below for completeness:
Set#

Searched for
Databases
Results
S5
(all(risk NEAR/2 assessment* OR risk NEAR/2 analys*) AND all((water OR groundwater)) AND all(health)) NOT stype.exact("Newspapers") AND pd(>20000101)
ProQuest Public Health

5.2 Full-Text Review Categorization

THEMES	CATEGORY	DEFINITION/EXAMPLE (if applicable)
Publication Type (choose one)	Journal	Peer reviewed journal
	Conference Paper/Proceeding	Conference document not published
	Thesis	Masters/PhD
	Non-peer reviewed article	Government, public document, opinion paper, etc.
	Other (describe)	Other category of publication
What is the publication year?	Year published	Year of publication
Does the journal/article fit into one of these categories? (choose all that apply)	Human Health, Health and Social Sciences, Social Sciences, Toxicology, Epidemiology, Agriculture, Engineering, Medicine, Environmental/Resource Management	Based on journal title, scope of journal, and/or content of the paper
	Unspecified	Unable to determine the research category
	Other (describe)	Other research field
What is the application of the HHRA? (choose all that apply)	Hypothetical/Theoretical	Method paper, randomly generated data, etc.
	Observational/Field study	Field data is collected or historical data used in 'real life' context
	Unspecified	Unable to determine the application
	Other (describe)	Other application of the HHRA
What is the scope of the HHRA? (choose all that apply)	Integrated Risk Assessment (wide scope)	Ecological & human assessment of risk which may include socio-economic components (Bridges 2003; Sekizawa and Tanabe 2005; WHO/IPCS 2001)
	Human Health Risk Assessment	Only human health risk assessment conducted

	Holistic	Considers non-traditional factors that may influence overall risk; includes non-traditional data integration (Arquette et al. 2002; Bridges 2003; Serre et al. 2003). Does not include the mention of non-traditional factors or interpretation of risk relative to non-traditional data but rather data that contributes quantitatively to the overall determination of risk.
	Other (describe)	Other risk assessment scope was used
How is the study described by the authors? (choose all that apply)	Human Health Risk Assessment	"…is the process to estimate the nature and probability of adverse health effects in humans who may be exposed to chemicals in contaminated environmental media, now or in the future." (United States Environmental Protection Agency (US EPA 2015)
	Risk Assessment	"The probabilities and consequences of adverse events are assumed to be produced by physical and natural processes in ways that can be objectively quantified by risk assessment." (Slovic 1999).
	Health (Risk) Assessment	Risk assessment as defined by Ware (1987) with the broad scope of 'health' and all of its dimensions as identified by Ware (1987) - physical, mental, social function, role function, general health perceptions but more than absence of disease but "presence of well-being" (Slovic 1999; Ware 1987).
	Not Reported	Authors don't describe the study in any terms
	Other (describe)	Other study description
What method of HHRA was used? (choose one)	Stochastic/Probabilistic	"Risk assessment that uses probability distributions to characterize variability or uncertainty in risk estimates with the outcome described as a probability distribution rather than a single number" (United States Environmental Protection Agency (US EPA 2001). Chowdhury et al. (2009) provide examples of methods.
	Traditional/Deterministic	Outcomes described with a single number (Health Canada 2010)
	Both	Both probabilistic/stochastic and deterministic methods used
	Unspecified	Unable to identify the method used
	Other (describe)	Other method of HHRA used
Was a standard method used? (choose all that apply)	Health Canada, US EPA, WHO	Standard national or international HHRA method
	Unspecified	Unable to determine method used
	Other (describe)	Other method referenced

Geographic Location	Country	State the country
	Undetermined	Unable to identify the country in which the research was conducted
What is the drinking water source? (choose all that apply)	Ground	Well of any type (e.g. shallow, deep, GUDI, hand-dug, drilled, bored, etc.)
	Surface	Lakes, rivers, streams, dugouts
	Rain collection	e.g. Roof top
	Cistern	Water hauled from any of the above sources
	Bottled	e.g. commercial or regulated bottled water (i.e. bottled water from a government or private treatment facility)
	Undetermined	Unable to identify the water source
	Other (describe)	Other drinking water source
What is the drinking water type? (choose all that apply)	Treated	Subject to regulated treatment
	Not-Treated	Private or unregulated/unknown treatment
	Unspecified	Cannot identify if source is treated or not
	Other (describe)	Other drinking water type
What data informed the risk assessment? (choose all that apply)	Water source tested	As outlined in Health Canada's Guidance on peer review of HHRA for federal contaminated sites in Canada (Health Canada 2010b).
	Proxy tested	e.g. bio-indicators
	Predicted/extrapolated	Prediction modeling or extrapolation
	Based on historical data	Not based on current data but pre-existing information
	Unspecified	Cannot identify data type
	Other (describe)	Other data source
How is the community defined? (choose all that apply)	Cultural/Spiritual	FN, Aboriginal, Indigenous, language, ethnicity
	Geographic	Country, city, town, province, etc.
	Topographic	Watershed
	Unspecified	Unable to identify the community
	Other (describe)	Other definition for the community
What is the population of concern? (choose all that apply)	Urban	As defined by the study and the country in which it was conducted. This is the approach the United Nations takes and the World Bank defines 'rural' when comparing different countries (United Nations 2015).

	Rural	Responsible for establishing source water, not receiving centralized, distributed, treated, and regulated water (e.g. farms, villages, hamlets, private well owners, etc).
	Remote	Geographically isolated or too far from urban centres to receive treated, regulated, distributed water.
	Both	Both urban and rural communities studied
	Unspecified/Undefined	Unable to determine or define the population the population accurately the way it is described by the authors
	Other (describe)	Other description of the population
What are the hazards identified? (choose all that apply) *do not interpret, only answer with reported info	Chemical (natural)	e.g. associated with natural geological characteristics to which the water is exposed
	Chemical (anthropogenic)	e.g. human induced, agricultural, industrial, etc.
	Microbiological/Pathogen	bacteria, protozoans, viruses
	Radiation	e.g. radon, uranium
	Undefined	Unable to determine the hazard
	Other (describe)	Other hazard identified
Who are the receptors? (choose all that apply)	Responsible for Source Water	Receptor is responsible for point of use water quality
	First Nations/Aboriginals	Native/Indigenous populations
	Infants, toddler, child, teen, adults, or senior	Age categories or as described in the study
	General Public	Paper states or describes the general population without distinguishing any age group in particular
	Local Residents	People in the area that may be exposed to the hazard
	Local Farmers and their families	Specifically described as farmers and/or their families
	Employees	People exposed through work place
	Any of the above without age identified?	Note if any of the above did not have the specific age or age category defined
	Undefined	Unable to determine the receptors
	Other (describe)	Other receptor identified in the study
What are the exposure pathways? (choose all that apply)	Oral, dermal, inhalation	Exposure pathways as described by Health Canada (Health Canada 2010b)
	Undefined	Unable to determine exposure pathway

Was uncertainty acknowledged? (choose all that apply) *was it at least discussed	Sufficiency of sampling, analytical detection limits, data gaps, QA/QC, seasonal/environmental factors	(Health Canada 2010a) identifies these areas of potential uncertainty for discussion.
	Quality of historical use information to identify chemicals of potential concern	Relevant if exposure was determined using estimated or historical data.
	Was there a section addressing uncertainty?	An explicit section of the paper was dedicated to addressing uncertainty associated with the risk assessment.
	Other (describe)	Other source of uncertainty identified
What other factors were acknowledged? (choose all that apply) *discussion only	Risk perception	Perception of water or risk associated with any aspect of drinking water
	Economic	e.g. income levels, etc.
	Social	e.g. education, gender, etc.
	Cultural/Spiritual	e.g. homelands, historical use, generational, etc.
	Undefined	Unable to identify other factors acknowledged in the risk assessment
	Geography	Geography is mentioned as influencing exposure to hazards or identifying receptors
	Other (describe)	Other factor acknowledged in the risk assessment
What other factors were applied in the RA? (choose all that apply) *is represented by data that is included in risk assessment analysis	Risk perception	Perception of water or risk associated with any aspect of drinking water
	Economic	See Economic – What other factors were acknowledged?
	Social	See Education – What other factors were acknowledged?
	Cultural/Spiritual	See Cultural/Spiritual – What other factors were acknowledged?
	Geography	Geography data is used to determine areas of increased risk or comparison of regions
	Undefined	Unable to determine if a factor was applied to the risk assessment
	Other (describe)	Other factor applied in the risk assessment
What were the results of the assessment? (choose all that apply)	Exposure assessment, hazard/toxicology assessment, hazard quotient	As outlined in HC Guidance on peer review of HHRA for federal contaminated sites in Canada (Health Canada 2010b).
	Epidemiological assessment/analysis	Use of epidemiological studies in the evaluation/setting of microbiological guidelines for recreational water, wastewater re-use, and drinking

		water. As defined by Blumenthal et al. (2001)not Ryan (Ryan 2003) in which epidemiological information informs a full risk assessment.
	Qualitative assessment	Differs from quantitative because conclusions are based on 'hazard qualitative description and potency' not DNELs, and risk characterization is justified not calculated (European Chemicals Agency 2012).
	Other (describe)	Other result was provided
Did the journal/article conclude the risk assessment? (choose one)	Yes, quantitatively.	Quantitative result - has a quantified result stating there is a risk
	Yes, qualitatively.	Qualitative result - has a description identifying a risk.
	Yes, both quantitative & qualitative	Both qualitative and quantitative conclusions were made
	No	No conclusion was made by the authors
	Undefined	Cannot determine if there is a conclusion or not
	Other (describe)	Other conclusion was provided
What gaps in the literature are identified?	Literature gaps	List gaps in research as identified by the authors
	Describe literature gaps	

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5.3 Example of Model Code for Bayesian Human Health Risk Assessment

```
model {
###TIME related variables###
res.t ~dunif(20, 59)  #residence time - uniform distribution for adults age 20-59
exp.f ~dunif(0.93, 0.96)  #i.e. between 340-350 days per year
lif.exp~dnorm(life.ex,tau)  #80 year life expectancy assuming SD = 10
#semi-informative using mean=10 & variance = 0.8 in Parameter Solver
        sigma ~ dgamma(125,12.5)  #shape=125, scale=0.08, rate=12.5
        tau <- pow(sigma, -2)  #calculated tau prior for the precision on the life.ex.dist
###CHEM.EXP###
chem.c~ dlnorm(LNAs.ugl,tau2)  #chemical exposure
```

```
	LNAs.ugl~ dnorm(0, 0.00001)  #likelihood for mean (LN study mean) & uninformative
prior
	sigma2 ~ dgamma(0.0001,0.0001)  #likelihood for SD (LN study SD) & uninformative
prior
	tau2 <- pow(sigma2, -2)  #calculated tau2 for the precision on the As chemical
distribution
h2o.in ~ dlnorm(d.rate, tau3)  #water consumption
	 d.rate<- intake*t.risk  #calculate drinking water rate with HC x P(use|s/ns)
	 intake~dnorm(0,0.00001)  #likelihood for mean on LN HC calculated drinking water rate
	 sigma3 ~ dgamma(0.0001,0.0001)  #likelihood for SD (LN HC SD) & uninformative
prior
	 tau3 <- pow(sigma3, -2)  #calculated tau3 prior for the precision on water intake
#probability of use| the perception they feel it is safe or not safe to drink
t.risk <- ((prop.s*prob.s)+(prop.ns*prob.ns))  #sum of P(use|s)+P(use|ns)
	prob.s ~ dbeta(27,1)		#proportion that think it is safe and drink = 26
				#proportion that think it is is safe and don't drink = 0
	prob.ns ~ dbeta(8,12)		#proportion that think it is not safe and drink = 7
				#proportion that think it is not safe and don't drink = 11
	prop.s ~ dbeta(57,19)  #proportion that answered safe to drink = 26
				#proportion that answered not safe to drink = 18
	prop.ns ~ dbeta(19,57)		#proportion that answered not safe to drink = 18
				#proportion that answered safe to drink = 26
###RECEPTORS###
recp.t~dlnorm(adu.wt, tau4) #receptor weight
	adu.wt~dnorm(0,0.00001) #likelihood for mean (LN HC adult body weight) &
uninformative prior
	sigma4~dgamma(0.0001,0.0001) #likelihood for SD (LN HC SD) & uninformative prior
	tau4<-pow(sigma4, -2) #calculated tau4 prior for the precision on adult weight
###EXPOSURE###
## Dose (mg/kg bw/day) = Cw × IRw × RAFOral × D2 ×D3×D4/ BW × LE ##
exp <- (chem.c* h2o.in * exp.f * res.t ) / (recp.t* lif.exp)  #exposure in mg or ug/bw.day
###RISK###
risk.adu <- exp/SF.As  #risk for carcinogenic substance EDI*(1/slope factor)
p.ILCR <- step(risk.adu - 0.00001)  #step fuction to get probability of population over 1:100,000
}
Data
list(life.ex=80,  LNAs.ugl=-0.207 , sigma2=1.24 , intake=0.28, sigma3=0.50, adu.wt=4.24,
sigma4=0.20, SF.As = 1800)
Inits
list( res.t=30,  h2o.in = 1, d.rate = 1, recp.t = 75, adu.wt=75, sigma = 0.001, sigma3 = 0.001,
sigma2=0.001,  sigma4=0.001, res.t=20)
```