Intrinsic groundwater vulnerability assessments: A review of the state-of-the-art And A statistical approach to incorporating uncertainty into groundwater vulnerability assessments

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Abstract

Groundwater vulnerability assessments, often presented in the form of a thematic map, provide a measure of the relative susceptibility of a groundwater system to contamination introduced at or near the ground surface. However, most groundwater vulnerability assessments rely on deterministic, point estimates based on averaged input parameters, and result in a single output value without any indication of the uncertainty or variation around this value. To facilitate the most effective application and interpretation of groundwater vulnerability assessments, a method for incorporating the uncertainty associated with the natural variation of input parameters into groundwater vulnerability assessments was developed and demonstrated in south-central Saskatchewan. A comprehensive literature review and synthesis, including a review of the conceptual basis of intrinsic groundwater vulnerability assessment methods, a critical evaluation of common and representative methods, and a review of the current research in the field illustrated opportunities for extending the application of these methods as decision support tools. A modified, depth-defined Aquifer Vulnerability Index (AVI) method was developed based on statistically derived, depth-defined hydraulic conductivity distributions generated from hydraulic conductivity data for the Pleistocene-aged glacial till aquitards of the Interior Plains region of Saskatchewan. This modified AVI method was used to produce three sets of vulnerability indices based on the range of probable hydraulic conductivity values, allowing for the pseudo-quantitative assessment of the uncertainty associated with the variability of the input parameter. A final vulnerability map was produced showing the mean (expected) AVI value with an overlay indicating areas of elevated uncertainty. Comparisons of the modified AVI method with a classic AVI assessment revealed the impact of geological controls over groundwater vulnerability assessment results. The methods developed for incorporating and presenting uncertainty in groundwater vulnerability assessments are not limited to local applications of the AVI method, but can be applied to any deterministic vulnerability assessment method where a statistical characterization of the input parameters is possible. Furthermore, valuable and accessible reference information presented here in the form of a hydraulic conductivity database, summary tables, and conceptual models will aid in the effective selection, application, and interpretation of intrinsic groundwater vulnerability assessments.

Acknowledgements

Encouragement and assistance over and above all expectations was offered by Dr. Grant Ferguson and Dr. Chris Hawkes, both of whom were instrumental in shaping my experience at the College of Engineering into an overwhelmingly positive one. Additional review and feedback beyond what was expected from a member of my advisory committee was provided by Dr. Chris Hawkes, greatly easing the development of the manuscripts presented herein. Assistance provided by Dr. S. Lee Barbour during the research and early stages of manuscript development of Chapter 3 is gratefully acknowledged. Administrative assistance, support, kindness, and understanding provided by Ms. Alison Draude, Graduate Assistant, and Ms. Cynthia Hanke of the Department of Civil, Geological and Environmental Engineering were essential to the success of this research project and my endeavours as a graduate student in general.

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List of Abbreviations

AR	Analogical Relation
AVI	Aquifer Vulnerability Index
CDEM	Canadian Digital Elevation Model
COP	Concentration of flow, properties of Overlying Layers, Precipitation
COST	European Cooperation in Science and Technology
DAT	Downward Adventive Time of travel
DI	DRASTIC Index
DRASTIC	Depth, Recharge, Aquifer media, Soil, Topography, Impact of vadose zone, hydraulic Conductivity
EPIK	Epikarst, Protective Cover, Infiltrating conditions, Karst network development
EPM	Equivalent Porous Media
GIS	Geographic Information System
GLA	German acronym for evaluating protective function of overlying strata
GOD	Groundwater confinement, Overlying strata, Depth to groundwater
HCS	Hydrogeological Complex and Setting
IAH/IHP	International Association of Hydrogeologists
ISI	Intrinsic Susceptibility Index
MASL	Meters Above Sea Level
MBGL	Meters Below Ground Level
MOE	Ministry of the Environment
MS	Matrix System
NRC	National Research Council
NTS	National Topographic System
NUM	Numerical Model
P10, P90	10th Percentile, 90th Percentile
P3	Probability, Protection, and Precipitation
PCSM	Point Count System Model
PI	Protective cover, Infiltration conditions
REV	Representative Elementary Volume

RS	Rating System
RTt	Rainfall and Travel time
SDCM	Square Difference from the Class Mean
SFCCNI	Sylvia Fedoruk Canadian Centre for Nuclear Innovation
SINTACS	Italian acronym translated to depth, infiltration, unsaturated and soil attenuation capacity, saturated zone, hydraulic conductivity, slope
SMNR	Small Modular Nuclear Reactor
WSA	Water Security Agency
WWDR	Water Well Driller's Report

1. Introduction

The importance of fresh groundwater resources around the world is undeniable. Groundwater accounts one-third of the world’s fresh water withdrawals and nearly half of all water used for agricultural irrigation [Alley et al., 2002; Siebert et al., 2010], with these numbers projected to increase in coming years [Wada et al., 2014]. In addition to the importance of groundwater resources for anthropogenic consumption, groundwater systems are also an integral component of the Earth's hydrological and ecological system, forming complex relationships with surface water, sensitive ecosystems, and climatic cycles at a variety of temporal and spatial scales [Alley et al., 2002; Rodell et al., 2018]. Despite the incredible importance of groundwater resources and the hydrogeological system, these hidden resources remain poorly understood, and large gaps exist in our understanding of these complex systems [Famiglietti, 2014; Fan, 2015]. The management and protection of these vital, sensitive resources are one of the pressing issues facing humanity in the coming years as the challenges presented by changing climate and global water distributions are confronted [Famiglietti, 2014; Gleeson et al., 2010].

One aspect of managing and protecting groundwater resources is informed land use planning and site selection for facilities or operations that may present a risk of groundwater contamination. This requires decision support tools such as groundwater vulnerability assessments that provide policy makers with the information needed to make defensible decisions. Groundwater vulnerability assessments, which indicate the relative susceptibility of a groundwater system to contamination introduced at the land surface, guide the development of informed, sustainable, and economic groundwater management and protection policies and aid land use planning and site selection. To contribute to the development and improvement of the decision support tools available for managing and protecting the world's fresh groundwater resources, the research presented in this manuscript-based thesis has been conducted to develop and improve groundwater vulnerability assessment and presentation methods for land use planning and site selection.

1.1 Research project background

This research project was initiated by the Sylvia Fedoruk Canadian Centre for Nuclear Innovation (SFCCNI) as part of a multi-disciplinary project involving 14 researchers from the University of Regina and the University of Saskatchewan investigating the issues related to the siting of a small modular nuclear reactor (SMNR) in a non-nuclear jurisdiction, using Saskatchewan as a case study. As part of this project, I was tasked with investigating methods for delineating areas most appropriate for a SMNR from a groundwater perspective. While the greater project is focused on the issues specific to SMNR facilities, site selection with consideration of regional groundwater systems is chiefly based on common issues regardless of facility or development type. For this reason, the research presented in this thesis is focussed on extending the application of general methods for assessing groundwater vulnerability for land-use planning and site selection in south-central Saskatchewan. When considering how existing groundwater vulnerability assessment methods could be extended to assist planners in the preliminary siting of high-risk facilities in south-central Saskatchewan and elsewhere, three general questions present themselves:

1. How can the most appropriate method of assessing groundwater vulnerability be selected for a given purpose?
2. How can the hydrogeological processes influencing contaminant transport be most accurately represented by groundwater vulnerability assessments?
3. How can the resulting groundwater vulnerability assessment be effectively presented, facilitating an appropriate and meaningful interpretation of the results?

1.2 Purpose and objectives

The purpose of investigating these general questions is to facilitate the most effective application of groundwater vulnerability assessments and to assist in the interpretation of groundwater vulnerability assessments. Following a thorough literature review, it was concluded that this could be achieved by developing a method for incorporating and representing the uncertainty associated with the natural variation of input parameters into a deterministic, index-based groundwater vulnerability assessment. With this purpose in mind, the following objectives were established:

1. Provide a concise state-of-the-art review of intrinsic groundwater vulnerability assessment concepts, models, and methods and identify areas of opportunity for future development in the field of groundwater vulnerability assessments.
2. Identify and characterize the dominant hydrogeological properties of Pleistocene-aged glacial till aquitards at a regional scale of tens to hundreds of kilometers.
3. Constrain regionally representative hydraulic conductivity estimates for Pleistocene-aged glacial tills in south-central Saskatchewan.
4. Develop and demonstrate a methodology for conducting a regional groundwater vulnerability assessment incorporating the uncertainty associated with the natural variability of regionally representative input data.
5. Develop and demonstrate a methodology for displaying the results of a regional groundwater vulnerability assessment and the uncertainty associated with the assessment by means of a groundwater vulnerability map.

1.3 Methodology

The research presented in this thesis was conducted in three distinct phases, each addressing specific research program objectives. These three phases are 1) the review and synthesis of literature, research, and conceptual models associated with groundwater vulnerability assessments; 2) the collection and analysis of hydraulic conductivity data to be used as input data in a regional groundwater vulnerability assessment; and 3) the development of a modified groundwater vulnerability assessment method that more accurately represents and communicates the hydrogeological conditions in south-central Saskatchewan. Each of these three phases are presented as a separate, stand-alone manuscript chapter which includes the manuscript abstract, full contents (including introduction, methodology, results and discussion, and conclusion where appropriate), and references. Each manuscript chapter is also prefaced with a discussion of how the manuscript contributes to the overall purpose and objectives of this thesis, an explicit statement of the contributions of each of the manuscript's authors, a statement of the current status of the manuscript, and any citations associated with the chapter contents.

These manuscript chapters are:

- Chapter 2 – A review of the groundwater vulnerability concept and the state-of-the-art of groundwater vulnerability assessment methods

- Chapter 3 – Regional characterization of the hydraulic conductivity of glacial till aquitards in Saskatchewan, Canada
- Chapter 4 – Incorporating uncertainty into groundwater vulnerability assessments – A modified AVI method and case study of NTS map area 073B (Saskatoon)

This manuscript-based thesis ends with a concluding chapter that presents the integrated results and overall implications of the findings, and a discussion of further research opportunities presented by this research program.

Although this research program is focussed on extending the application of groundwater vulnerability assessments in south-central Saskatchewan, each of the manuscript chapters are presented from a global context, as it is expected that any developments made in understanding the groundwater and hydrogeological systems of Saskatchewan can be leveraged towards furthering global endeavours promoting sustainable and economic water resource development. The decision support tools such as the groundwater vulnerability concept and assessment methods developed here not only serve to assist decision makers in developing informed groundwater management and protection policies, but also promote an awareness of the importance of the hydrogeological system to all aspects of our lives. This thesis therefore represents a small step in creating the ecological literacy and awareness required to secure a sustainable future for generations to come.

1.4 References

Alley WM, Healy RW, Labaugh JW, Reilly TE. 2002. Flow and storage in groundwater systems. Science 296:1985-1990.

Famiglietti JS. 2014. The global groundwater crisis. Nat. Clim. Chang. 4:945-948. doi:10.1038/nclimate2425.

Fan Y. 2015. Groundwater in the Earth’s critical zone: Relevance to large-scale patterns and processes. Water Resour. Res. 51:3052–3069. doi:10.1002/2015WR017037.

Gleeson T, Vandersteen J, Sophocleous MA, Taniguchi M, Alley WM, Allen DM, Zhou Y. 2010. Groundwater sustainability strategies. Nat. Geosci. 3:378-379. doi:10.1038/ngeo881.

Rodell M, Famiglietti JS, Wiese DN, Reager JT, Beaudoing HK, Landerer FW, Lo M-H. 2018. Emerging trends in global freshwater availability. Nature 557:651-659. doi:10.1038/s41586-018-0123-1.

Siebert S, Burke J, Faures J, Frenken K, Hoogeveen J, Döll P, Portmann F. 2010. Groundwater use for irrigation - a global inventory. Hydrol. Earth Syst. Sci. 14:1863-1880. doi:10.5194/hess-14-1863-2010.

Wada Y, Wisser D, Bierkens MFP. 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 5:15–40. doi:10.5194/esd-5-15-2014.

2. A review of the groundwater vulnerability concept and the state-of-the-art of intrinsic groundwater vulnerability assessment methods

2.1 Preface

The following manuscript chapter presents an extensive literature review and synthesis and an exploration of the groundwater vulnerability concept that was conducted as a part of the problem definition stage of my M.Sc. research program. This chapter establishes the background research, terminology, and knowledge necessary to approach the primary focus of this thesis – to facilitate the most effective application of groundwater vulnerability assessments and to assist in the interpretation of groundwater vulnerability assessments by developing a method for incorporating and representing uncertainty in groundwater vulnerability assessments.

As an independent manuscript, this chapter represents a substantive and original contribution to the field of groundwater vulnerability assessments in the novel framework I present for synthesizing the various systems and models for classifying intrinsic groundwater vulnerability assessment methods. This manuscript also presents original conceptual figures and tables that form a valuable reference for academic and practicing professionals who work with groundwater vulnerability assessments.

My role in this research and in preparing this manuscript was that of lead researcher, author, and corresponding author for the manuscript submission and peer review process. Dr. Grant Ferguson and Dr. Chris Hawkes provided valuable review and feedback throughout the research and early manuscript development stages, and Dr. Grant Ferguson also provided thorough review and editing suggestions during the final preparation of the manuscript for submission. The conceptual diagram representing the various parameters and processes influencing groundwater vulnerability (appearing as Figure 2.3) was produced by University of Saskatchewan Media Productions Department to my exact specifications, as communicated by my detailed sketches and written instructions.

2.2 Abstract

Groundwater resources are increasingly relied upon to satisfy the world’s growing fresh water demands, yet these critical resources are increasingly threatened by contamination. One of the tools that have emerged to guide the protection and management of groundwater resources is the groundwater vulnerability assessment. However, the relative, non-measurable nature of the groundwater vulnerability concept and the broad range of applications for vulnerability assessments has resulted in the development of an overwhelming variety of classification systems, models, and assessment methods. To provide clarity and a basis for the effective application and interpretation of groundwater vulnerability assessments, we synthesize several influential models and classification systems by systematically evaluating the three elements common to intrinsic groundwater vulnerability assessment methods: the input parameters, the rating and weighting system, and the method of aggregation. We then present the state-of-the-art of intrinsic groundwater vulnerability assessments by summarizing and critically evaluating widely applied and representative vulnerability assessment methods. A review of studies comparing these popular methods emphasizes the importance of selecting a vulnerability assessment method that is suitable for the intended purpose and hydrogeological setting at the scale of interest, while balancing the data requirements and computational complexity with available resources. Current developments and future opportunities in the field of groundwater vulnerability assessments indicate the increasing role of technology such as geographic information systems and a trend towards interdisciplinary cooperation and the development of large-scale, integrated models for addressing pressing global environmental issues.

2.3 Introduction

The protection and management of the world’s fresh groundwater resources are among the many pressing issues facing humanity in the coming years. Groundwater accounts for as much as 1/3 of fresh water withdrawals globally [Siebert et al., 2010], and nearly 2 billion people rely on groundwater as their primary source of drinking water [Alley et al., 2002]. In addition to these direct human applications, groundwater forms a critical, integrated component of the Earth’s hydrological cycle and is intimately associated with surface water, sensitive ecosystems such as wetlands, and broad climatic cycles [Rodell et al., 2018; Zektser and Everett, 2004]. As demand for this limited natural resource increases and the effects of the changing climate and global water distributions are felt, fresh groundwater reserves will take on an even greater importance [Famiglietti, 2014; Gleeson et al., 2010]. Already, irreparable degradation of the quality and quantity of groundwater resources has resulted in economic and social pressure, as exemplified in groundwater depletion in California [Famiglietti, 2014] and widespread contamination and depletion in India [Tamta, 2003].

Despite the importance of groundwater resources and the dire consequences of mismanagement and contamination, these invisible resources attract less management attention than the more visible surface hydrology systems, while in the developing world groundwater protections are often entirely non-existent [Gleeson et al., 2010; Famiglietti, 2014]. Among the many calls for action is the need for the development of sound groundwater management and protection policy based on defensible hydrogeological theory [Gleeson et al., 2010]. High-level hydrogeological evaluations referred to as groundwater vulnerability assessments, which commonly result in the production of vulnerability maps indicating the region's relative susceptibility to contamination introduced at the land surface, are one of the tools available to guide land-use and groundwater management and protection policy [Vrba and Zaporozec, 1994; Gogu and Dassargues, 2000]. The adaptability of groundwater vulnerability assessments to satisfy a broad variety of applications and the easy to understand, visual presentation of groundwater vulnerability maps makes these ideal tools for guiding groundwater diplomacy and decision making when these vulnerability assessments are applied and interpreted appropriately.

However, the broad variety of hydrogeological settings and the relative, non-measurable nature of the groundwater vulnerability concept has defied the efforts of hydrogeologists to reach consensus regarding the appropriate methodology for conducting a groundwater vulnerability assessment and has resulted in a bewildering array of conceptual models, classification systems, and vulnerability assessment methods. In order to provide clarity and a basis for effectively selecting, applying, and evaluating vulnerability assessments, the first objective of this review is to synthesize and consolidate the concepts, framework, and models associated with groundwater vulnerability assessments. The second objective of this review is to provide a concise state-of-the-art review of intrinsic groundwater vulnerability assessment methods and to identify areas of opportunity for future developments in the field of groundwater vulnerability assessments.

The purpose of this review is not to replace but is to compliment and supplement the existing review articles [Gogu and Dassargues, 2000; Kumar et al., 2015], providing a useful reference for the developers and end users of groundwater vulnerability assessments alike.

Rather than emphasizing the individual classification and vulnerability assessment methods, we instead focus on the underlying foundational concepts and take a systematic approach to understanding groundwater vulnerability assessments methods through the synthesis of several influential models and classification systems. This is followed by a critical review of influential and representative vulnerability assessment methods and a summary of comparative evaluations. We conclude this review with a discussion of four areas of development and opportunity, pointing the way to future applications of groundwater vulnerability assessments. By taking this approach, we demystify this important and dynamic topic and lay the foundation for further work contributing to the development and improvement of tools for managing and protecting the world's fresh groundwater resources.

2.3.1 The purpose and application of groundwater vulnerability assessments

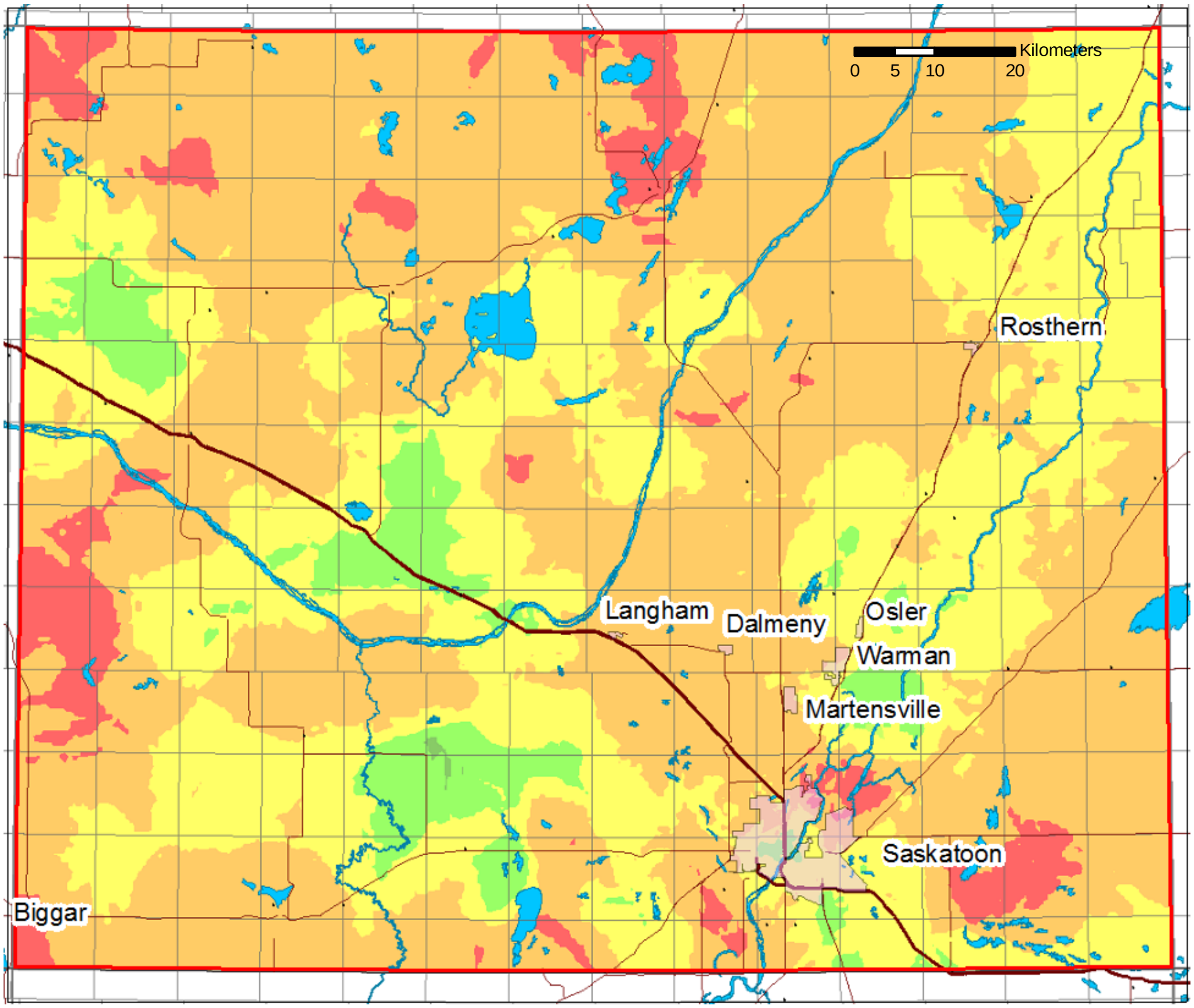
The concept of groundwater vulnerability and groundwater vulnerability assessments developed from a need for a tool to create awareness of the danger of groundwater contamination and to identify areas where protective measures were most needed [Margat, 1968; Vrba and Zaporozec, 1994]. Since then, groundwater vulnerability assessments have been used for a variety of applications. These applications for groundwater vulnerability assessments can be placed into one of three categories: 1) land use planning and environmental policy development, 2) groundwater risk and environmental impact assessments, and 3) general education and awareness [Vrba and Zaporozec, 1994].

The most direct application of a groundwater vulnerability assessment is to guide land use planning and the development of environmental policy. For this application, regional and local vulnerability maps can be used by planners and policy makers to guide decisions that affect water quality such as land use, siting industrial facilities, and establishing regulatory boundaries [National Research Council, 1993]. Vulnerability maps can also be used to classify and prioritize high-vulnerability areas and to direct limited resources to those areas most in need of protection [Freeze and Cherry, 1979; National Research Council, 1993].

Groundwater vulnerability assessments may also be applied as one part of a more detailed groundwater risk or environmental impact assessment or as a part of a preliminary site assessment. The general characterization of the hydrogeological environment provided by the vulnerability assessment can be combined with source well and spring mapping, known hazards, and consequences for a complete risk assessment [Foster et al., 2002]. The application of groundwater vulnerability assessment methods in conducting risk assessments has been developed and documented by the Geological Survey of Ireland [1999] and is described in academic literature [Foster et al., 2002] and government, regulatory, and consultant reports [Canadian Nuclear Safety Commission, 2012; Dillon Consulting Ltd., 2008; Ontario MOE, 2001].

Groundwater vulnerability assessments and maps can also serve as a valuable educational tool to promote awareness of the sensitivity of groundwater and the broader hydrological systems. Regional groundwater vulnerability assessments can sensitize policy makers to the issues relating to groundwater and environmental protection and can contribute to developing a consensus regarding the need to take action to protect groundwater resources from adverse impact [National Research Council, 1993; Vrba and Zaporozec, 1994]. Vulnerability maps can also be used to develop an awareness of environmental issues and to promote an understanding of important hydrogeological processes among the general public due to the intuitive nature of groundwater vulnerability maps and index rating systems.

Understanding the purpose and appropriate use of groundwater vulnerability assessments is especially important due to the opportunity for misuse presented by the simple, colour-coded vulnerability index maps that are often produced as part of a vulnerability assessment, such as the Aquifer Vulnerability Index map that presents relative groundwater vulnerability on a scale from 1 to 5, corresponding to very high vulnerability (1, red) to very low vulnerability (5, dark green) (Figure 2.1). Vulnerability assessments are often undertaken over large areas and represent characteristics influencing regional-scale hydrogeological processes. Vulnerability assessments are not suitable for characterizing local hydrogeological processes or point-source contaminant vulnerability and are not a suitable substitution for detailed site investigations [National Research Council, 1993]. Presenting the results of a groundwater vulnerability assessment as a continuous vulnerability map may also obscure important information such as data density and reliability and can easily be misinterpreted. Groundwater vulnerability maps should be accompanied, at a minimum, by explanatory documentation clearly describing the meaning of the vulnerability classes, the appropriate scale of use, and the confidence level of the vulnerability assessment [Vrba and Zaporozec, 1994].



Aquifer Vulnerability Index	Vulnerability Rating	Vulnerability Color Codes
1	very high	very high
2	high	high
3	moderate	moderate
4	low	low
5	very low	very low

Figure 2.1 Example of a colour-coded, index-based groundwater vulnerability map for the Saskatoon, Saskatchewan area

2.3.2 A brief history of groundwater vulnerability assessments

The development of a systematic approach to classifying sources of contamination and the potential for groundwater contamination began in the 1960s, and the first maps showing “vulnerability of groundwater to contamination” were produced during this period in France [Margat, 1968; Albinet and Margat, 1970]. These initial groundwater vulnerability maps were produced as a specialized subset of hydrogeological maps intending to create awareness of the danger posed by pollution to groundwater and to draw attention to the areas where protective measures were most needed [Vrba and Zaporozec, 1994].

Throughout the 1970s and 1980s, some efforts were made to establish a universal definition of groundwater vulnerability, while increasing urban development, intensive pesticide and fertilizer application, and a growing awareness of the limits of the world’s groundwater systems encouraged further development of methods for protecting groundwater resources [Foster et al., 1987, Vrba and Zaporozec, 1994]. During this time many local methods for assessing groundwater vulnerability were developed, particularly in Europe, incorporating many of the parameters used in the common groundwater vulnerability assessment methods today [Margat et al., 1987; Roeper, 1990; Vrba and Zaporozec, 1994]. By the late 1980s efforts were being made to develop a standardized approach for assessing groundwater vulnerability with two influential methods – GOD [Foster et al., 1987] and DRASTIC [Aller et al., 1987] – being published at that time.

In 1993 the Committee on Techniques for Assessing Ground Water Vulnerability issued the report Ground Water Vulnerability Assessment: Predicting Relative Contamination Potential Under Conditions of Uncertainty [National Research Council, 1993], followed shortly afterward by the International Association of Hydrogeologists’ (IAH/IHP) Guidebook to Mapping Groundwater Vulnerability [Vrba and Zaporozec, 1994]. These reports established the conceptual framework for groundwater vulnerability assessments and clearly identified the areas where further research was needed, stimulating academic interest in the field [Civita, 1994; Merchant, 1994; Napolitano and Fabbri, 1996].

In Europe, the COST (COST is an acronym for European Cooperation in Science and Technology) Action 65, from 1991 to 1995, addressed the topic of “hydrologic aspects of groundwater protection in karstic areas” [Daly et al., 2002], and the COST Action 620, from 1997 to 2003, continued this work by addressing the topic of “vulnerability and risk mapping for the protection of carbonate (karstic) aquifers” [Daly et al., 2002; Zwahlen, 2004; Vias et al., 2006] and promoted the development of methodology for assessing groundwater vulnerability in karstic aquifers and in aquifers in general [Doerfliger et al., 1999; Goldscheider et al., 2000; Gogu and Dassargues, 2000b].

Since the mid-1990s work in the field of groundwater vulnerability assessments has included the calibration, validation, and verification of existing methods [Napolitano and Fabbri, 1996; Ducci, 2010; Armengol et al., 2014; Elci, 2017; Javadi et al., 2017], comparisons of existing methodology [Neukum et al., 2008; Guastaldi et al., 2014; Luoma et al., 2017; Sullivan and Gao, 2017], and development of modified methods to address local or regional hydrogeological conditions [Civita, 1994; Civita and De Maio, 2004; Huan et al., 2012; Shirazi et al., 2012].

Continued developments in geographic information systems (GIS) technology and in modelling software has created the potential for new and innovative ways to conduct, calibrate, and verify vulnerability assessments [Machiwal et al., 2018; Napolitano and Fabbri, 1996; Ross et al., 2004; Shirazi et al., 2012]. Increasing availability of high quality remotely sensed data has presented the opportunity to develop methods for assessing groundwater vulnerability in areas that lack the detailed field data required for conventional methods [Oke et al., 2016], and to provide additional methods for verifying and calibrating existing methods [Sullivan and Gao, 2011].

2.4 Conceptual model for groundwater vulnerability

The concept of groundwater vulnerability originates from the recognition that the geological and hydrogeological properties at a specific location may offer some natural protection, attenuation capacity, or resistance to contaminants which are introduced into system. This natural resistance is dependent on properties that are spatially variable, and in fact, the factors and properties which influence natural resistance may also change from one hydrogeological system to the next. Groundwater vulnerability can be thought of as the inverse of this natural protection, attenuation capacity, or resistance to contaminants. A groundwater vulnerability assessment seeks to characterize the relative vulnerability at different locations within the region of investigation, indicating the locations that offer greater or lesser resistance to contaminant migration.

By definition, groundwater vulnerability is not a deterministic, objective, or measurable property – it is a relative, descriptive, and non-measurable property [Vrba and Zaporozec, 1994]. Although the properties which may be used to infer groundwater vulnerability may be measured objectively, the resulting vulnerability assessment is always a predictive statement with inherent uncertainty. Because of the relative nature of groundwater vulnerability and the extreme variability of the world's hydrogeological settings, developing universal guidelines for assessing groundwater vulnerability is neither feasible nor useful [National Research Council, 1993; Vrba and Zaporozec, 1994]. However, most groundwater vulnerability assessments share a common conceptual model that represents the natural properties and processes that contribute to the natural protection, attenuation capacity, or resistance to contaminants.

2.4.1 Source-pathway-receptor model

The conceptual model on which nearly all groundwater vulnerability assessment methods are based is the source-pathway-receptor contaminant transport model (Figure 2.2). The source, or origin of contamination, is the point at which contaminants are introduced into the system. Groundwater vulnerability assessments are based on a non-point (diffuse) source distributed over a large area defined at or near the land surface. The pathway is the geological and hydrogeological system between the source and the receptor. The receptor, or target, is the hydrogeological system or feature that could be affected by contamination.

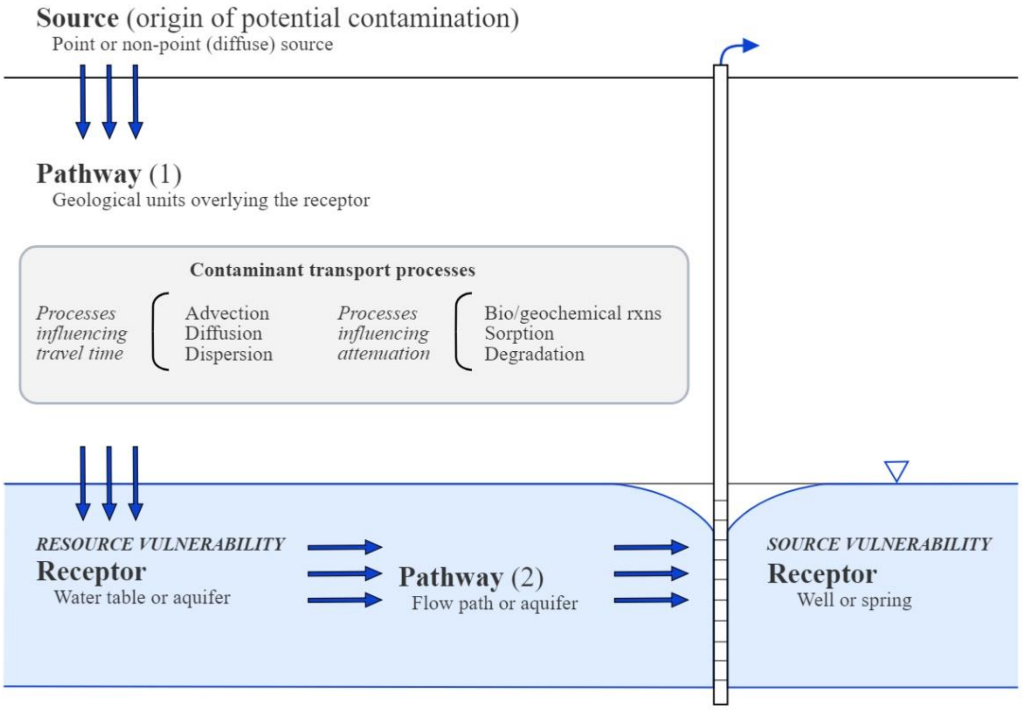


Figure 2.2 Source-pathway-receptor conceptual model for groundwater vulnerability assessments [after Zwahlen, 2004]

The selection of the receptor determines whether the vulnerability of an entire aquifer (resource vulnerability) or a specific well, spring, or point of abstraction (source vulnerability) is to be assessed. For a resource vulnerability assessment, the receptor is defined as the water table or the upper bound of the aquifer of interest, and a single pathway is represented. The receptor for a source vulnerability assessment is a specific point of discharge or abstraction. This distinction is important as a source vulnerability assessment must take into consideration two distinct pathways – the pathway from the source to the groundwater resource (aquifer), and the pathway through the aquifer to point of interest.

This conceptual model lends itself to the assessment of groundwater vulnerability on the basis of two basic attributes: hydraulic inaccessibility and contaminant attenuation capacity [Foster et al. 2002; Civita and de Maio 2004]. Hydraulic inaccessibility is often quantified in terms of travel time inferred from the geological and hydrogeological properties such as unit thickness and hydraulic conductivity, while natural contaminant attenuation capacity is relatively more difficult to quantify but may be characterized by the geological properties of the soil, vadose zone, and aquifer.

In an effort to develop a uniform and defensible method of assessing groundwater vulnerability, many methods define groundwater vulnerability as “the relative ease with which… contaminants can reach the upper boundary of an aquifer by downward advective, unretarded and non-reactive transport” [Ross et al., 2004]. While this simplifies the conceptual model and reduces the subjectivity of the assessment by eliminating factors such as attenuation and retardation capacity, the required assumptions may not be appropriate in all hydrogeological settings. In many cases, for example, diffusion-related processes are the dominant form of contaminant transport, with advective processes making little significant contribution to the time in which contaminants will reach a given point in the stratigraphic column [Hendry and Wassenaar, 2011; Barbour et al., 2012]. However, many of the important natural processes that result in contaminant attenuation or retardation of transport are directly or indirectly related to factors that influence travel time, allowing travel time to be a general indicator for both hydraulic inaccessibility and contaminant attenuation capacity [Goldscheider et al., 2000].

2.4.2 Intrinsic and specific groundwater vulnerability

Groundwater vulnerability assessments based on the source-pathway-receptor model have been divided into two broad groups – intrinsic groundwater vulnerability and specific groundwater vulnerability. Intrinsic (or general) groundwater vulnerability assessment methods, which are the focus of this paper, are based solely on the geological and hydrogeological properties of the region of interest, and do not include the properties of any specific contaminant or activity. Specific (or integrated) groundwater vulnerability assessments are based on the same conceptual model but are conducted to assess the vulnerability of a system to a specified contaminant, contaminant class, or human activity. Specific groundwater vulnerability assessments are based on the geological and hydrogeological properties of the system, and the properties of the contaminant(s) and the interactions of the contaminant(s) with the various components of the system [Gogu and Dassargues, 2000]. Specific groundwater vulnerability assessment methods have evolved separately from intrinsic vulnerability assessment methods, often conducted on site-by-site basis in response to local conditions, or requiring specialized modelling software [National Research Council, 1993]. The intrinsic groundwater vulnerability assessment methods are the most prevalent method of vulnerability assessment due to their broad applicability and adaptability, low data requirements, and ease of use [Gogu and Dassargues, 2000; Vrba and Zaporozec, 1994; Kumar et al., 2015].

2.5 The three elements of intrinsic groundwater vulnerability assessment methods

The broad variety of available methods for assessing intrinsic groundwater vulnerability coupled with a lack of consensus regarding the appropriate application of these methods has resulted in the need for a systematic process for classifying and evaluating groundwater vulnerability assessment methods. There are three principle elements of intrinsic groundwater vulnerability assessment methods that may be used as the basis of a systematic evaluation: the input parameters considered, the rating and weighting (if any) applied to those parameters, and the method by which those parameters are aggregated to generate an indication of vulnerability. Understanding the impact of these elements on the methods of assessing groundwater vulnerability allows a user to make sense of the variety of methods available, select an appropriate method to suit their needs, and effectively evaluate the results of the assessment.

2.5.1 Input parameters

All groundwater vulnerability assessment methods are based on a selected set of input parameters which are those factors, processes, and properties of the natural geological and hydrogeological system that have been identified as a measure of the groundwater system's vulnerability to contamination. The selected parameters are one of the most important differentiating features of the various groundwater vulnerability assessment methods, as the selection of parameters determines what hydrogeological and contaminant transport processes are represented in the assessment.

By the early 1990s, hydrogeologists recognized that establishing a single set of parameters wasn’t possible due to the “complexity and local nature of conditions leading to groundwater vulnerability” [National Research Council, 1993]. In the absence of a single, universally recognized set of parameters, the parameters included in groundwater vulnerability assessments are selected on the basis of the method’s conceptual vulnerability model, the availability of data, and the intended simplicity of the method – an increased number of parameters may provide a more accurate representation of groundwater vulnerability, but can also result in increased cost, subjectivity, and uncertainty [Sorichetta et al., 2011].

Vrba and Zaporozec [1994] group the principle parameters influencing groundwater vulnerability into three general systems:

1. The hydrogeological framework – characteristics of the soil, unsaturated zone, and aquifer materials, and depth to groundwater;
2. the groundwater flow system – the direction and velocity of the groundwater flow and topography; and
3. the climate – the amount of recharge to groundwater.

Others have conceptually separated the hydrogeological framework into parameters that influence hydraulic inaccessibility and attenuation capacity [Goldscheider et al. 2000; Civita and de Maio 2004]. The most common parameters included in groundwater vulnerability assessments (Figure 2.3) are summarized in Table 2.1.

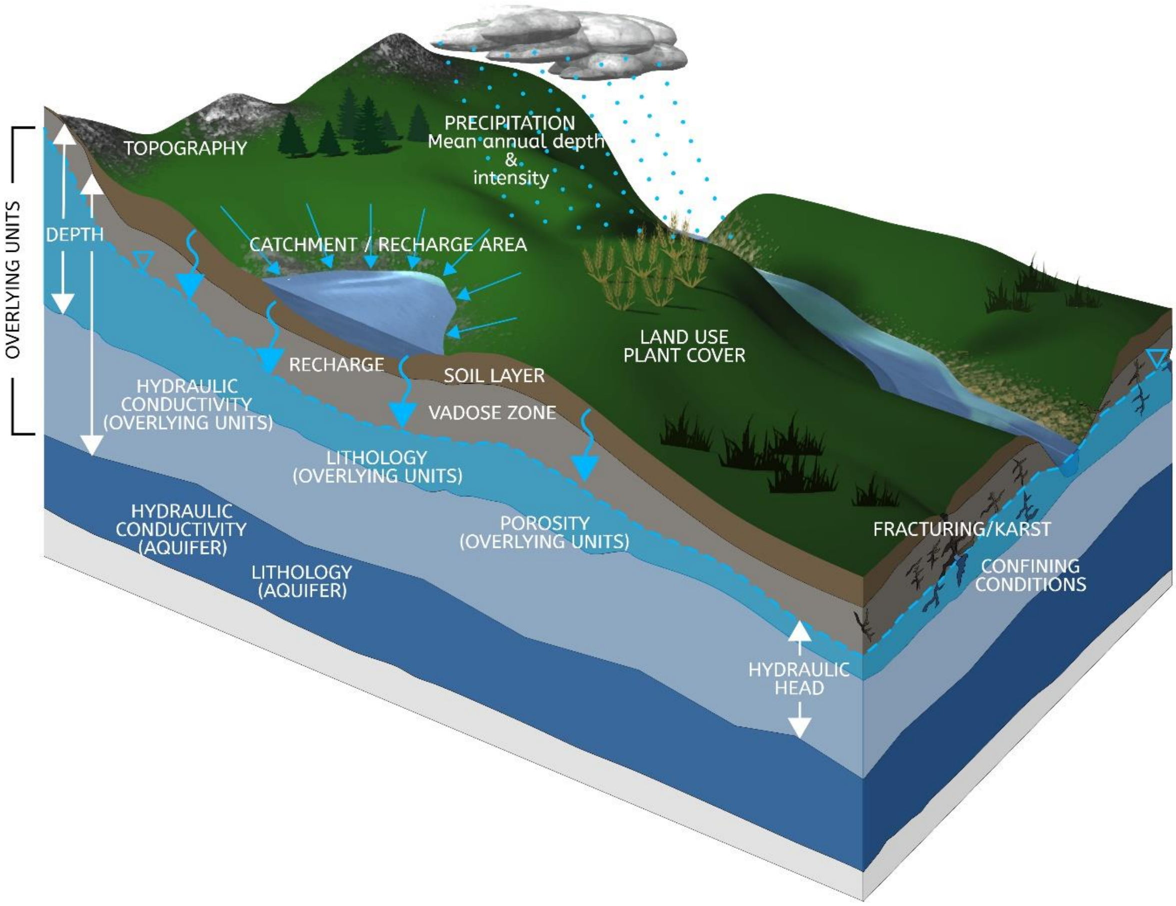


Figure 2.3 A conceptual representation of the parameters representing the factors, processes, and properties influencing intrinsic groundwater vulnerability

Among the factors influencing intrinsic groundwater vulnerability, the depth to water/depth of overlying units is almost universally included in vulnerability assessments, as this parameter indicates both the time of travel and the potential for attenuation regardless of hydrogeological conditions. Other common parameters are those which indicate the degree of protection offered by the overlying strata, characterized by the hydraulic conductivity of overlying units or by the subsoil, surficial geology, or lithology of overlying units. Other parameters, most of which indicate an increased vulnerability or a reduced natural protection, attenuation capacity, or resistance to contaminants are often specific to the method of assessing groundwater vulnerability.

Some geological and hydrogeological properties included as parameters in vulnerability assessments have been interpreted to influence groundwater vulnerability in different, and sometimes contradictory ways. Topographic slope is one parameter that has been interpreted to influence vulnerability in different ways and is included as a parameter in five different vulnerability assessment methods. The DRASTIC method [Aller et al., 1987] conceptualizes topographic slope as a factor that reduces groundwater vulnerability – as slope increases, infiltration decreases, and vulnerability decreases. Conversely, topographic slope is inferred to increase groundwater vulnerability in the RTt, EPIK, and PI conceptual models, as an increased slope is thought to increase concentrated recharge [Doerfliger et al., 1999; Goldscheider et al., 2000; Oke et al., 2016]. The COP method includes a topographic slope parameter in evaluating groundwater vulnerability in recharge zones, where increased slope increases vulnerability, and in non-recharge zones, where increased slope indicates a decreased vulnerability [Vias et al., 2006].

No groundwater vulnerability assessment method can, nor should attempt to include all parameters. An awareness of the hydrogeological, geochemical, and environmental factors influencing groundwater vulnerability and contaminant transport in the area of interest can help to identify the dominant hydrogeologic processes – a method of groundwater vulnerability assessment can then be selected that captures the most important processes for the area and application of interest.

2.5.2 Rating and weighting systems

Once the parameters are selected, the data must be converted to a common system of measurement that relates the quantitative or qualitative parameter description to a measure of the system's vulnerability. Depending on the method chosen, there may be two steps to this process; rating, which quantifies the expected effect of the parameter on groundwater vulnerability, and weighting, which quantifies the relative contribution of each of the parameters to the overall vulnerability of the groundwater system.

The selected parameters are often described using dramatically different forms of quantitative or qualitative measurement collected at different spatial and temporal scales. These disparate values must be converted into a common measure in order to arrive at a common measure of vulnerability. Many rating systems assign a vulnerability index value by dividing the parameter's natural range into discrete intervals, each of which are associated with a numeric

Table 2.1 Primary parameters influencing intrinsic groundwater vulnerability

Parameter *Controls over groundwater vulnerability*	***Assessment methods*** *Assessment methods that include parameter*	***Description*** *Definition of the parameter*	***Impact on groundwater vulnerability*** *Effect of the parameter on contaminant transport and groundwater vulnerability*
1 Consideration of multiple overlying units	SINTACS, AVI, PI, ISI, COP	The subdivision of the material overlying the saturated zone into effective hydrostratigraphic units. The subdivision is based on the qualitative description in Water Well Driller's Reports (AVI, ISI) or on the depth of soil horizons in the region (AVI, COP).	The subdivision of the overlying material allows for a more accurate representation of the physical processes governing advective transport.
2 Hydraulic conductivity of overlying unit(s)	AVI, ISI, DAT, RTt, PI	The estimated hydraulic conductivity of the units overlying the saturated zone. Saturated hydraulic conductivity estimates are often assigned on the basis of regional lithologic descriptions. The hydraulic conductivity is applied directly in a deterministic calculation (AVI, DAT) or used to assign an index rating (ISI, RTt, PI).	A lower hydraulic conductivity will increase the hydraulic resistance and time for advective transport, lowering the vulnerability of the system to contamination.
3 Depth to water, depth of overlying units	DRASTIC, SINTACS, AVI, ISI, DAT, RTt, GOD, EPIK, PI, COP	The depth to water is defined differently for each groundwater vulnerability assessment method, but is commonly defined as the depth from ground level to the water table (for unconfined aquifers) or the depth from ground level to the base of the confining layer (for confined aquifers).	An increased depth to groundwater will increase the time for advective transport and increase the time for attenuating processes to take place, lowering vulnerability.
4 (Net) Recharge	DRASTIC, SINTACS, DAT, PI	The net recharge is the water available to transport a contaminant vertically to the aquifer and is quantified as the portion of precipitation per unit area of land that infiltrates the ground surface and percolates through the overlying units to reach the water table. The net recharge is compared with calculated specific discharge (DAT) and is used to directly calculate travel time or is used to assign an index rating (DRASTIC, SINTACS, PI).	The recharge to the aquifer is mode of transport for contaminants, therefore as recharge increases, the vulnerability increases. The SINTACS method is the only method that reflects the effect of dilution, by reducing vulnerability index once recharge exceeds a specified value (as recommended, but not applied, within DRASTIC).
5 Aquifer media, lithology	DRASTIC, SINTACS	The aquifer media is a lithologic description of the aquifer unit and is used to assign an index value.	Consideration of the aquifer media is most relevant for water *source* vulnerability (versus *resource* vulnerability). The aquifer media affects contaminant transport and attenuation through route length and tortuosity, sorption, dispersion, reactivity. In the DRASTIC/SINTACS system, aquifer media with low clay content, low surface area, and high primary and secondary porosities increase vulnerability.
6 Soil (topsoil)	DRASTIC, SINTACS, EPIK, COP	The soil media is the uppermost portion of the vadose zone, typically 2 meters or less from the ground surface, which characterized by extensive biological activity, high organic carbon, and extensive weathering of mineral components. The soil media is parameterized by assigning an index rating based on soil texture and lithology, with thickness of soil media considered for EPIK and COP.	The biologically active soil zone, with higher clay content, organic matter, and bacterial populations, increases the possibility of contaminant attenuation, and can lower the vulnerability of the groundwater system. High clay and organic soils decrease vulnerability more than sandy soils.
7 Topography (percent slope)	DRASTIC, SINTACS, RTt, EPIK, PI, COP	The topography refers to the slope of the land surface and is commonly represented as a percent gradient. The topographic slope can be used to infer the gradient of subsurface interflow and the water table. In all systems, an index rating is assigned based the percent slope value.	In the DRASTIC method, higher slope is inferred to increase runoff and reduce infiltration and recharge, therefore reducing vulnerability. In the RTt, EPIK, and PI method, vulnerability increases with increasing slope, as it is assumed that runoff and interflow is directed towards recharge zones and bypasses protective cover. In the COP method, the topography of recharge areas is considered separately from non-recharge areas, and in considered to increase and decrease vulnerability, respectively.
8 Vadose zone effect	DRASTIC, SINTACS	The vadose zone is the unsaturated zone above the water table. For the purpose of groundwater vulnerability assessments, the vadose zone is considered to be the material below the soil horizon and above the aquifer of interest. An index rating is assigned on the basis of vadose zone lithology.	The impact of the vadose zone is considered to be dependent on the potential of the material to retard advective transport and facilitate the attenuation of contaminants. High clay and shale content is inferred to reduce vulnerability, while coarse clastic lithology, or karst limestone is inferred to increase vulnerability.
9 Hydraulic conductivity of aquifer	DRASTIC, SINTACS	The estimated saturated hydraulic conductivity of the aquifer of interest. An index rating is assigned based on the hydraulic conductivity, which is often estimated from the aquifer media lithology.	The hydraulic conductivity of the aquifer is only considered in DRASTIC-based methods and reflects a perception that the aquifer is a fundamental part of the pathway and is not the receptor itself. A low hydraulic conductivity will increase the time the contaminant will spend in the aquifer before reaching the receptor and will reduce vulnerability.

Table 2.1 Primary parameters influencing intrinsic groundwater vulnerability (continued)

	Parameter *Controls over groundwater vulnerability*	**Assessment methods** *Assessment methods that include parameter*	**Description** *Definition of the parameter*	**Impact on groundwater vulnerability** *Effect of the parameter on contaminant transport and groundwater vulnerability*
10	Precipitation	RTt, COP	The precipitation is the amount of rainfall the area receives, expressed as mean annual rainfall in depth per year, and is assigned an index rating.	The rainfall is used to represent the source of contaminants and to indicate maximum potential infiltration and recharge to the aquifer. For the RTt and COP methods, increased precipitation indicates increased vulnerability, although the COP method accounts for dilution by reducing vulnerability once precipitation exceeds a specified threshold value. The PI method implicitly relies on an estimated average storm rainfall in developing the vulnerability assessment.
11	Fracturing, karst, preferential flow paths	EPIK, PI, COP	Karst and fracture development is qualitatively described and assigned an index rating.	The development of fractures, karst features, and preferential flow paths increases the potential for flow to bypass protective covers and increases system vulnerability.
12	Subsoil, surficial geology, lithology of overlying unit(s)	GOD, EPIK, PI, COP	The subsoil, or surficial geology, is defined as the unlithified geologic material below the soil horizon and above the aquifer of interest. The subsoil is described on the basis of grainsize distribution or texture and assigned an index rating. PI and COP methods further differentiates the lithified overlying units. The lithified geologic material is described by lithology and assigned an index rating.	The effect of the subsoil is dependent on the ability of the material to retard adventive transport and facilitate attenuation of contaminants. Fine, well-sorted grainsize distributions and high organic content are inferred to reduce aquifer vulnerability. The lithified geologic material is considered to reduce aquifer vulnerability by retarding advective transport. Low hydraulic conductivity materials reduce vulnerability.
13	Proximity of catchment, recharge zones	EPIK, PI, COP	The EPIK method qualitatively considers proximity of losing streams, sinkholes and catchment areas in conjunction with slope and vegetation to assign an infiltrating conditions index rating. For PI, the proximity of a catchment area is quantified as the distance to a swallow hole or sinking stream. The proximity is determined by delineating zones on a catchment map and assigning an index rating. The COP method differentiates between recharge areas and non-recharge areas - within the recharge area, the distance to swallow holes and sinking streams is quantified in meters and assigned an index rating.	The proximity of a catchment area indicates the degree to which recharge and contaminants can bypass protective geologic cover. Close proximity to a catchment area or recharge zone will increase vulnerability.
14	Hydraulic head loss between surface and aquifer	DAT	The hydraulic head loss between the surface and the aquifer is quantified as the topographic elevation of the ground surface less 2 meters minus the hydraulic head in the aquifer. This value is input directly into the deterministic calculation of specific discharge.	The greater the loss of hydraulic head between the surface and the aquifer, the greater the specific discharge through the overlying units which increases recharge, and the rate of advective transport of contaminants, to the aquifer therefore increasing vulnerability.
15	Temporal distribution of rainfall	COP	The temporal distribution of rainfall, a measure of average rainfall event intensity, is determined by dividing the mean annual precipitation by the number of rainy days and is assigned one of three possible index ratings in the COP method.	The temporal distribution of rainfall is used to indicate the increased likelihood of flow concentration, rapid infiltration, and bypassing of protective cover, and increasing vulnerability. A higher temporal distribution of rainfall value indicates intense rainfall events and increases vulnerability.
16	Porosity of overlying unit(s)	DAT, RTt	The porosity of the overlying units is assigned on the basis of sediment type lithology and is used directly as an input to calculate downward advective flow travel time in a deterministic calculation (DAT). The RTt method estimates porosity on the basis of texture for soils and lithology for rock, which is used to assign an index rating.	The porosity of the overlying units influences the ease of advective transport. A higher porosity will be associated with a lower linear groundwater velocity for a given hydraulic conductivity, therefore reducing vulnerability. For DAT, a higher porosity increases advective travel time and reduces vulnerability, but porosity and permeability may not be independent parameters when both are determined on the basis of lithology. For RTt, a higher porosity results in increased vulnerability.
17	Land use, plant cover	EPIK, PI, COP	The land use is described qualitatively, described as forest, field/meadow/pasture, cultivated fields, or settlement (EPIK, PI); high or low (COP). The land use parameter is combined with slope (EPIK, COP) or slope and soil type (PI) in a matrix-style chart, to determine an index rating.	A high degree of vegetation reduces the risk of infiltration and the bypassing of the protective geologic cover and reduces vulnerability, while cultivation, settlement, or low vegetation concentrates runoff and increases vulnerability.
18	Confining conditions	GOD, PI, COP	The confining conditions of the aquifer of interest are described qualitatively as no aquifer, overflowing, confined, semi-confined, unconfined: covered, and unconfined (GOD); as artesian or non-artesian conditions (PI), or as unconfined, semi-confined, and confined (COP), and assigned an index rating.	The confining conditions influences the advective time of travel and the hydraulic behaviour of overlying units, and the hydraulic head which influences sub-surface water flow conditions. An increase in aquifer confinement generally corresponds to a decrease in vulnerability.

value indicating vulnerability [Aller et al., 1987; Civita and de Maio, 2004; Gogu and Dassargues, 2000]. In some methods, the rating is assigned after primary calculations are made [Goldscheider et al., 2000; Van Stempvoort et al., 1993]. The rating process, although necessary for producing easy to understand vulnerability assessments, may obscure subtle variations in vulnerability by reducing the resolution of the input data [National Research Council, 1993]. The division of the parameter's natural range into discrete intervals is inherently arbitrary and results in an additional source of uncertainty in the final vulnerability rating [Gogu and Dassargues, 2000].

The methods for assigning parameter weights can range from simple, fixed-weighting systems that minimize subjectivity to analysis-intensive weighting systems that provide flexibility in representing varying hydrogeological conditions. The DRASTIC method represents the end-member for simple weighting methods. The weighting of the seven DRASTIC parameters, determined by the Delphi consensus approach, are fixed, and do not change. This method allows for the relative importance of each parameter to be incorporated into the vulnerability assessment without additional subjectivity originating from the user's judgement [Aller et al., 1987]. The SINTACS method [Civita and de Maio, 2004] – a modification of the DRASTIC method – represents the other end-member for weighting assignment, where the weighting of each parameter is selected based on the hydrogeologic and environmental setting at each point of evaluation. This method accommodates the changing conditions and the corresponding change in the influence of each parameter on groundwater vulnerability throughout the region under investigation [Civita and de Maio, 2004; Napolitano and Fabbri, 1996]. Due to the subjective and arbitrary nature of weighting systems, the method of applying weightings has been the subject of much attention, and modified weightings for common methods have been proposed using calibration methods based on observed contaminant concentrations [Elci, 2017; Panagopoulos, 2006; Shirazi et al., 2012].

2.5.3 Method of aggregation

After the parameters have been selected and the rating and weighting system applied, the parameters are combined to arrive at a vulnerability rating. The methods of aggregation range from empirical, observational methods based on the judgement of experienced hydrogeologists [Aller et al, 1987; Foster et al., 1987], analogical or detailed calculations intended to approximate physical processes [Oke et al., 2016; Ross et al., 2016; Van Stempvoort et al., 1993], and statistical analysis of known contamination incidents [Kingsbury et al., 2017; Worral and Kolpin, 2003]. The method of aggregation is commonly used to group the various methods of assessing groundwater vulnerability into classes. While intended to simplify the selection of an assessment method appropriate for the user's needs, the various classification systems presented over the last three decades have resulted in an overwhelming number of classes and categories. The most commonly cited classification systems, the NRC's "Three classes of vulnerability assessments" [National Research Council 1993] and Vrba and Zaporozec's methods and techniques of vulnerability assessment [Vrba and Zaporozec, 1994], are related in Figure 2.4, resulting in four categories of vulnerability assessment.

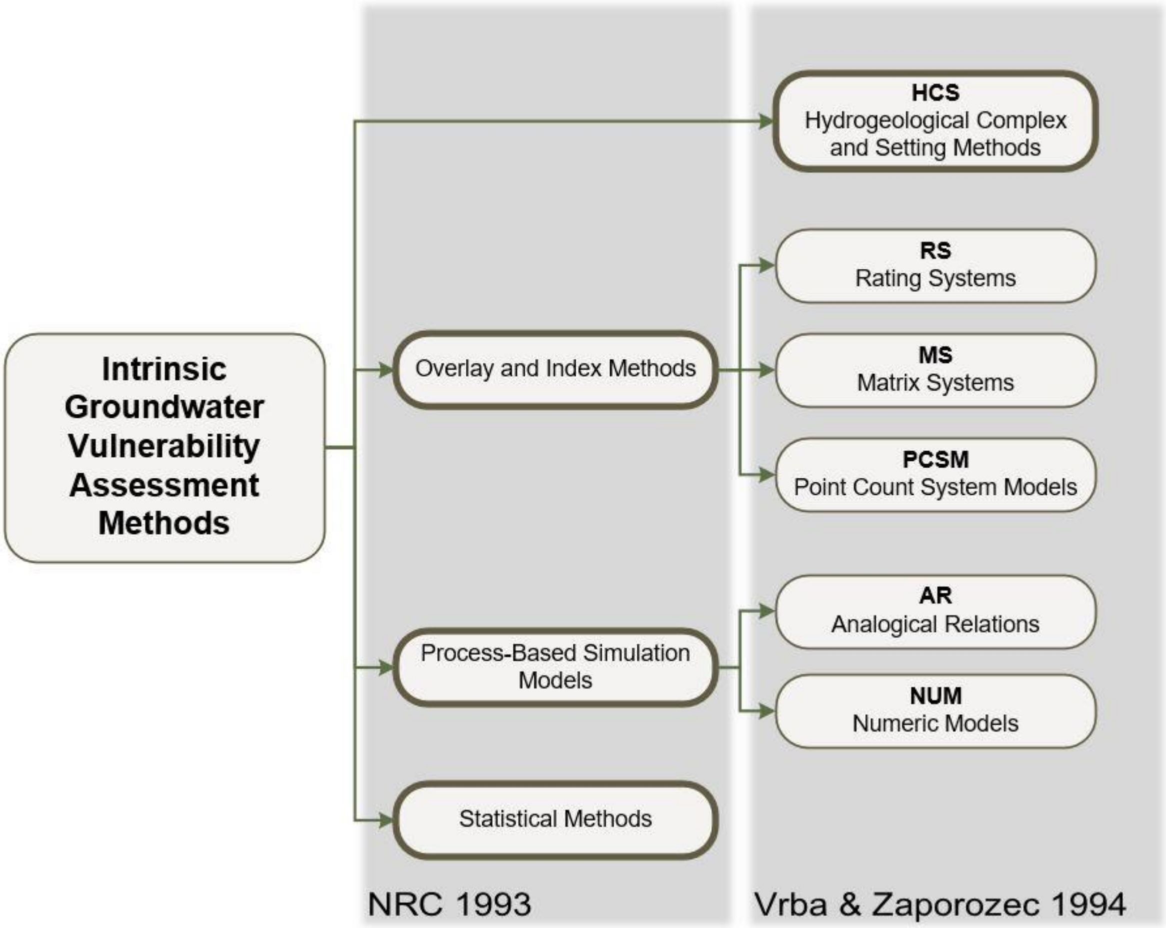


Figure 2.4 Classification of intrinsic groundwater vulnerability assessment methods

While there are some methods of assessing or mapping groundwater vulnerability that may not fall into these categories and some hybrid methods, these four categories are universally recognized and provide a suitable basis for evaluating vulnerability assessments.

Hydrogeological complex and setting methods

The hydrogeological complex and setting (HCS) method describes groundwater vulnerability only in qualitative terms. The regional physiographic and hydrogeological features are identified, and vulnerability is assessed by comparing these features to areas of known vulnerability. A hierarchical system of vulnerability classes is then developed based on experience and professional judgement to produce thematic maps.

Overlay and index methods

Overlay and index methods, also referred to as parametric system methods, are quantitative or semi-quantitative compilations and interpretations of spatial data where physical characteristics, properties, and processes which are known to influence vulnerability are parameterized by assigning values and/or weightings to produce a numerical index. These parameter values are then applied using one of three systems; a) matrix systems (MS) where vulnerability class is assigned by means of a rating matrix, b) rating systems (RS), where the values assigned to each parameter are summed or multiplied, and the resulting collection of ratings are divided into vulnerability groups, and c) point count system models (PCSM), also referred to as parameter weighting and rating methods, where the values assigned to each parameter are assigned a weighting prior to being aggregated into vulnerability classes.

Process-based simulation models

Process-based simulation models assess groundwater vulnerability using mathematical relationships to approximate the behaviour of contaminants in the subsurface environment. These methods range from simple one-dimensional advective transport approximations to complex coupled, unsaturated-saturated two and three-dimensional numeric models. These methods include analogical relations (AR) and numerical models (NUM) which are based on parameters or calculations directly related to physical contaminant transport processes.

Statistical methods

Statistical methods for assessing groundwater vulnerability rely on the behaviour and outcome of known contamination incidents to generate correlations and associations to predict contaminant concentration or the probability of contamination. These methods are typically applied only to areas in which extensive contamination data is available.

2.6 The state-of-the-art of intrinsic groundwater vulnerability assessment methods

Ten representative groundwater vulnerability assessment methods are summarized in Table 2.2, indicating the type of assessment method, whether the vulnerability rating is assigned based on qualitative or quantitative ratings, and which parameters are included in the assessment. These ten methods were selected for being among the most popular or representative methods for assessing groundwater vulnerability. These methods are described in detail in current literature, such as the review articles by Gogu and Dassargues [2000], Chenini et al. [2015], and Kumar et al. [2015], and additional observations are discussed here.

2.6.1 Review of groundwater vulnerability assessment methods

DRASTIC

The DRASTIC method was developed by the National Water Well Association and U.S. Environmental Protection Agency to promote the systematic evaluation of groundwater vulnerability (referred to as pollution potential) with data commonly available throughout the United States [Aller et al., 1987]. The DRASTIC method was one of the first parametric system models that was developed to be easily applied in a variety of hydrogeologic settings, and it is one of the most popular methods of assessing groundwater vulnerability worldwide. The original DRASTIC method included two separate components – the characterization of the hydrogeologic setting (HCS method) and the relative ranking using a numeric DRASTIC index (PCSM method). In application, it has been the numeric DRASTIC index which has garnered the most attention.

The DRASTIC hydrogeologic setting is defined as “a mappable unit with common hydrogeologic characteristics, and…common vulnerability to contamination by introduced pollutants” [Aller et al., 1987]. The hydrogeologic setting is defined to “orient the user to typical geologic and hydrologic configurations…and to help focus the reader’s attention on significant parameters which are important in pollution potential assessment” [Aller et al., 1987]. Each unique hydrogeologic setting is assigned a range of possible parameter index values to constrain subsequent DRASTIC index analysis.

Table 2.2 Classification and parameter summary of representative intrinsic groundwater vulnerability assessment methods

Groundwater vulnerability assessment method	***Source/ citation***	***Year***	**Type of assessment method**	**Qualitative rating**	**Consideration of multiple overlying units**	**Hydraulic conductivity of overlying unit(s)**	**Depth to water, depth of overlying units**	**(Net) Recharge**	**Aquifer media, lithology**	**Soil (topsoil)**	**Topography (percent slope)**	**Vadose zone effect**	**Hydraulic conductivity of aquifer**	**Precipitation**	**Fracturing, karst, preferential flow paths**	**Subsoil, surficial geology, lithology of overlying unit(s)**	**Proximity of catchment, recharge zones**	**Hydraulic head loss between surface and aquifer**	**Temporal distribution of rainfall**	**Porosity of overlying unit(s)**	**Land use, plant cover**	**Confining conditions**
DRASTIC *(D)epth, (R)echarge, (A)quifer media, (S)oil, (T)opography, (I)mpact of vadose zone, hydraulic (C)onductivity*	Aller et al.	1987	PCSM & HCS	Y			Y	Y	Y	Y	Y	Y	Y									
SINTACS *Depth, infiltration, unsaturated and soil attenuation capacity, saturated zone, hydraulic conductivity, slope*	Civita	1994	PCSM	Y	Y		Y	Y	Y	Y	Y	Y	Y									
AVI *(A)quifer (V)ulnerability (I)ndex*	Van Stempvoort et al.	1993	AR		Y	Y	Y															
ISI *(I)ntrinsic (S)usceptibility (I)ndex*	Ontario MOE	2001	AR /RS		Y	Y	Y															
DAT *(D)ownward (A)dvective (T)ime of travel*	Ross et al.	2004	NUM			Y	Y	Y										Y		Y		
RTt *(R)echarge and (T)ravel (t)ime*	Oke et al.	2016	RS /AR			Y	Y				Y			Y						Y		
GOD *(G)roundwater confinement, (O)verlying strata, (D)epth to groundwater*	Foster et al.	1987	RS	Y			Y									Y						Y
EPIK *(E)pikarst, (P)rotective cover, (I)nfiltration conditions, (K)arst network development*	Doerfliger et al.	1999	PCMS	Y			Y			Y	Y				Y	Y	Y				Y	
PI *(P)rotective cover, (I)nfiltration conditions*	Goldscheider et al.	2000	RS /MS	Y	Y	Y	Y	Y			Y				Y	Y	Y				Y	Y
COP *(C)oncentration of flow, properties of (O)verlying Layers, (P)recipitation*	Vias et al.	2006	RS /MS	Y	Y		Y			Y	Y			Y	Y	Y	Y		Y		Y	Y

PCSM, Point-Count System Model; HCS, Hydrogeological Complex and Setting Method; AR, Analogical Relation; RS, Rating System; NUM, Numerical Model; MS, Matrix System

The DRASTIC index method involves quantifying aquifer vulnerability through 7 parameters: (D) depth to water, (R) recharge to the aquifer, (A) aquifer media, (S) soil media, (T) topography, (I) impact of the vadose zone, and hydraulic (C) conductivity of the aquifer. A rating is assigned to each of these parameters based on predefined ranges given in both tabular and graphic format [Aller et al., 1987]. The relative importance of each of these parameters to aquifer vulnerability is expressed through a weighting scheme which assigns a weight between 1 and 5 to each of the parameters (Table 2.3).

Table 2.3 Weightings assigned to DRASTIC parameters

Parameter	**Rating**	**Weight**
D - Depth to Water	1-10	5
R - Net Recharge	1-9	4
A - Aquifer Media	1-10	3
S - Soil	1-10	2
T - Topography	1-5	1
I - Impact of Vadose Zone	1-10	5
C - Hydraulic Conductivity	1-10	3

The DRASIC index, (DI), is calculated as the sum of the product of the parameter's rating (X_r) and weight (X_w) (Equation 2.1).

$$\text{DRASTIC Index (DI)} = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad (2.1)$$

The DRASTIC method is unique among common intrinsic groundwater vulnerability methods as the properties of the aquifer are considered in determining the DRASTIC index. The inclusion of the aquifer properties in assessing groundwater vulnerability implies that the conceptual target, or receptor, is the point of abstraction, and not the groundwater resource itself; however, the DRASTIC index is still regarded as a measure of resource vulnerability.

The selection of parameters used, and the weighting applied to the parameters, has been the primary source of contention with respect to the DRASTIC method. A concern often cited regarding the DRASTIC method is the non-independence and redundancy of several of the parameters (i.e. hydraulic conductivity and aquifer material, impact of vadose zone and soil) [Foster et al., 2002; Ducci, 2010; Elci, 2017]. The non-independence of these parameters is aggravated when the DRASTIC method is used in areas that lack sufficient data for a robust vulnerability assessment – in these cases, several of the parameters may be inferred from a single known attribute.

The DRASTIC system is often also criticized for the arbitrary weighting scheme, which was determined through a Delphi consensus approach [Van Stempvoort et al., 1993; Elci, 2017]. The proposed weighting scheme is constant, and is intended to be applied in all cases, regardless of hydrogeological setting or confining conditions. While this weighting scheme facilitates the objective and consistent application of the DRASTIC method, the lack of adaptability limits the usefulness of this method. To address the limitations of the single, fixed weighting scheme, an alternative DRASTIC method, called Pesticide DRASTIC has been developed to address the specific needs of assessing groundwater vulnerability to pesticides [Gogu and Dassargues, 2000]. This alternative weighting scheme places a higher weight on soil media and topography, and a lower weight on the impact of the vadose zone and the hydraulic conductivity of the aquifer.

Several modifications of the DRASTIC method have been developed [Civita and De Maio, 2004; Bojorquez-Tapia et al., 2009; Shirazi et al., 2012]. SINTACS is an Italian modification of the DRASTIC methods which uses the same parameters as inputs, but the parameters are applied in a complex structure that offers greater flexibility [Civita, 1994; Civita and De Maio, 2004]. The SINTACS method was developed for use with GIS software, and incorporates hydrogeological conditions and land use descriptions to assign parameter weightings using parallel weight strings.

AVI

The Aquifer Vulnerability Index, or AVI, is an analogical relation (AR) method for assessing groundwater vulnerability developed in 1992 by Van Stempvoort et al. of the (Canadian) National Hydrology Research Institute. The AVI method was developed to address the perceived complexity and arbitrary nature of methods of assessing aquifer vulnerability such as DRASTIC and the overly simplistic and site-specific methods developed and used by various government organizations in the 1980s and early 1990s [Van Stempvoort et al., 1992]. The AVI method quantifies aquifer vulnerability through two parameters – thickness and hydraulic conductivity of each sedimentary layer overlying the uppermost saturated aquifer surface – parameters which are inferred from Water Well Driller's Reports (WWDR). Van Stempvoort et al. [1992] concluded that these parameters adequately represent the hydrogeological properties governing aquifer vulnerability in the area of interest (the Interior Plains region of North America) without the redundancy and subjectivity of additional parameters.

The AVI index is based on hydraulic resistance, c (T), a theoretical factor which describes the resistance of an aquitard to vertical flow, and is calculated as

$$\boldsymbol{c} = \sum {\boldsymbol{d_i}}/{\boldsymbol{K_i}} \tag{2.2}$$

where d (L) is the thickness of sedimentary layer *i* above the uppermost, saturated aquifer surface, and K (L/T) is the corresponding estimated hydraulic conductivity of sedimentary layer *i*. Although hydraulic resistance has units of time, it should not be considered a travel time for water or contaminants, but is instead a process-based analogical relation that can be used to indicate relative groundwater vulnerability. Once calculated, the hydraulic resistance, c or Log(c), can be contoured and plotted as iso-resistance maps or related to the qualitative AVI description (Table 2.4) and plotted [Van Stempvoort et al., 1992].

Table 2.4 Hydraulic resistance and Aquifer Vulnerability Index

Hydraulic Resistance, c	**Log(c)**	**AVI**
0 – 10 y	<1	Extremely high
10 – 100 y	1 – 2	High
100 – 1000 y	2 – 3	Moderate
1000 – 10,000 y	3 – 4	Low
>10,000	>4	Extremely Low

The advantage of the AVI method is that it is dependent only on those parameters which are quantifiable by standardized methods and readily available in, or inferred from, WWDRs. The ease of access of information, and the lack of subjective and arbitrary parameters and artificial weightings, allows the AVI to be calculated independently by different parties while achieving standardized results. This method also facilitates the mapping of aquifer vulnerability using a GIS automated process. The AVI method also considers all distinct geological units overlying the water table, which more accurately reflects the geological control over downward advective transport of contaminants.

Van Stempvoort et al. [1993] identify the dependence on WWDRs for classifying and delineating the different sedimentary units overlying the uppermost saturated aquifer surface as a limitation of the AVI method. WWDRs vary in quality and detail, and often use different qualitative descriptions. Van Stempvoort et al. [1993] suggest using additional sources of shallow subsurface information including provincial test-hole logs and geophysical logs where stratigraphic interpretations are available.

A similar method for assessing groundwater vulnerability is the ISI (Intrinsic Susceptibility Index) method [Ontario MOE, 2001]. The ISI method involves assigning a hydraulic conductivity factor (K-factor) which is then multiplied with the thickness for each unit overlying the point of interest. Although based on the analogical relationship between hydraulic conductivity and advective transport, the ISI method is a hybrid AR/RS method because a K-factor (rating) is used rather than the hydraulic conductivity value. The ISI method differentiates between unconfined and confined aquifers – for unconfined aquifers, only that geological material between the ground surface and the water table is considered to offer resistance, while for a confined aquifer all overlying geological material is included in the vulnerability assessment [Ontario MOE, 2001].

Ross et al. [2004] further developed the idea of quantifying 1D transport of groundwater by proposing a groundwater vulnerability assessment method based on the downward advective time of travel, or DAT. The DAT method combines 3D geological model software with deterministic calculations based on Darcy's Law using parameters for unit thickness, hydraulic conductivity, porosity, and head loss between the surface and the aquifer of interest. The DAT method results in a vulnerability parameter with units of time that has physical meaning and can be directly related to the travel time of advective flow.

RTt

The RTt (rainfall and travel-time) method for assessing groundwater vulnerability is a RS and AR hybrid method proposed by Oke et al. [2016] to facilitate groundwater vulnerability assessments in areas that lack detailed hydrogeological information. This method is different from many of the common groundwater vulnerability methods because of its reliance on input parameters that are derived from readily available regional and remote sensing data, rather than detailed hydrogeological investigations. The groundwater vulnerability is evaluated through two factors – the R (rainfall) factor and the Tt (travel time) factor.

The RTt method is based on the assumption that precipitation is the driving force behind vertical infiltration of groundwater recharge, and thus the advective transport of contaminants. The R factor quantifies the amount of water available to transport contaminants to the water table and into the groundwater system. Where available, known recharge can be substituted for rainfall, with a modified rating, for a more representative R factor.

The Tt factor in the RTt method is a measure of the natural resistance to vertical, advective flux of recharge to the groundwater system. The Tt factor is based upon Darcy's law, and is expressed as

$$\mathrm{Tt} = \frac{D \; x \; S}{K_{sat}/_{\theta}} \tag{2.3}$$

where D is the depth from ground surface to the aquifer parameter, S is the topographic slope parameter, K_{sat} is the saturated hydraulic conductivity parameter, and θ is the effective porosity parameter [Oke et al., 2016]. In this formulation, the topographic slope, S, is not an analogue for hydraulic gradient; as the slope increases, the Tt factor increases, decreasing the resultant vulnerability. Using this method, Oke et al. recommend producing a rainfall (R factor) index map and a travel time (Tt factor) index map, and producing a final RTt vulnerability index map by summing and contouring the R and Tt factors.

Oke et al. [2016] acknowledge the limitations of the RTt method that are inherent in the simplified input parameters but demonstrate a reasonable correlation between RTt and common groundwater vulnerability methods such as DRASTIC, PI, and AVI. The RTt method also demonstrates a reasonable correlation with chloride concentrations within the Dahomey Basin study area ($R^2 = 0.57$), suggesting the potential for using remote sensing data for groundwater vulnerability assessments [Oke et al., 2016].

GOD

The GOD method was first proposed by Foster [1987] and, together with DRASTIC, was one of the first groundwater vulnerability assessment methods developed to be applied in a variety of hydrogeologic settings. The GOD method, for groundwater confinement (G), overlying strata (O), and depth to water table or strike (D), is an empirical rating system (RS) method which was developed to be an integral part of a risk assessment method which was to include pollution loading events [Foster, 1987]. In practical application, the GOD rating system was used independently as an intrinsic groundwater vulnerability method.

The GOD method conceptualizes groundwater vulnerability as the result of two factors – the hydraulic inaccessibility of the target aquifer, and the attenuation capacity of the geologic material overlying the aquifer. To arrive at an estimation of the groundwater vulnerability, the groundwater confinement (G) conditions are identified and a parameter is assigned. The grade of consolidation followed by lithological character of the overlying material is then specified and the (O) parameter is assigned. Last, the depth to the water table or first groundwater strike (for confined aquifers) is estimated and the (D) parameter is assigned. The "aquifer pollution vulnerability" class is then assigned based on the product of the GOD terms. The GOD method has been modified through several versions. In the first iteration, the overlying strata term (then referred to as the overall aquifer class) was only applied in the case of unconfined aquifer conditions [Foster, 1987].

Foster et al. notes that the parameterization of the O factor was deliberately developed to place a greater emphasis on attenuation capacity rather than recharge lag time. The development of preferential flow paths and fractures is considered the most critical factor in reducing attenuation capacity and increasing groundwater vulnerability, and this is related empirically to the O factor strata classes [Foster et al., 2002]. Foster et al. also notes that the presence of surficial soils is a significant factor in characterizing the attenuation capacity of overlying strata and recommends the addition of a soil leaching susceptibility index to any modification of the GOD method [2002].

COP

The COP method presented by Vias et al. [2006] is one example of several methods of assessing groundwater vulnerability originating in Europe to address the unique conditions presented by karst aquifers. This method was developed when it was found that existing methods for assessing groundwater vulnerability, often applying travel time as an analogue for attenuation capacity, were inappropriate for karst landscapes characterized by preferential flow paths and swallow holes [Doerfliger et al., 1999]. The COP method developed from research associated with COST Action 620 project, which identified three parameters – concentration of overland flow (C factor), overlying layers (O factor), and precipitation (P factor) – relevant to the intrinsic resource vulnerability of karst aquifers, and one additional factor – karst network development (K factor) – relevant to source vulnerability [Daly et al., 2002; Zwahlen, 2004]. The COP method uses the parameters identified as relevant to resource vulnerability of karst aquifers by a

RS/MS hybrid methodology that can be applied in a variety of climatic conditions and with different levels of available data [Vias et al., 2006].

The COP method conceptualizes groundwater vulnerability as the balance between the natural protection and attenuation capacity of the overlying soils and unsaturated zone (O factor), the capacity of the recharge to concentrate and bypass the protective layers (C factor), and the availability of precipitation to concentrate and transport contaminants (P factor) [Vias et al., 2006]. Each of the three factors of the COP method is arrived at by considering several parameters. The O factor is derived from two subfactors; the soil subfactor and lithology subfactor, the C factor is arrived at by one of two scenarios based on the presence of swallow holes or points of concentrated recharge, and the P factor reflects the quantity and frequency of precipitation.

Conceptually, the COP index, arrived at by taking the product of C, O, and P factors, can be regarded as a re-weighting of the O factor based on the potential for recharge to bypass the protective layers. The COP vulnerability index can range from 0 to 15, and, based on the COP index, one of five vulnerability classes is assigned, and these vulnerability classes can then form the basis of an intrinsic groundwater vulnerability map. The COP method can be applied in a comprehensive resource and source vulnerability assessment method referred to as the European Approach through an overlay process with the K factor [Daly et al., 2002; Zwahlen, 2004].

One advantage of the COP method is the flexibility in representing diffuse or concentrated flow scenarios. This is especially relevant in karst landscapes but may also be applicable in other hydrogeologic settings where two distinct hydrogeologic regimes exist within the same region. Other methods suitable for karst landscapes have been developed on the basis of characterizing the protective cover or attenuation capacity of overlying strata and the potential for bypassing flow, including EPIK, PI, GLA, and P3 methods [Gogu and Dassargues, 2000b; Doerfliger et al., 1999; Goldscheider et al., 2000; Holting et al., 1995; Sullivan and Gao, 2017].

Other methods

Numerous other methods have been developed for assessing intrinsic groundwater vulnerability. One alternative approach to assessing groundwater vulnerability involves the use of water chemistry data. An example of this approach is Kingsbury et al.'s [2017] application of age-date tracer data, which was correlated to the occurrence of nitrate, chloride and synthetic organic compounds, to indicate of regions vulnerable to the vertical migration of contaminants to aquifers. Worral and Kolpin used direct observations of several contaminants to generate a statistically-derived probabilistic groundwater vulnerability assessment [2003]. Worral and Kolpin compared the proportion of detections of the contaminants in the region with that observed at the borehole. Through their statistical methodology, the relative groundwater vulnerability of a given area is represented by the probability of contaminants being detected at that location, given the proportion of contaminants detected in the region [Worral and Kolpin, 2003].

2.6.2 Comparisons of groundwater vulnerability assessments methods

The variety of methods for assessing groundwater vulnerability has encouraged the comparison of groundwater vulnerability assessments produced by different methods at the same site [Ronneseth et al., 1995; Gogu and Dassargues, 2000; Vias et al., 2006; Neukum et al., 2008; Guastaldi et al., 2014; Oke et al., 2016]. Direct, one-to-one comparisons and assessment validation by comparing different intrinsic groundwater vulnerability methods is not advisable since each method assesses the relative vulnerability by considering different hydrogeological and contaminant transport processes [Kumar et al., 2015]. However, comparisons of different methods may yield interesting observations regarding the suitability of the various methods for different conditions and applications.

At a regional scale, relatively simple methods with fewer parameters such as GOD and AVI compare favourably with data and analysis-intensive methods and produce similar vulnerability maps [Ronneseth et al., 1995; Gogu and Dassargues, 2000; Guastaldi et al., 2014] often following trends in surficial geology and regional aquifer boundaries [Ronneseth et al., 1995]. However, methods with few parameters (GOD, AVI) are often insensitive to subtle changes in vulnerability and tend to produce homogeneous vulnerability class distributions [Vias et al., 2006; Gogu and Dassargues, 2000]. The inclusion of additional parameters, however, is not necessarily sufficient to capture local variabilities in vulnerability – DRASTIC, with seven parameters, was found to be insensitive to local variability when that variability is only reflected in one or two parameters [Ronneseth et al., 1995; Ross et al., 2004; Neukum et al., 2008]. Although developed from the DRASTIC model, SINTACS has demonstrated a greater sensitivity to changing conditions and produces maps that better capture local vulnerability variations [Gogu and Dassargues, 2000; Guastaldi et al., 2011].

More important than the inclusion of additional parameters in producing a representative vulnerability assessment is the inclusion of parameters that adequately capture the dominant processes that control groundwater vulnerability in the area of interest. An important distinction to make is between vulnerability controlled by changing lithology and vulnerability resulting from preferential flow paths such as those found in karst landscapes. DRASTIC, SINTACS, AVI, and GOD are common methods appropriate for assessing vulnerability controlled by lithology, but these methods are not effective for vulnerability controlled by preferential flow paths and rapid infiltration in karst conditions better accommodated by the EPIK, PI, and COP methods [Vias et al., 2006; Neukum et al. 2008].

Few comparisons have been made between intrinsic groundwater vulnerability assessments and numerical simulations of contaminant transport times, tracer tests, or of known vulnerability profiles, but in these cases the methods that incorporate a higher number of parameters and a high degree of flexibility in application, such as SINTACS [Gogu and Dassargues, 2000] and COP [Vias et al., 2006; Guastaldi et al., 2014] provide the most reliable vulnerability assessments by reflecting subtle changes in vulnerability.

From these comparative studies, general conclusions can be drawn regarding the suitability of various methods for certain applications. Relatively simple methods that are insensitive to subtle changes in vulnerability and produce homogeneous vulnerability distributions such as GOD are suited to generalized studies of large areas, while data and analysis intensive methods incorporating numerous parameters and/or weighting strings such as SINTACS and COP are better adapted to situations requiring detailed analysis of a smaller area [Kumar et al., 2015]. Regardless of the number of parameters, vulnerability assessments are only appropriate if the parameters capture dominant hydrogeologic processes.

2.7 Current developments and future opportunities

The growing awareness of the importance of groundwater resources worldwide and the current limitations and challenges of groundwater vulnerability assessments presents several areas of opportunity to advance the field of groundwater protection. Primary areas for future work include developing methods for calibrating and validating groundwater vulnerability models; effectively representing the uncertainty inherent in intrinsic groundwater vulnerability assessment methods; leveraging developments in technology, geographic information systems (GIS), and remote sensing data; and developing global-scale groundwater vulnerability models.

2.7.1 Calibrating and validating groundwater vulnerability assessments

Much of the current work in the field of groundwater vulnerability involves developing methods for the calibration and validation of groundwater vulnerability assessments [Elci, 2017; Huan et al., 2018; Sorichetta et al., 2011; Zwahlen, 2004]. A complete and objective validation of any intrinsic groundwater vulnerability method is not possible since groundwater vulnerability is a relative, descriptive concept; however, relating the groundwater vulnerability rating to a measurable, physical processes can provide a method for evaluating the validity of the vulnerability assessment. Methods being developed for calibrating and validating groundwater vulnerability assessment methods include evaluation of stable isotopes to constrain the age and residence time of groundwater [Zwahlen, 2004], groundwater quality indicators such as nitrate concentrations [Elci, 2017; Huan et al., 2012; Sorichetta et al., 2011], and in the case of rapid travel times in karst geology, tracer tests [Doerfliger et al., 1999; Vias et al., 2006]. Empirical calibration and validation of relative groundwater vulnerability ranking can be conducted at locations where contamination has already occurred. However, the calibrated and verified methodology is unlikely to remain valid under different hydrogeological and contaminant loading conditions and cannot therefore be applied to vulnerability assessments in other areas with a high degree of confidence [Vrba and Zaporozec, 1994]. Groundwater models, statistical methods, and numerical simulations can also provide another method of validating groundwater vulnerability assessments [Neukum et al., 2008; Sorichetta et al., 2011].

2.7.2 Understanding and representing uncertainty

The need for effective natural resource and groundwater management decision support tools presents another opportunity to improve groundwater vulnerability assessments by defining, quantifying, and reducing the uncertainty inherent in available groundwater vulnerability assessments. Groundwater vulnerability assessment methods often rely on deterministic point estimates based on average values, but sound, justifiable decision-making and effective risk analysis will depend on a fulsome understanding of probabilities and possible outcomes [Uusitalo et al., 2015]. The critical importance of quantifying and including uncertainty in groundwater vulnerability assessments has been broadly recognized as early as 1993 [National Research Council]; however, except for statistically derived groundwater vulnerability assessment methods, current methodology does not incorporate uncertainty directly [Armengol et al., 2014; Li et al., 2018].

Uncertainty is present in every step of the vulnerability assessments process and arises from several sources including the quality and distribution of the input data, the method of assessment, the interpolation and generation of the vulnerability map, and the method and language of presenting the assessment. Armengol et al. [2014] have further specified sources of uncertainty in groundwater vulnerability assessments and have developed a novel approach to incorporating the uncertainty associated with DRASTIC input parameters, allowing for a vulnerability assessment based on a desired degree of confidence. Recent research addressing uncertainty in groundwater vulnerability and resource assessments has been focused on quantifying the uncertainty associated with the interpolation of point data through the application of common statistical methods such as indicator kriging, stochastic methods, multiple linear regression, and Monte Carlo simulation [Cooper et al., 2015; Llopis-Albert et al., 2014; Li et al., 2017]; however, there is the opportunity to further define and develop methodology for quantifying and presenting uncertainty in groundwater vulnerability assessments.

2.7.3 Integrating technological developments

Among the greatest opportunities in the field of groundwater vulnerability assessments are the opportunities presented by technological developments to integrate various vulnerability assessment and validation methods, data sources and management tools, statistical analyses, and methods of visual presentation. Especially important are developments of GIS that support merging and integrating data from a variety of sources, allowing data of variable quality, resolution, and temporal and spatial scales to be reconciled to produce a reliable vulnerability assessment [Alley et al., 2002; Shirazi et al., 2012]. GIS and data management software create opportunities for the development and application of integrated soil, hydrological, hydrogeological, and geological databases, improving global access to quality data [Shirazi et al., 2012]. These improvements in data collection, management, and analysis also create opportunities to integrate conventional index and overlay groundwater vulnerability assessments with more complex numerical models [Afshar et al., 2007; Pathak et al., 2011].

The improvements in quality and availability of remote sensing data provide another source of topographic, hydrological, and surficial data that can provide information relevant to groundwater vulnerability, particularly in areas where conventional hydrogeological data is sparse [Hoffmann and Sander, 2007; Jha et al., 2007]. While the use of remote sensing data for hydrogeological applications is still at an early stage, Sullivan and Gao have demonstrated that remote sensing data integrated with GIS and statistical analysis has been useful in reducing the exploration bias and resulting error in groundwater vulnerability assessments that resulted from conventional ground-collected data [Sullivan and Gao, 2017]. Remote sensing is particularly valuable in providing spatially distributed data, which can be used to supplement conventional ground-collected point data in groundwater vulnerability assessments [Hoffmann and Sander, 2007].

2.7.4 Developing integrated, large-scale groundwater vulnerability models

Looking to the future, there is an increasing potential and an increasing need for large-scale integrated tools and models to predict and respond to global-scale processes and environmental issues such as climate change, changing global distributions of water, and regional shortages of potable water. Researchers have identified a need to evaluate and map the quality and quantity of groundwater resources in major aquifers worldwide [Famiglietti 2014; Gleeson 2010] and to develop an understanding of the factors influencing the deterioration of the quality of global groundwater supplies [Alley et al., 2002; Famiglietti, 2014; Jackson et al., 2013; Luoma et al., 2017]. Recent global scale hydrological and hydrogeological databases and models [Fan et al., 2013; Gleeson et al., 2011; Rodell et al., 2018] and global maps of reported groundwater contamination [Margat and van der Gun, 2013] have demonstrated the possibility of developing useful models at this scale and presents an opportunity to develop large-scale groundwater vulnerability models. For example, Gleeson et al.'s [2011] global map of near-surface permeability and Fan et al.'s [2013] global patterns of groundwater table depth could be integrated to produce an approximation of groundwater vulnerability to contaminants introduced at the ground surface. Remote sensing technology could be applied here to provide further large scale, continuous data needed for national and global-scale vulnerability assessments.

The groundwater vulnerability concept and vulnerability assessment methods may prove to be a valuable starting point for developing new conceptual models for groundwater vulnerability to address the risk to groundwater resources from changing climate conditions, seawater intrusion, and contaminant migration along wellbores as well as natural and induced fractures. Assessing and mapping these primary risks to groundwater quality around the world would be a valuable tool for assigning limited resources for groundwater management and protection. Developing new conceptual models and assessment methods that accurately characterize the factors influencing groundwater vulnerability to these hazards will require the cooperation of engineers and geoscientists, hydrogeologists, and environmental scientists and may help drive the interdisciplinary cooperation necessary for addressing emerging global water resources problems.

2.8 Conclusion

Over the past several decades, the groundwater vulnerability concept and vulnerability assessments have proven to be a valuable tool with a variety of applications for policy development, groundwater management and protection, and general education. However, the development a single, unified approach to groundwater vulnerability assessment is neither feasible nor desirable due to the broad range of applications and the variety of the hydrogeological processes influencing the vulnerability of groundwater systems. Instead, groundwater vulnerability assessments have developed as a number of diverse and flexible models and methods. It is therefore necessary for users of groundwater vulnerability assessments to have a sound understanding of the vulnerability concept and of the factors that contribute to the assignment of a vulnerability rating. This begins with understanding the source-pathway-receptor conceptual model and the three elements of intrinsic groundwater vulnerability assessment methods: the input parameters, the rating and weighting system, and the method of aggregation.

Currently, there are several effective and widely used methods of assessing intrinsic groundwater vulnerability and numerous adaptations of these methods, each developed to overcome the limitations of existing methods or to more accurately represent local hydrogeological conditions. In the manner of Occam’s razor, intrinsic groundwater vulnerability assessment methods strive to limit the number of input parameters and computational complexity while most accurately representing the dominant contaminant transport processes at the scale of interest. Comparative evaluation studies and validation efforts have demonstrated the importance of carefully selecting parameters and a vulnerability assessment method that best represents the processes of interest to the user.

We are currently at a turning point in the field of groundwater vulnerability assessments. The need for sound, data-driven environmental policy and groundwater management and protection plans has never been greater. There is potential for the groundwater vulnerability concept and assessment methods to be further developed and applied to guide environmental stewardship and groundwater diplomacy by incorporating technological developments in data acquisition and management, modelling, and mapping. There is a great need to develop a new approach to managing the Earth's resources, and, with further development, the groundwater vulnerability concept and assessments can fill this need and help us achieve a sustainable future.

2.9 References

Afshar A. 2007. Rule-Based Fuzzy System for Assessing Groundwater Vulnerability. Afshar A, editor. J. Environ. Eng. 133:532–540. doi:10.1061/(ASCE)0733-9372(2007)133:5(532).

Albinet M, Margat J. 1970. Cartographie de la vulnerabilite a la pollution des nappes d'eau souteraine [Mapping of ground water vulnerability to contamination]. Bull. BRGM, 2eme Ser. 3:13–22.

Aller L, Bennett T, Lehr JH, Petty RJ, Hackett G. 1987. DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential using Hydrogeologic Settings. United States Environment Protection Agency, EPA/600/2-87/035.

Alley WM, Healy RW, Labaugh JW, Reilly TE. 2002. Flow and storage in groundwater systems. Science 296:1985–1990.

Armengol S, Sanchez-Vila X, Folch A. 2014. An approach to aquifer vulnerability including uncertainty in a spatial random function framework. J. Hydrol. 517:889–900. doi:10.1016/j.jhydrol.2014.06.016.

Barbour SL, Hendry MJ, Wassenaar LI. 2012. In situ experiment to determine advective-diffusive controls on solute transport in a clay-rich aquitard. J. Contam. Hydrol. 131:79–88. doi:10.1016/j.jconhyd.2011.12.002.

Bojórquez-Tapia LA, Cruz-Bello GM, Luna-González L, Juárez L, Ortiz-Pérez MA. 2009. V-DRASTIC: Using visualization to engage policymakers in groundwater vulnerability assessment. J. Hydrol. 373:242–255. doi:10.1016/j.jhydrol.2009.05.005.

Canadian Nuclear Safety Commission. 2012. Protection of Groundwater at Nuclear Facilities in Canada, Discussion Paper DIS-12-01. Ottawa, Ontario.

Chenini I, Zghibi A, Kouzana L. 2015. Hydrogeological investigations and groundwater vulnerability assessment and mapping for groundwater resource protection and management: State of the art and a case study. J. African Earth Sci. 109:11–26. doi:10.1016/j.jafrearsci.2015.05.008.

Civita M. 1994. La carte della vulnerabilita degli acquiferi all'inquinamento. Bologna.

Civita M, De Maio M. 2004. Assessing and mapping groundwater vulnerability to contamination: The Italian “combined” approach. Geofis. Int. 43:513–532.

Cooper H, Zhang C, Selch D. 2015. Incorporating uncertainty of groundwater modeling in sea-level rise assessment: a case study in South Florida. Clim. Change 129:281–294. doi:10.1007/s10584-015-1334-1.

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu I, Zwahlen F. 2002. Main concepts of the ``European approach’’ to karst-groundwater-vulnerability assessment and mapping. Hydrogeol. J. 10:340–345. doi:10.1007/s10040-001-0185-1.

Dillon Consulting Limited. 2008. Groundwater Vulnerability Analysis Report for the Cataraqui Source Protection Area. Glenburnie, ON.

Doerfliger N, Jeannin PY, Zwahlen F. 1999. Water vulnerability assessment in karst environments: a new method of defining protection areas using a multi-attribute approach and GIS tools (EPIK method). Environ. Geol. 39:165–176.

Ducci D. 2010. Aquifer Vulnerability Assessment Methods: The Non-Independence of Parameters Problem. J. Water Resour. Prot. 02:298–308. doi:10.4236/jwarp.2010.24034.

Elçi A. 2017. Calibration of groundwater vulnerability mapping using the generalized reduced gradient method. J. Contam. Hydrol. 207:39–49. doi:10.1016/j.jconhyd.2017.10.008.

Famiglietti JS. 2014. The global groundwater crisis. Nat. Clim. Chang. 4:945–948. doi:10.1038/nclimate2425.

Fan Y, Li H, Miguez-Macho G. 2013. Global Patterns of Groundwater Table Depth. Science 339:940–943.

Fan Y. 2015. Groundwater in the Earth’s critical zone: Relevance to large-scale patterns and processes. Water Resour. Res. 51:3052–3069. doi:10.1002/2015WR017037.

Foster SSD, Duijvenbooden W, Van Waegengh HG. 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. Versl. en Meded. - Comm. voor Hydrol. Onderz. T.N.O. 38:69–86.

Foster S, Hirata R, Gomes D, D’Elia M, Paris M. 2002. Groundwater Quality Protection. Washington, D.C.: The World Bank.

Freeze RA, Cherry JA. 1979. Groundwater. Englewood Cliffs, NJ: Prentice-Hall Inc.

Geologic Survey of Ireland. 1999. Groundwater Protection Schemes. Dublin, Ire.

Gleeson T, Smith L, Moosdorf N, Hartmann J, Dürr HH, Manning AH, van Beek LPH, Jellinek AM. 2011. Mapping permeability over the surface of the Earth. Geophys. Res. Lett. 38:1–6. doi:10.1029/2010GL045565.

Gleeson T, Vandersteen J, Sophocleous MA, Taniguchi M, Alley WM, Allen DM, Zhou Y. 2010. Groundwater sustainability strategies. Nat. Geosci. 3:378–379. doi:10.1038/ngeo881.

Gogu RC, Dassargues A. 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environ. Geol. 39:549–559. doi:10.1007/s002540050466.

Gogu RC, Dassargues A. 2000b. Sensitivity analysis for the EPIK method of vulnerability assessment in a small karstic aquifer, southern Belgium. Hydrogeol. J. 8:337–345. doi:10.1007/s100400050019.

Goldscheider N, Klute M, Sturm S, Hotzl H. 2000. The PI method - A GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers. Zeitschrift fur Angew. Geol. 46:157–166.

Guastaldi E, Graziano L, Liali G, Brogna FNA, Barbagli A. 2014. Intrinsic vulnerability assessment of Saturnia thermal aquifer by means of three parametric methods: SINTACS, GODS and COP. Environ. Earth Sci. 72:2861–2878. doi:10.1007/s12665-014-3191-z.

Hendry MJ, Wassenaar LI. 2011. Millenial-scale diffusion migration of solutes in thick clay-rich aquitards: evidence from multiple environmental traces. Hydrogeol. J. 19:259–270.

Hoffmann J, Sander P. 2007. Remote sensing and GIS in hydrogeology. Hydrogeol. J. 15:1–3. doi:10.1007/s10040-006-0140-2.

Holting B, Haertle T, Hohberger K, Nachtigall K, Villinger E, Weinzierl W, Wrobel J. 1995. Konzept zur Ermittlung der Schutzfunktion der Grundwasserüberdeckung [Concept for the evaluation of the protective function of the unsaturated stratum above the water table]. Geol Jahrb C63:5–24.

Huan H, Wang J, Teng Y. 2012. Assessment and validation of groundwater vulnerability to nitrate based on a modified DRASTIC model: A case study in Jilin City of northeast China. Sci. Total Environ. 440:14–23. doi:10.1016/j.scitotenv.2012.08.037.

Jackson RE, Gorody AW, Mayer B, Roy JW, Ryan MC, Van Stempvoort DR. 2013. Groundwater Protection and Unconventional Gas Extraction: The Critical Need for Field-Based Hydrogeological Research. Groundwater 51:488–510. doi:10.1111/gwat.12074.

Javadi S, Hashemy SM, Mohammadi K, Howard KWF, Neshat A. 2017. Classification of aquifer vulnerability using K-means cluster analysis. J. Hydrol. 549:27–37. doi:10.1016/j.jhydrol.2017.03.060.

Jha MK, Chowdhury A, Chowdary VM, Peiffer S. 2007. Groundwater management and development by integrated remote sensing and geographic information systems: prospects and constraints. Water Resour. Manag. 21:427–467. doi:10.1007/s11269-006-9024-4.

Kingsbury JA, Barlow JRB, Jurgens BC, McMahon PB, Carmichael JK. 2017. Fraction of young water as an indicator of aquifer vulnerability along two regional flow paths in the Mississippi embayment aquifer system, southeastern USA. Hydrogeol. J. 25:1661–1678. doi:10.1007/s10040-017-1566-4.

Kumar P, Bansod BKS, Debnath SK, Thakur PK, Ghanshyam C. 2015. Index-based groundwater vulnerability mapping models using hydrogeological settings: A critical evaluation. Environ. Impact Assess. Rev. 51:38–49. doi:10.1016/j.eiar.2015.02.001.

Li F, Zhu J, Deng X, Zhao Y, Li S. 2018. Assessment and uncertainty analysis of groundwater risk. Environ. Res. 160:140–151. doi:10.1016/j.envres.2017.09.030.

Llopis-Albert C, Palacios-Marqués D, Merigó JM. 2014. A coupled stochastic inverse-management framework for dealing with nonpoint agriculture pollution under groundwater parameter uncertainty. J. Hydrol. 511:10–16. doi:10.1016/j.jhydrol.2014.01.021.

Luoma S, Okkonen J, Korkka-Niemi K. 2017. Comparison of the AVI, modified SINTACS and GALDIT vulnerability methods under future climate-change scenarios for a shallow low-lying coastal aquifer in southern Finland. Hydrogeol. J. 25:203–222. doi:10.1007/s10040-016-1471-2.

Machiwal D, Cloutier V, Güler C, Kazakis N. 2018. A review of GIS-integrated statistical techniques for groundwater quality evaluation and protection. Environ. Earth Sci. 77. doi:10.1007/s12665-018-7872-x.

Margat J. 1968. Vulnerabilite des nappes d’eau souterraine a la pollution [Ground water vulnerability to contamination]. Bases la catorgraphie 68 SGC 198HYD, BGRM, Orleans.

Margat J, Suais-Parascandola MF, Duijvenbooden W, Van Waegengh HG. 1987. Mapping the vulnerability of groundwater to pollution; some lessons from experience in France. Versl. en Meded. - Comm. voor Hydrol. Onderz. T.N.O. 38:433–436.

Margat J, van der Gun J. 2013. Groundwater around the world: a geographic synopsis. van der Gun J, Francis T&, editors. CRC Press, Taylor & Francis Group.

Merchant JW. 1994. GIS-based groundwater pollution hazard assessment - a critical review of the DRASTIC model. Photogramm. Eng. Remote Sens. 60:1117–1128.

Napolitano P, Fabbri AG. 1996. Single parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS. In: HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference, April 1996). IAHS Publ. no. 235. 559–556.

National Research Council. 1993. Ground Water Vulnerability Assessment: Predicting Contamination Potential Under Conditions of Uncertainty. Washington, D.C.: National Academy Press.

Neukum C, Hötzl H, Himmelsbach T. 2008. Validation of vulnerability mapping methods by field investigations and numerical modelling. Hydrogeol. J. 16:641–658. doi:10.1007/s10040-007-0249-y.

Oke SA, Vermeulen D, Gomo M. 2016. Aquifer vulnerability assessment of the Dahomey Basin using the RTt method. Environ. Earth Sci. 75:964–971. doi:10.1007/s12665-016-5792-1.

Ontario MOE. 2001. Technical Terms of Reference for the 2001/2002 Groundwater Studies.

Pathak DR, Hiratsuka A. 2011. An integrated GIS based fuzzy pattern recognition model to compute groundwater vulnerability index for decision making. J. Hydro-environment Res. 5:63–77. doi:10.1016/j.jher.2009.10.015.

Rodell M, Famiglietti JS, Wiese DN, Reager JT, Beaudoing HK, Landerer FW, Lo M-H. 2018. Emerging trends in global freshwater availability. Nature 557:651–659. doi:10.1038/s41586-018-0123-1.

Roeper UVR. 1990. Regina aquifers sensitivity mapping and land use guidelines. Regina, SK.

Ronneseth K, Wei M, Gallo M. 1995. Evaluating Methods of Aquifer Vulnerability Mapping for the Prevention of Groundwater Contamination in British Columbia.

Ross M, Martel R, Lefebvre R, Parent M, Savard MM. 2004. Assessing rock aquifer vulnerability using downward advective times from a 3D model of surficial geology: A case study from the St. Lawrence Lowlands, Canada. Geofis. Int. 43:591–602.

Shirazi SM, Imran HM, Akib S. 2012. GIS-based DRASTIC method for groundwater vulnerability assessment: a review. J. Risk Res. 15:991–1011. doi:10.1080/13669877.2012.686053.

Siebert S, Burke J, Faures J, Frenken K, Hoogeveen J, Döll P, Portmann F. 2010. Groundwater use for irrigation - a global inventory. Hydrol. Earth Syst. Sci. 14:1863–1880. doi:10.5194/hess-14-1863-2010.

Sorichetta A, Masetti M, Ballabio C, Sterlacchini S, Beretta G Pietro. 2011. Reliability of groundwater vulnerability maps obtained through statistical methods. J. Environ. Manage. 92:1215–1224. doi:10.1016/j.jenvman.2010.12.009.

Sullivan TP, Gao Y. 2017. Development of a new P3 (Probability, Protection, and Precipitation) method for vulnerability, hazard, and risk intensity index assessments in karst watersheds. J. Hydrol. 549:428–451. doi:10.1016/j.jhydrol.2017.04.007.

Tamta S. 2003. Groundwater contamination in India. Indian J. public Adm. xlix:578–584.

Uusitalo L, Lehikoinen A, Helle I, Myrberg K. 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environ. Model. Softw. 63:24–31. doi:10.1016/j.envsoft.2014.09.017.

Van Stempvoort D, Ewert L, Wassenaar L. 1993. Aquifer Vulnerability Index: A GIS - compatible method for groundwater vulnerability mapping. Can. Water Resour. J. / Rev. Can. des ressources hydriques 18:25–37. doi:10.4296/cwrj1801025.

Van Stempvoort D, Ewert L, Wassenaar L. 1992. AVI: A method for groundwater protection mapping in the prairie provinces of Canada: final report, March 31, 1992. Saskatoon, SK.

Vías JM, Andreo B, Perles MJ, Carrasco F, Vadillo I, Jiménez P. 2006. Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Hydrogeol. J. 14:912–925. doi:10.1007/s10040-006-0023-6.

Vrba J, Zaporozec A. 1994. Guidebook on mapping groundwater vulnerability. Int. Assoc. Hydrogeol. (International Contrib. to Hydrogeol. 16:1–131.

Worrall F, Kolpin DW. 2003. Direct assessment of groundwater vulnerability from single observations of multiple contaminants. Water Resour. Res. 39:1345–1352. doi:10.1029/2002WR001212.

Zektser IS, Everett LG, editors. 2004. Groundwater resources of the world and their use. IHP-VI. Series on groundwater No.6. Tech. Doc. Hydrol. 1–342.

Zwahlen F. 2004. COST Action 620: Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers - Final Report.

3. Regional characterization of the hydraulic conductivity of glacial till aquitards in Saskatchewan, Canada

3.1 Preface

The following manuscript chapter represents work conducted to develop the data set required for a statistical characterization of glacial till aquitards in south-central Saskatchewan. This statistical characterization of till aquitards was necessary to develop appropriate input parameters that could be used to demonstrate the method for incorporating the uncertainty associated with the variability of input parameters into groundwater vulnerability assessments, as presented in Chapter 4 of this thesis. In addition to providing the required data set, the research presented in this manuscript yielded valuable findings relevant to field of prairie hydrogeology.

My role in this research and preparing this manuscript was that of lead researcher, lead author, and corresponding author for the peer review process. I reviewed and compiled all data, conducted all analyses, and wrote the manuscript. Dr. Grant Ferguson provided guidance and suggestions throughout the research and manuscript preparation stages, often suggesting valuable sources, providing multiple reviews and edits, and making substantial suggestions regarding the analysis and presentation of the data. Dr. Ferguson also introduced me to Mr. Greg Potter. Mr. Potter provided me with unique data sets that I would otherwise have not included and provided substantial reviews and edits of the manuscript on two occasions, suggesting substantial rewordings of several passages of the manuscript.

The data set compiled through the research presented in this study was published by the Federated Research Data Repository on 19 March 2019, and is associated with the citation: Ferris DM, Ferguson G, Potter G. 2019. Aggregate hydraulic conductivity data from site investigations in south-central Saskatchewan, Canada [Dataset]. Federated Research Data Repository. doi: 10.20383/101.0140.

3.2 Abstract

Pleistocene-aged glacial sediments are found in many parts of the Northern Hemisphere and are often composed of clay-rich tills which form aquitards that can control drainage and influence groundwater movement and contaminant transport to and from underlying aquifers. The development of Earth System Models, effective land use policies, and groundwater vulnerability assessments requires an understanding of the hydraulic conductivity of these units at a regional scale of tens of kilometers. Site scale investigations have revealed that the hydraulic conductivity of glacial till aquitards can vary by several orders of magnitude; however, these studies have not been expanded to a regional scale. Here, we characterize the regional hydraulic conductivity of Pleistocene-aged glacial till aquitards from data collected at 15 sites compiled from 21 studies, across south-central Saskatchewan, Canada. These data were grouped based on test scale: lab tests, conducted at the centimeter scale; in-situ tests, at the meter scale; and model data, including various methods observing hydraulic phenomenon at a scale of tens of meters. The data reveals the scale dependence of hydraulic conductivity measurements in glacial tills and indicates a relationship between hydraulic conductivity and depth. The results support the existence of a shallow, fracture-dominated active groundwater zone, and a deep, unfractured zone characterized by matrix permeability. The variability of the data occurred primarily at the site scale, while the central tendency and variability of the data was consistent between sites separated by hundreds of kilometers suggesting that statistically-derived, depth-defined hydraulic conductivity estimates can be meaningful at the regional scale.

3.3 Introduction

Pleistocene-aged glacial sediments are common features across the Northern Hemisphere. These glacial sediments are often composed of clay-rich till that form important hydrogeological units that influence terrestrial water storage and govern groundwater movement and the transport of contaminants to and from intertill or bedrock aquifers where present [Clark et al., 2015; Hendry, 1982; Keller et al., 1988]. An understanding of the hydrogeological processes and properties of these glacial till aquitards is necessary for a variety of earth process and water resource applications, yet these units remain poorly understood [Cuthbert et al., 2010; Gleeson et al., 2011]. In fact, characterizing the factors influencing groundwater-surface water interactions and improving data sets on hydraulic conductivity of shallow hydrogeological units has been identified as one of the key opportunities for developing land surface models and addressing water resource problems [Clark et al., 2015; Fan, 2015; Gleeson et al., 2011].

Studies investigating the hydrogeology of glacial till aquitards have been conducted throughout the Northern Hemisphere, with influential studies being conducted in Saskatchewan and other Canadian provinces [D’Astous et al., 1989; Grisak and Cherry, 1975; Harrington et al., 2007; Hendry, 1982; Rutland et al., 1991], in the United Kingdom [Cuthbert et al., 2010; Hiscock and Tabatabai Najafi, 2011] and Scandinavia [Jorgensen et al., 2002; Kessler et al., 2012; Sidle et al., 1998]. These studies have shown that although significant heterogeneity is observed at the site scale, the Pleistocene-aged glacial till aquitards share common hydrogeological characteristics, and research conducted in one region has been found applicable to analog sites in other regions of glacial deposits [Cuthbert et al., 2010; Hiscock and Tabatabai Najafi, 2011; Kessler et al., 2012].

The hydrogeological properties of these glacial till aquitards are characterized in part by hydraulic conductivity. Hydraulic conductivity, however, can vary over several orders of magnitude [D’Astous et al., 1989; van der Kamp, 2001]. The variability of hydraulic conductivity is especially significant in shallow glacial till aquitards that have been subject to significant weathering and fracturing [D’Astous et al., 1989; van der Kamp, 2001; Hendry, 1988].

Hydrogeological investigations characterizing the hydraulic properties of glacial tills are often conducted on a site scale of tens to hundreds of meters. Important among these investigations are studies characterizing the hydrogeology of glacial tills at the Dalmeny and Warman sites in Saskatchewan, Canada [Keller et al., 1986; 1988; 1989]. By comparing hydraulic conductivity test data and studying the hydraulic head distributions, tritium profiles, and geochemical signatures, Keller et al. [1988] provided evidence that the bulk permeability of shallow, fractured till exceeds its matrix permeability, and provided the basis for characterizing the hydrogeological properties of glacial tills. Comparable observations demonstrating a bulk hydraulic conductivity in shallow glacial till aquitards orders of magnitude greater than the matrix permeability were made at numerous other sites across Canada and other regions of Pleistocene-aged glacial tills [Cuthbert et al., 2010; Hendry, 1982; Rutland et al., 1991]

Despite the comparable hydrogeological properties of glacial till aquitards at various sites throughout the Northern Hemisphere, we are unaware of any studies that explore the regional characteristics and spatial variability of the hydraulic conductivity of glacial till aquitards on a scale of tens to hundreds of kilometers. To address this research gap, the objectives of this study are to (1) constrain regionally representative hydraulic conductivity estimates, and (2) to identify and characterize the dominant hydrogeological properties of Pleistocene-aged glacial till aquitards that are observed at a regional scale of tens to hundreds of kilometers. These objectives were achieved by compiling and analyzing hydraulic conductivity data obtained from tests conducted at different scales and collected from multiple sites across the Interior Plains region of Saskatchewan, Canada. A statistical evaluation of this data produced a regionally representative quantitative characterization of the central tendency and variability of the hydraulic conductivity of the glacial till aquitards. Aggregating and comparing hydraulic conductivity data obtained at different scales revealed the dominant hydrogeological processes at various depths.

The aggregated hydraulic conductivity data demonstrates that a regionally representative characterization of Pleistocene-aged glacial till aquitards is feasible. The results of this study will help lay the foundation for further work developing regionally relevant hydrogeological characterizations of Pleistocene-aged glacial till aquitards throughout the Northern Hemisphere. Characterizing these regional scale processes will do much to advance both local hydrogeological applications and the development of the land component of the Earth System Models that are critical to understanding and predicting global environmental change [Clark et al. 2015; Gleeson et al., 2011].

3.4 Pleistocene-aged glacial tills

Glacial till deposits can be found across the Northern Hemisphere where massive ice sheets repeatedly advanced and retreated throughout the Pleistocene Epoch. During the last global ice age, ending approximately 12,000 years before present, approximately 30% of the Earth’s surface was covered by glaciers (Figure 3.1) [Houmark-Nielsen, 2010; Kehew and Teller, 1994].

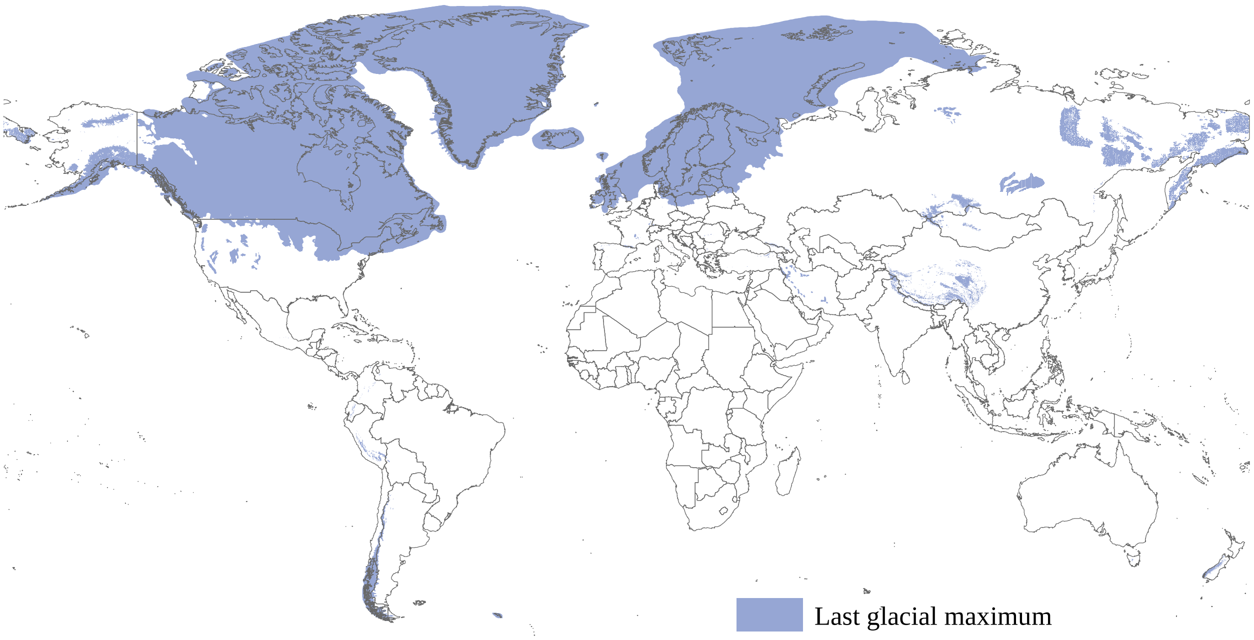


Figure 3.1 Global extent of ice cover during the last glacial maximum [layers from Ehlers et al., 2010]

The repeated cycles of glacial advance followed by glacial retreat and warmer interglacial periods resulted in heterogeneous deposits that often form complex hydrogeological systems composed of variable lithology with local beds of irregular geometry and variable lateral extent. These Pleistocene-aged glacial deposits form important hydrogeological systems in areas of the United Kingdom [Cuthbert et al., 2010; Hiscock and Tabatabai Najafi, 2011], Scandinavia and northern Europe [Kessler et al., 2012, Houmark-Nielsen, 2010], Canada [Christiansen, 1992; Hendry, 1982; Rutland et al., 1991], the United States [Allred, 2000; Trooien and Reichman, 1989], and many other countries. Despite the highly variable local conditions, Pleistocene-aged glacial tills share common characteristics, and research conducted in one region can be applicable at analog sites in other regions of glacial deposits [Cuthbert et al., 2010; Hiscock and Tabatabai Najafi, 2011; Kessler et al., 2012].

3.4.1 Study area – Interior Plains region of Saskatchewan

The Pleistocene-aged deposits of the Interior Plains region of south-central Saskatchewan vary in thickness from a few meters to over 300 m, and in some locations may be absent altogether (Figure 3.2).

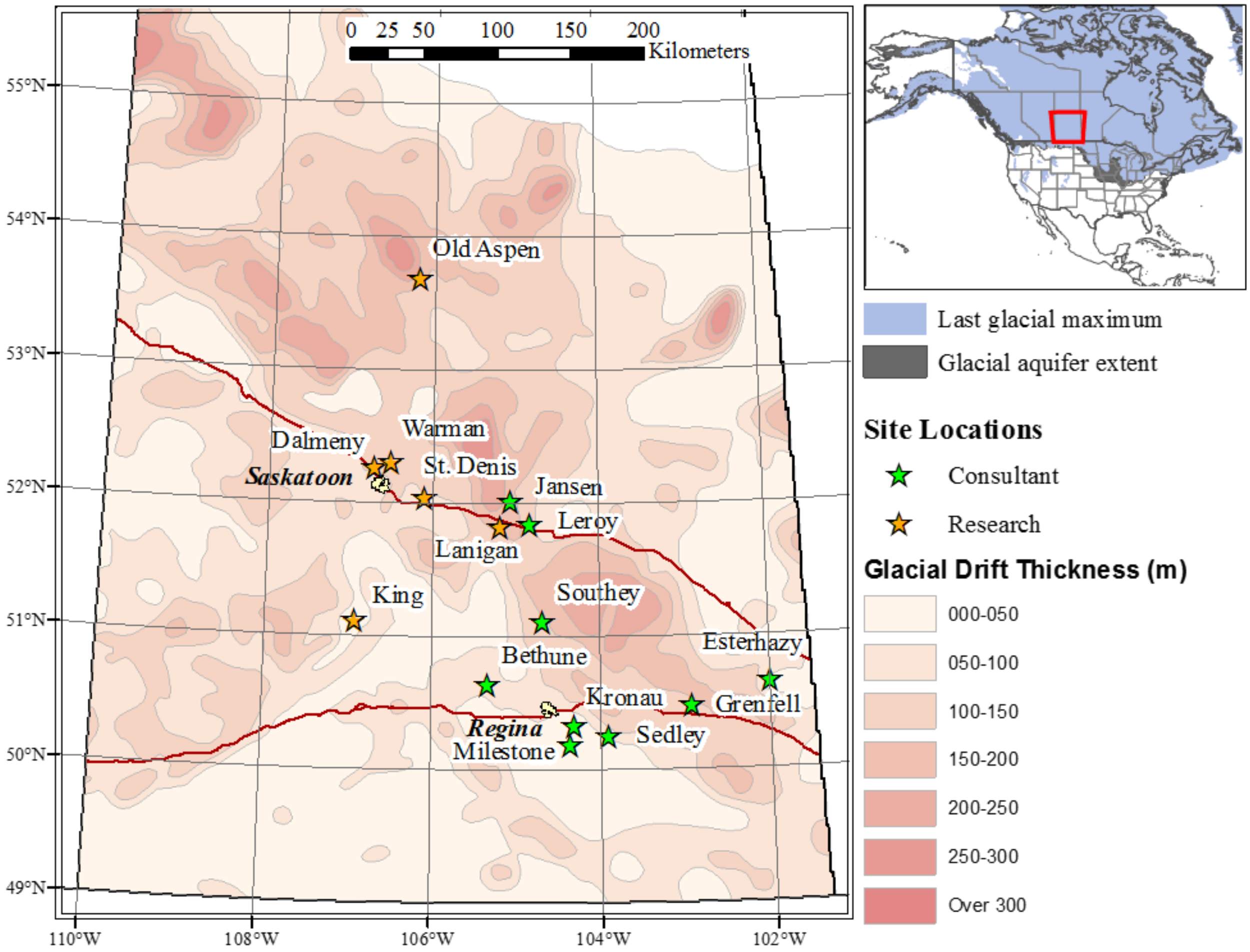
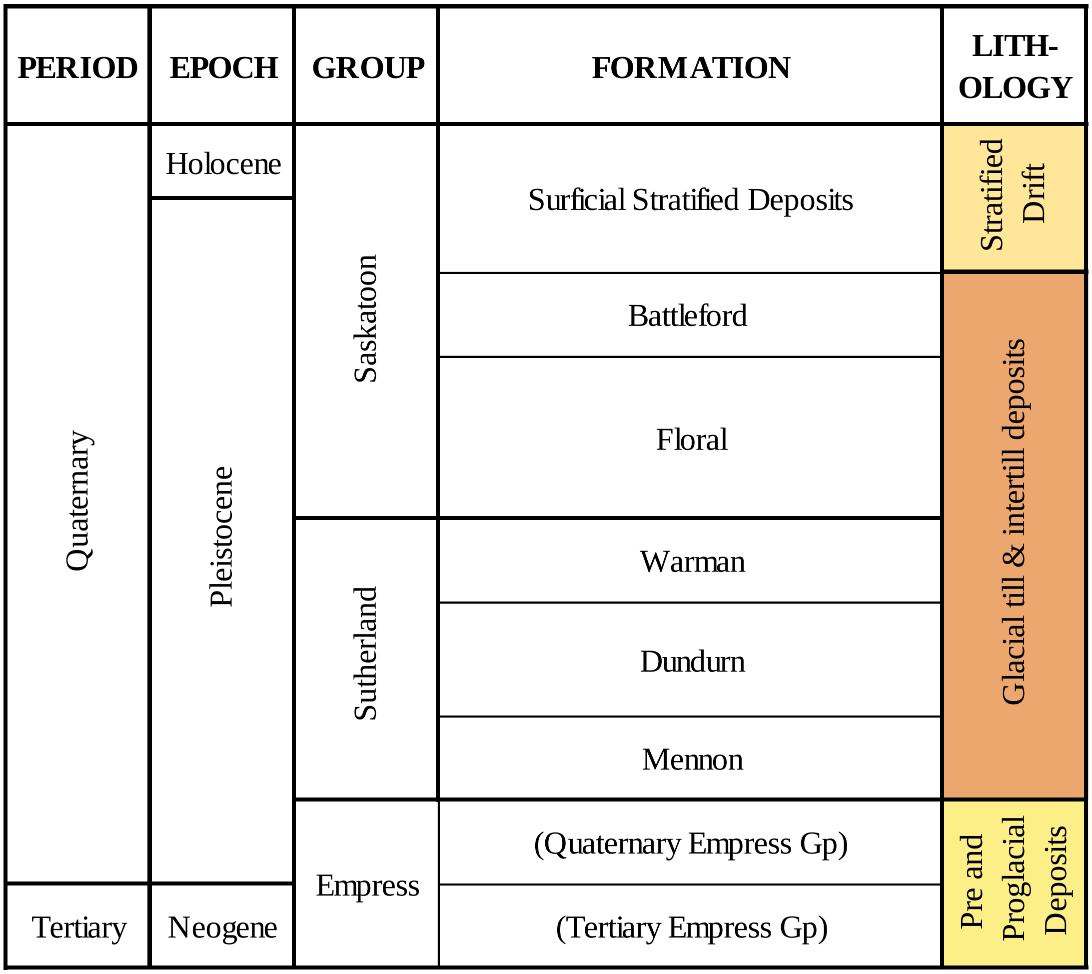


Figure 3.2 Location of sites included in the study [Layers from Ehlers et al., 2010; Mossop and Shetsen, 1994]

Pleistocene-aged sediments commonly overly bedrock of the Late Cretaceous or Tertiary Period in Saskatchewan. The Pleistocene-aged deposits in south-central Saskatchewan may consist of pro-glacial Empress Group sands and gravels, intermittently present as buried-valley fill [Cummings et al., 2012], and the Sutherland Group and Saskatoon Group glacial and interglacial deposits [Christiansen, 1968; 1992; Christiansen and Sauer, 1998] (Figure 3.3).



PERIOD	EPOCH	GROUP	FORMATION	LITH-OLOGY
Quaternary	Holocene	Saskatoon	Surficial Stratified Deposits	Stratified Drift
	Pleistocene		Battleford	Glacial till & intertill deposits
			Floral	
		Sutherland	Warman	
			Dundurn	
			Mennon	
		Empress	(Quaternary Empress Gp)	Pre and Proglacial Deposits
Tertiary	Neogene		(Tertiary Empress Gp)	

Figure 3.3 Simplified Quaternary Period stratigraphy of south-central Saskatchewan [after MDH Engineered Solutions Corp., 2010a]

The Sutherland Group is divided into the Mennon, Dundurn, and Warman Formations. The Saskatoon Group is divided into the Floral Formation, the Battleford Formation, and the Surficial Stratified Deposits. These formations contain glacial tills, intertill and intratill stratified deposits, and variable clay, silt, sand, gravel and coarser content [Christiansen and Sauer, 1998; MDH Engineered Solutions Corp., 2011]. The Sutherland and Saskatoon Groups in the south-central Saskatchewan region were deposited during at least eight periods of glacial advance and retreat, each separated by interglacial periods of varying durations [Christiansen, 1992; Christiansen and Sauer, 1998]. Each glacial advance resulted in erosional processes and subjected the existing deposits to high stress conditions [MDH Engineered Solutions Corp., 2011].

An important feature of the Pleistocene-aged deposits in Saskatchewan is the presence of oxidized (weathered) zones and fracturing. These oxidized zones are commonly several meters thick and extend most deeply along joints and fractures [Christiansen, 1992]. These zones are identified by colour changes associated with the oxidation of iron and manganese and the precipitation of iron oxides and gypsum crystals within fractures in the oxidized zone [Christiansen, 1992; Hendry, 1982; Rutland et al., 1991].

The presence of oxidized zones deeper within the tills indicate discontinuities in the stratigraphic succession [Christiansen, 1992], but it is the oxidized and fractured zone near the modern topographic surface that is of the most interest when characterizing the hydrogeological properties of glacial till aquitards. While fracturing is associated with weathering processes, the changes in stress and consolidation conditions due to repeated glacial advance and retreat may be a cause of fracturing in Pleistocene-aged deposits, therefore fractures that are not associated with weathering processes may be present in unoxidized tills below the present-day water table [Keller et al., 1986; Rutland et al., 1991].

3.5 Data compilation

Numerous local, site-scale studies investigating the hydrogeological properties of Pleistocene-aged glacial till aquitards have been conducted throughout the Interior Plains region of Saskatchewan. The hydraulic conductivity data associated with these studies had to be collected and synthesized into a database that could be sorted on the basis of relevant criteria before any meaningful analysis could be conducted.

3.5.1 Method of data collection

To develop a regional-scale characterization of the hydraulic conductivity of Pleistocene-aged glacial till aquitards, a database was developed from studies and site investigations across the south-central region of Saskatchewan (Figure 3.2). The development of the database began with a literature review of academic papers and dissertations and was expanded to include publicly available consultant reports and site assessments. With the relevant reports gathered, hydraulic conductivity data was selected for inclusion based on three criteria: 1) the test method must be credible and adequately described, 2) the data must be from an original test, 3) the data must be associated with a spatial location and a depth.

The selected hydraulic conductivity data was compiled in a spreadsheet, along with associated data including source, referencing metadata, and the type of test. Every effort was made to collect identifying information such as well or piezometer number, geographic spatial data, depth, stratigraphic unit, and lithological descriptions. Additional fields were created in the spreadsheet specific to each test type to provide the means to conduct additional analyses and as an indication of the reliability of the data.

The compiled data were reviewed for reliability, and the following test data were excluded from subsequent analysis:

- Tests conducted in aquifers
- Tests conducted in local sand lenses
- Tests conducted in surficial soils or disturbed samples
- Tests conducted in non-glacial till deposits
- Low reliability methodology
- Tests conducted outside of south-central Saskatchewan

In the case of repeat tests conducted on a single interval or sample, a single representative value was selected to avoid skewing the aggregate data.

3.5.2 Summary of hydraulic conductivity data

Following the methodology described above, data were collected from 15 sites across south-central Saskatchewan (Table 3.1). Data from reports detailing relevant hydrogeological investigations outside of south-central Saskatchewan were collected but were not included in the detailed analysis. Data from 21 reports were included in the analysis, including 9 publicly available consultant reports. In total, 606 data points were collected. After excluding non-glacial till or unreliable data (n=132), tests conducted outside of south-central Saskatchewan (n=47), and repeat tests (n=34), 393 data points remained.

Table 3.1 Site list and associated reports included in study

Site Name	Source	Report Type	Data
Bethune	Golder Associates 2010	Consultant	4
Dalmeny	Keller et al. 1986	Research	14
	Keller et al. 1988	Research	40
	Fortin et al. 1991	Research	1
Esterhazy	MDH Engineered Solutions Corp. 2010b	Consultant	2
Grenfell	SNC-Lavalin Inc. 2018a	Consultant	37
Jansen	MDH Engineered Solutions Corp. 2010c	Consultant	45
King	Barbour et al. 2012	Research	1
	Boldt-Leppin and Hendry 2003	Research	15
	Shaw 1997	Thesis	30
	Harrington et al. 2007	Research	28
Kronau	Golder Associates 2013a	Consultant	3
Lanigan	Boldt-Leppin and Hendry 2003	Research	12
	Kelln 2001	Thesis	49
Leroy	MDH Engineered Solutions Corp. 2009	Consultant	29
Milestone	Golder Associates 2013b	Consultant	3
Old Aspen	Anochikwa et al. 2012	Thesis	1
Sedley	SNC-Lavalin Inc. 2018b	Consultant	15
Southey	Golder Associates 2016	Consultant	1
St. Denis	Hayashi 1996	Thesis	20
Warman	Keller et al. 1988	Research	19
	Keller et al. 1989	Research	23
	Remenda et al. 1996	Research	1
15 Sites	21 Reports	Total data, n=	393

3.5.3 Hydraulic conductivity test groups

There are a variety of methods available for determining the hydraulic conductivity of low permeability clay-rich till aquitards. The methods associated with the hydraulic conductivity data collected for this study are categorized into three test groups, each of which capture hydrogeological processes on a different scale. These groups are lab tests, in-situ tests, and models (Table 3.2).

Table 3.2 Test groups by scale and method of tests included in study

Group	Test Method	Data
Lab	(1D) Oedometer	23
	(1D) Oedometer - falling head	16
	Triaxial	63
	Centrifuge	28
	Lab test data, n=	130
In-situ	Slug test - rising head	49
	Slug test - falling head	26
	Slug test - unidentified	150
	In-situ test data, n=	225
Model	Water balance	2
	Seasonal water level fluctuations	32
	Porewater pressure response	1
	Stable isotope profile	3
	Model data, n=	38

Lab tests

The lab tests are conducted on a scale of centimeters, as determined by the sample size. These small-scale tests are recognized as providing a measure of the matrix, or intergranular, permeability [Hendry, 1982; van der Kamp, 2001]. Lab tests for hydraulic conductivity are typically conducted by first preparing a sample of unremolded core. For example, the samples could be cut from Shelby tube cores that are trimmed to the dimensions required by the test apparatus.

The one-dimensional (1D) oedometer consolidation tests are used to determine hydraulic conductivity by relating the hydraulic conductivity, K, to the coefficient of volume change, m_v, and the coefficient of compressibility, c_v, at each stage of the consolidation test. The hydraulic conductivity is plotted against void ratio, and the hydraulic conductivity corresponding to the in-situ void ratio is then assigned to the sample. For the 1D oedometer-falling head consolidation tests, the apparatus and technique was modified to allow for the direct calculation of permeability after each stage of consolidation [Keller et al., 1989; Tavenas et al., 1983].

A triaxial apparatus can be used to conduct a constant head permeameter test. Pore fluid is passed through a confined sample under a controlled hydraulic gradient and the inflow and outflow rates are measured. The steady-state hydraulic conductivity for the sample can then be calculated from Darcy’s Law as described by ASTM D 5084-90 [ASTM, 1990; Shaw and Hendry, 1998].

A novel method of determining the hydraulic conductivity of lab samples is the use of a centrifuge apparatus. The hydraulic conductivity here is determined from the volume of the pore fluid that permeates through the sample, the rotation speed of the centrifuge, and the radial distance from the rotator to the top of the sample [Kelln, 2001].

In-situ tests

The in-situ tests included in this study are limited to variations of the slug test, or single-well response test. These tests are conducted on a scale of meters, as reflected by the radius of influence of the test response. The variations of slug tests include the rising and falling head methods, where a known volume of water is displaced in the well or piezometer, and the water level is recorded as it rises, or falls, to near-static conditions.

The slug tests were typically analyzed to determine the in-situ hydraulic conductivity by the methods described by Hvorslev [1951] or Cooper et al. [1967]. The method of analysis can result in varying hydraulic conductivity values [Keller et al., 1986]. Other in-situ testing and analyses methods suitable for low permeability clay-rich aquitards exist, but these were not used in data collected for this study.

Model data

Model data includes methods of determining hydraulic conductivity by observing hydrogeologic processes on a scale of tens to hundreds of meters. These methods include water balance – the inverse modelling of hydraulic conductivity by a constrained estimate of site-scale recharge processes [Fortin et al., 1991; Keller et al., 1986], the evaluation of the phase and amplitude of seasonal water level fluctuations [Boldt-Leppin and Hendry, 2003; Keller et al., 1989; Kelln, 2001], the analysis of porewater pressure response to loading [Anochikwa et al., 2012], and the inverse modelling of hydraulic conductivity by curve fitting stable isotope depth profiles [Barbour et al., 2012; Remenda et al., 1996; Shaw, 1997]. While these methods capture large-scale hydrogeologic process directly, a challenge of many of these methods is the need to make assumptions regarding transient geochemical, climatic, and hydraulic conditions over space and time.

The determination of hydraulic conductivity from any of the above tests or methods – lab, in-situ, or model – requires input values characterizing other aspects of glacial till aquitards. The accurate determination of storativity, S_s, which is an input parameter necessary for several of the methods described above, is particularly problematic. The storativity in most cases is estimated from lab tests and is recognized as not necessarily representing true in-situ conditions [Keller et al., 1989; van der Kamp, 2001].

3.6 Analysis of aggregate hydraulic conductivity data

The aggregate hydraulic conductivity data was analyzed by investigating the relationships between the hydraulic conductivity data and depth below ground level, and the hydraulic conductivity data and test group. The analysis of this data was conducted by both statistical and empirical means – novel methods of analysis and evaluation are described where relevant.

To assess the central tendency of the hydraulic conductivity data, the geometric mean, K_{geom}, was calculated as;

$$K_{geom} = \left(\prod_{i=1}^{n} K_i\right)^{1/n} \tag{3.1}$$

where K_i is the hydraulic conductivity data, and n is the number of data. The variability of the hydraulic conductivity data was evaluated as the standard deviation of the log-transformed hydraulic conductivity data, defined as;

$$\sigma_{-LogK} = \sqrt{\frac{\sum_{i=1}^{n}\{(-LogK_i)-(-LogK_{geom})\}^2}{n-1}} \tag{3.2}$$

where the standard deviation, σ_{-LogK}, is given in orders of magnitude.

3.6.1 Hydraulic conductivity results

The hydraulic conductivity data were sorted into test groups and plotted against depth in meters below ground level (mbgl) (Figure 3.4). There is an apparent trend of decreasing variability with depth, with a variability of up to five orders of magnitude in the shallow depths, decreasing to less than two orders of magnitude at lower depths.

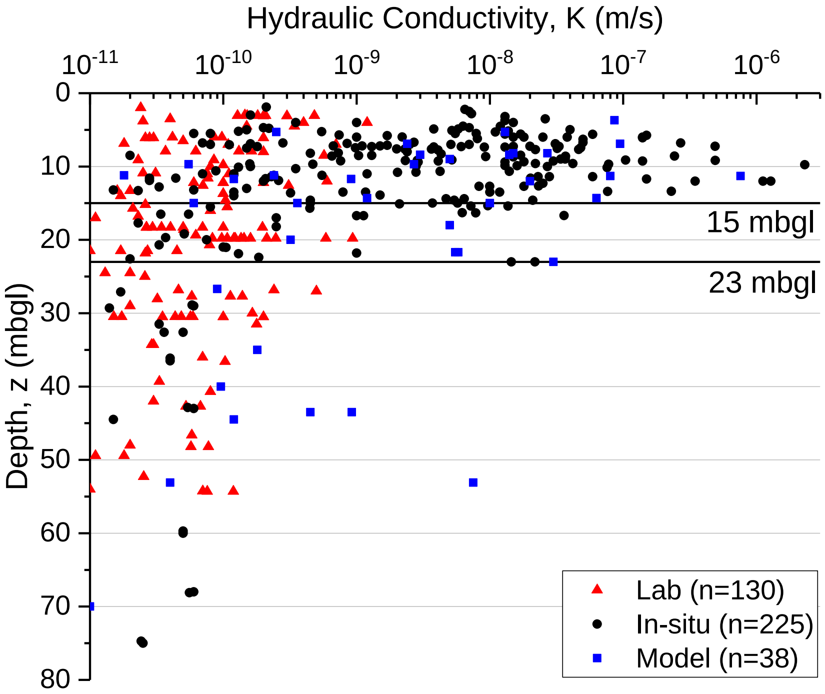


Figure 3.4 Aggregate hydraulic conductivity with depth, data classed by test group

The hydraulic conductivity data is shown again in Figure 3.5, plotted against test group as a box-and-whisker plot. The box shows the 1st, 2nd (median), and 3rd quartiles and the 10th and 90th percentiles are shown as whiskers.

The model data results in the greatest variability, with a geometric mean hydraulic conductivity of 1.8 x 10^{-9} m/s and a standard deviation of negative log-transformed hydraulic conductivity of 1.2 orders of magnitude. The in-situ test data is similar to the model data, with a geometric mean hydraulic conductivity of 2.0 x 10^{-9} m/s and a standard deviation of 1.2 orders of magnitude. The in-situ test data appears to reflect a bi-modal distribution, with two data clusters around approximately 10^{-10} m/s and 10^{-8} m/s. the lab test data is tightly distributed around the geometric mean hydraulic conductivity of 7.0 x 10^{-11} m/s, with a standard deviation of 0.5 orders of magnitude.

The difference between the aggregate lab test data and in-situ test data geometric mean hydraulic conductivity is approximately 1.5 orders of magnitude, which is consistent with the difference of between 1 to 3 orders of magnitude observed between lab and in-situ measured hydraulic conductivity for glacial tills commonly cited in literature [van der Kamp, 2001].

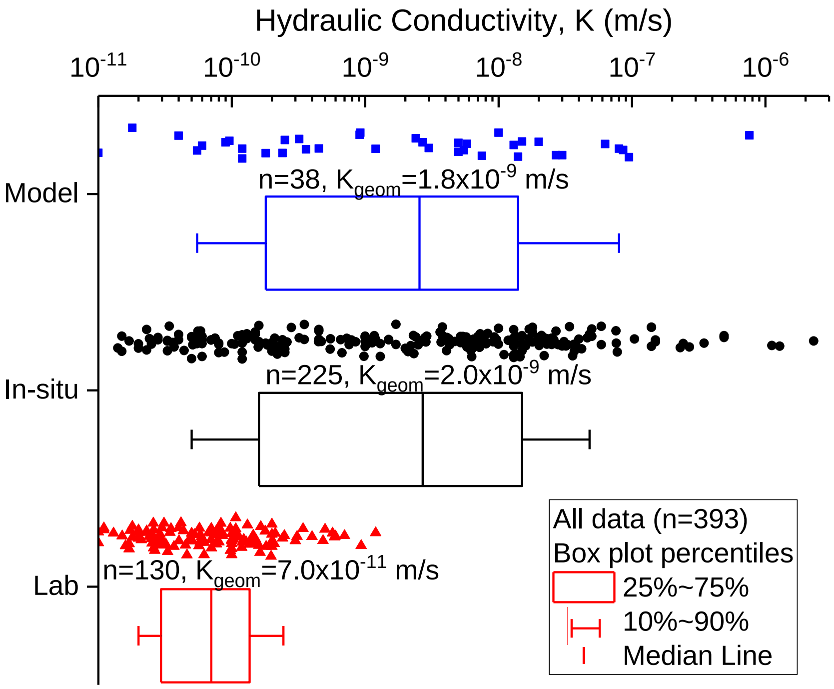


Figure 3.5 Box-and-whisker plot of test group hydraulic conductivity data

3.6.2 Depth-defined hydraulic conductivity intervals

To better constrain estimates of the central tendency and variability of the hydraulic conductivity of glacial tills in south-central Saskatchewan, the dataset was divided into three separate depth intervals using a novel method based on the Jenks natural breaks classification method [Jenks, 1967]. The depth intervals were defined by minimizing the variability within each depth class while maximizing the difference in geometric mean between the depth classes (Appendix A).

To minimize the variability within each depth class, the sum of the squared difference from the class mean (SDCM) of the negative log-transformed hydraulic conductivity data was calculated for depth interval combinations, as defined by depth to the nearest meter. The sum of the difference of the depth class means for depth interval combinations was also calculated. The selected depth-defined hydraulic conductivity intervals correspond to a local minimum sum of the SDCM and a local maximum difference of depth class mean. By this method, the first depth

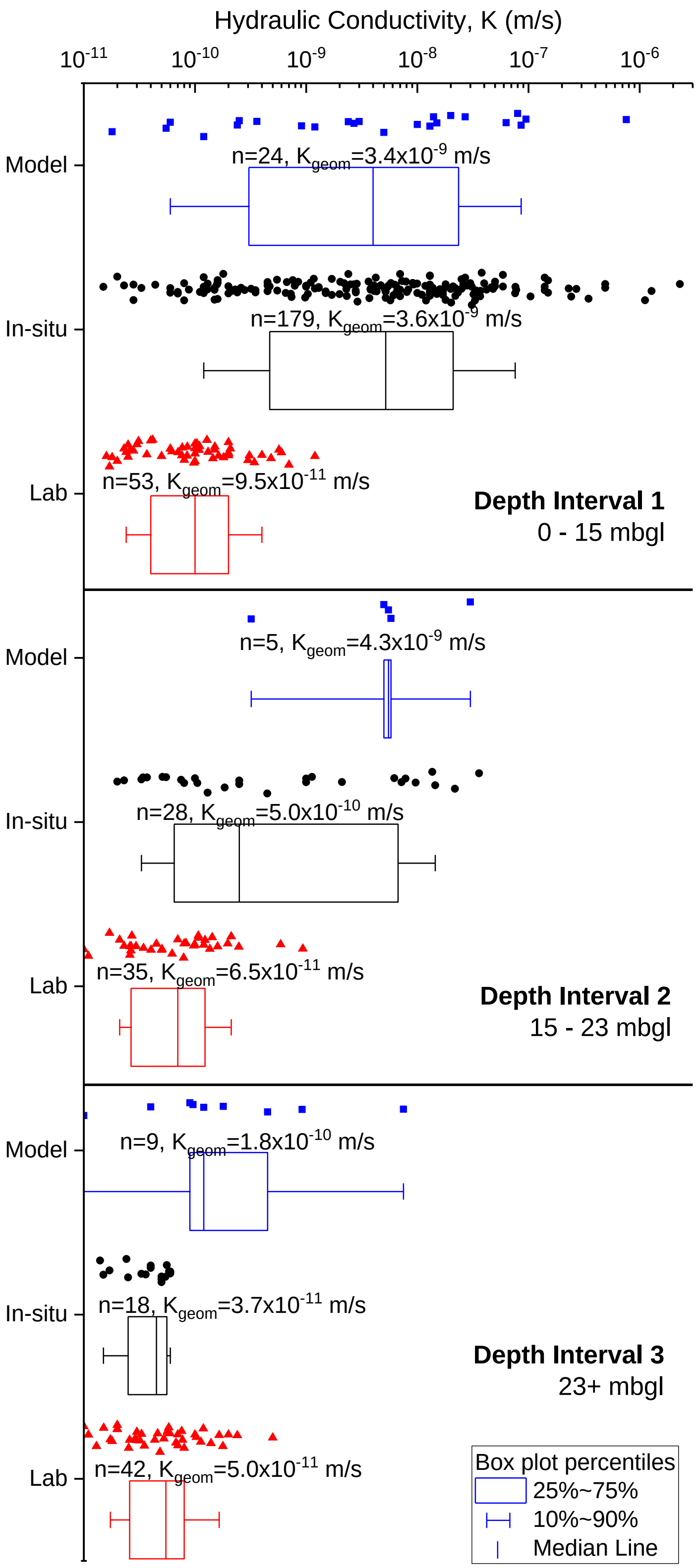


Figure 3.6 Box-and-whisker plot of test group hydraulic conductivity data, sorted by depth-defined intervals

interval was defined from 0 to 15 mbgl, the second interval from depths greater than 15 mbgl to 23 mbgl, and the third interval included all depths greater than 23 mbgl (Figure 3.6).

The hydraulic conductivity derived from model data exhibits some change in central tendency and variability with increasing depth, decreasing from the first depth interval geometric mean hydraulic conductivity of 3.4 x 10^{-9} m/s to a third depth interval geometric mean hydraulic conductivity of 1.8 x 10^{-10} m/s, with a corresponding decrease in standard deviation from 1.2 to 0.8 orders of magnitude with depth.

The in-situ test data revealed the most dramatic results, with a decrease of central tendency of 2 orders of magnitude from the first to the third depth interval, from a geometric mean hydraulic conductivity of 3.6 x 10^{-9} m/s to 3.7 x 10^{-11} m/s, with a corresponding decrease in standard deviation from 1.1 to 0.2 orders of magnitude.

In contrast with the model and in-situ test data, the lab test data exhibited only modest changes in central tendency and variability of hydraulic conductivity with increasing depth, decreasing from a geometric mean hydraulic conductivity of 9.5 x 10^{-11} m/s to 5.0 x 10^{-11} m/s, with a corresponding decrease in standard deviation from 0.5 to 0.4 orders of magnitude.

3.7 Interpretation and further evaluation of hydraulic conductivity data

The apparent relationships between hydraulic conductivity data, test scale, and depth provides insight into the issues of regional trends, representative elementary volume, fracture networks, and groundwater systems of Pleistocene-aged glacial till aquitards.

3.7.1 Regional trends

Notable among the results of this study is the consistency of both central tendency and variability of hydraulic conductivity at the different sites across the study area. The aggregate hydraulic conductivity data exhibits a total variability of 5 orders of magnitude, ranging from 10^{-11} m/s to 10^{-6} m/s. This variability is a characteristic of the site-scale data, with most sites exhibiting a variability of 3 to 4 orders of magnitude, rather than being a result of aggregating data from across south-central Saskatchewan.

Data collected from three sites separated by hundreds of kilometers – King, Jansen, and Grenfell – are shown in Figure 3.7. The variability of the hydraulic conductivity data at each of the sites is approximately 4 orders of magnitude, and the similarity of the central tendency and trend of decreasing hydraulic conductivity with depth at each of these sites is apparent. The data collected shows that the variability of hydraulic conductivity of glacial till aquitards in south-central Saskatchewan occurs on a scale of tens of meters, while the central tendency of the hydraulic conductivity of glacial till aquitards on a scale of hundreds of kilometers is notably consistent, with no regional drift detected.

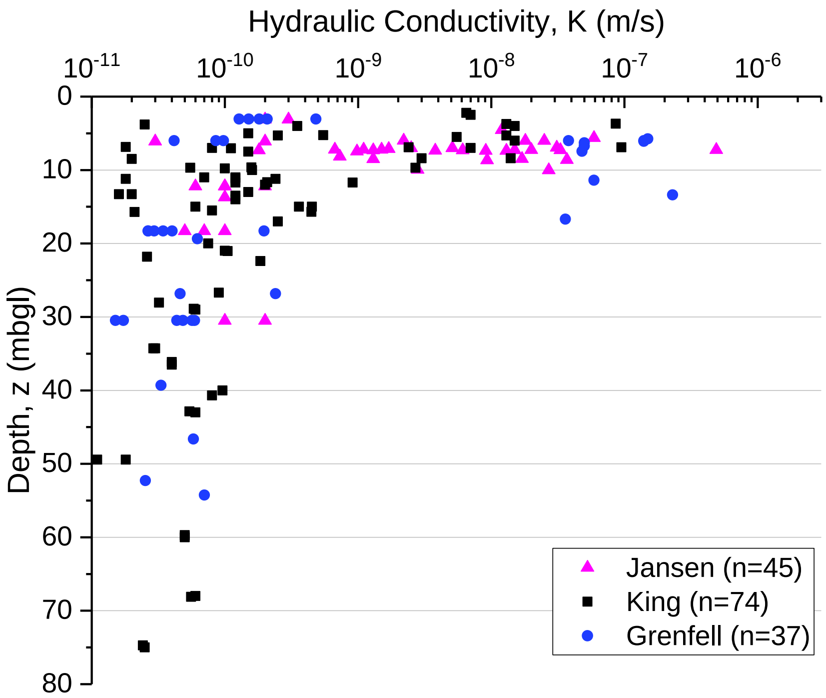


Figure 3.7 Hydraulic conductivity with depth, data classed by site: Jansen, King, and Warman

3.7.2 Representative elementary volume and test scale

The comparison of hydraulic conductivity values derived from tests conducted at different scales provides an indication of the magnitude of the scale dependence of hydraulic conductivity measurements and of the representative elementary volume (REV) for advective processes in glacial till aquitards.

The hydraulic conductivity data of lab tests, conducted on a scale of centimeters, are notably consistent across different depths, reflecting a decrease in geometric mean of only 0.3 orders of magnitude from samples collected at depths less than 15 mbgl to samples collected at depths greater than 23 mbgl. These results support the conclusion that lab tests provide an indication of the matrix permeability only and are not of a large enough scale to capture bulk hydraulic processes, especially at shallow depths.

For the first depth-defined hydraulic conductivity interval ($z < 15$ mbgl), a two-sample T-test was used to compare the model and in-situ test data demonstrating that the difference between the sample means is not significantly different from zero at a 0.05 level of significance (Appendix B). This similarity between the model data ($K_{geom} = 3.4 \times 10^{-9}$ m/s) and the in-situ test data ($K_{geom} = 3.6 \times 10^{-9}$ m/s) suggests that the in-situ tests are conducted at a scale large enough to capture the dominant hydraulic processes at shallow depths. This would indicate that the REV at depths less than 15 mbgl is on a scale of meters.

In the third depth interval ($z > 23$ mbgl), the lab test data ($K_{geom} = 5.0 \times 10^{-11}$ m/s) and the in-situ test data ($K_{geom} = 3.7 \times 10^{-11}$ m/s) are very similar, and the results of a two-sample T-test indicates that the difference between the sample means is not significantly different from zero at a 0.05 level of significance. The similarity between the lab test and in-situ test data at depth indicates that the meter scale in-situ tests are now representative of the matrix permeability only. The geometric mean hydraulic conductivity derived from model data at the third depth interval ($K_{geom} = 1.8 \times 10^{-10}$ m/s) is nearly an order of magnitude greater than the matrix hydraulic conductivity indicated by the lab and in-situ test data, which may suggest that the REV for some hydraulic processes in deep glacial till aquitards is on a scale of tens of meters.

3.7.3 Characterization of fracture networks

Fracture networks in clay and clayey glacial till aquitards have long been recognized as having a significant influence on hydraulic conductivity and contaminant transport behaviour [Allred, 2000; Cuthbert et al., 2010; D’Astous et al., 1989; Harrington et al., 2007; Hendry, 1982; van der Kamp, 2001]. Identifying the characteristic spacing and aperture of the fracture network can be important in determining and predicting the transport behaviour of contaminants [van der Kamp, 1992]. The data in this study may provide some information on such characteristic properties.

Recreating and expanding on the work of Keller et al. [1988], the in-situ test hydraulic conductivity data for the first depth interval was plotted against the length of the test interval (sandpack length, or if unavailable, the screen length) (Figure 3.8). As Keller et al. [1988] found, the hydraulic conductivity appeared to increase with increasing test interval length, indicating an increased likelihood of intercepting conductive features. A linear fit and regression analysis of the log-transformed data results in a Peason’s r of 0.42 and an R-squared of 0.18 with a P-value of 0.035 which supports the observed positive correlation and suggests that the length of the test interval has a measureable influence on the magnitude of the resulting hydraulic conductivity data (Appendix C). Similar results were found in glacial tills in Alberta, Canada, where longer in-situ sample interval consistently resulted elevated hydraulic conductivity results at depths less than 8 mbgl [Hendry, 1982]. In a fractured, clay-rich Pleistocene-aged till in Ontario, Canada, D'Astous et al. [1989] observed an increase of approximately 2 orders of magnitude from conventional in-situ piezometers by using large-diameter test wells (0.6 meter diameter).

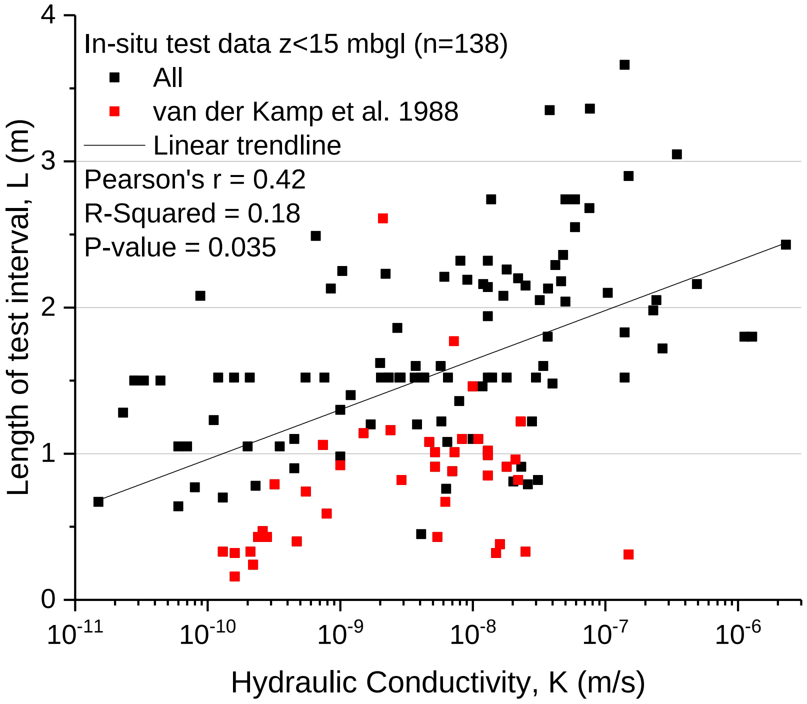


Figure 3.8 In-situ hydraulic conductivity and length of test interval (sand pack or screen length) for tests conducted at depths less than 15 mbgl [after Keller et al., 1988]

These results suggest that it may be possible to characterize the fracture spacing or aperture in fractured till using in-situ tests. If the matrix permeability is known, the bulk permeability from in-situ tests, in conjunction with the relationship between screen length and hydraulic conductivity could be empirically or statistically related to fracture spacing or aperture. Rutland et al. [1991] developed such a statistical relationship at the site scale, creating a chart of the probability of intersecting a fracture with depth for the St. Clair Plain in Ontario, Canada.

Allred [2000] likewise developed a theoretical relationship between fracture spacing and aperture, bulk hydraulic conductivity, and other geotechnical properties. Characterizing these fracture networks would have significant implications for modelling contaminant transport processes by providing guidance on the appropriateness of modelling the till aquitard as an equivalent porous media (EPM), or if a discreet fracture network or double-porous media model should be used.

3.7.4 Shallow, fracture-dominated active groundwater zone

The aggregated data presented in this study supports the existence of the shallow, fracture-dominated active groundwater zone in glacial till aquitards, and a deeper, unfractured zone as described by Rutland et al. [1991]. This is supported here by the dramatic decrease in mean hydraulic conductivity (2 orders of magnitude) and decrease in variability (from a standard deviation of 1.1 to 0.2 orders of magnitude) of the meter scale in-situ test data, and by the depth of observed seasonal water level fluctuations and isotopic evidence at other sites [D'Astous et al., 1989; Hendry, 1982; Keller et al., 1989; Rutland, 1991].

Identifying the base of this fractured-dominated active groundwater zone is critical when characterizing the hydraulic properties of a glacial till aquitard [Hendry, 1988]. The presence of visible fracturing and weathering has been associated with zones of elevated hydraulic conductivity [Hendry, 1982; Rutland et al., 1991]; however, the relationship between the hydraulically active, conductive fractures in this zone and oxidation and other weathering processes is not clearly established. As recognized by Keller et al. [1988; 1989] in Saskatchewan and by Rutland et al. [1991] in Ontario, Canada, the base of the fractured-dominated active groundwater zone frequently extends beyond the base of the oxidized zone and the depth of visible fractures.

In this study, the shallow tills exhibiting elevated hydraulic conductivity were often oxidized, but the qualitative descriptions of the samples were not consistent enough to allow for a definitive conclusion to be drawn regarding the relationship between oxidation and elevated hydraulic conductivity. Seasonal water level fluctuations, isotopic evidence, and enhanced permeability may provide a better indication as to the base of this active groundwater zone. Understanding this fracture-dominated zone and the mechanisms associated with it would have implications for important issues such as irrigation and surface drainage, aquifer recharge, contaminant transport, groundwater management, and mitigation planning.

3.7.5 Assigning hydraulic conductivity to glacial tills

Although the stratigraphic unit has been the principal means of assigning hydraulic conductivity to glacial tills in Saskatchewan, this study suggests that depth may be a more meaningful indicator of hydraulic conductivity on a regional scale, particularly where a statistical characterization of the central tendency and variability of the hydraulic conductivity is useful. This study did not investigate the relationship between matrix or bulk hydraulic conductivity and hydrostratigraphic unit. Although not all the data collected for this study was associated with a reliable stratigraphic interpretation, preliminary analysis did not indicate a meaningful correlation between hydraulic conductivity and stratigraphic unit at the regional scale. The data collected in this study indicates that hydraulic conductivity has a strong relationship with depth in glacial tills throughout south-central Saskatchewan. However, the extreme local variability (up to 4 orders of magnitude) consistently observed over tens of meters at the site scale emphasizes the importance of collecting site-specific hydraulic conductivity data where appropriate.

The scale-dependence of the tests used to characterize the hydraulic conductivity of glacial tills suggests that the in-situ tests result are the most representative hydraulic conductivity data for tills at site and regional scale applications, including drainage or recharge estimates, contaminant transport modelling, and groundwater vulnerability assessments. The extreme variability of the in-situ test data, especially within the shallow, fracture-dominated zone, makes multiple tests necessary in order to accurately characterize the bulk hydraulic conductivity at the scale of interest. The information provided by the centimeter scale lab tests, typically indicating matrix permeability, is valuable, especially when compared to in-situ data to indicate the presence of zones of elevated hydraulic conductivity. Data derived from larger scale models, such as observed seasonal water level fluctuation or stable isotope profiles, may likewise be valuable by providing an independent method of characterizing hydraulic conductivity and by indicating the presence of any hydraulic features not captured at the centimeter or meter scale.

3.8 Conclusion

Pleistocene-aged glacial deposits form important hydrogeological systems in many regions around the world, controlling recharge and protecting the fresh groundwater resources relied upon by domestic, agricultural, and industrial users, and forming an important element of the hydrosphere. Understanding the hydrogeological properties of these systems on a site scale and on a regional scale of tens to hundreds of kilometers is essential. This study, based on the collection of data from 15 sites across south-central Saskatchewan, was conducted to constrain representative hydraulic conductivity estimates and to identify and characterize the dominant hydrogeological properties of Pleistocene-aged glacial till aquitards that are observed over a regional scale of tens to hundreds of kilometers.

The aggregate data reveals a clear and consistent relationship between hydraulic conductivity and depth that was observed at all sites included in the study, regardless of spatial location or stratigraphic unit. While the aggregated hydraulic conductivity data varied by 5 orders of magnitude, much of this observed variability occurred at the site scale of tens of meters, while the central tendency and pattern of variability was remarkably consistent at a regional scale of tens to hundreds of kilometers. These results indicate that depth-defined hydraulic conductivity estimates can be meaningful at a regional scale, although site-specific studies are still valuable to the assessment of hydraulic conductivity at a local scale.
Sorting hydraulic conductivity data by test scale provided insight into the REV of the hydraulic processes in Pleistocene-aged glacial till aquitards and may provide further insight into the properties of conductive fracture networks. The evidence of a shallow, fracture-dominated active groundwater zone and a deep, unfractured zone characterized by matrix permeability is consistent with site-scale studies in Saskatchewan and with studies of Pleistocene-aged glacial till aquitards in other regions.

3.9 References

Allred, BJ. 2000. Survey of Fractured Glacial Till Geotechnical Characteristics: Hydraulic Conductivity, Consolidation, and Shear Strength. Ohio J. Sci. 100(3/4):63–72.

American Society for Testing and Materials (ASTM). 1990. ASTM D 5084-90. Standard test method for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. Philadelphia, Pa.

Anochikwa CI, van der Kamp G, Barbour SL. 2012. Interpreting porewater pressure changes induced by water table fluctuations and mechanical loading due to soil moisture changes. Can. Geotech. J. 49:357–366. doi: 10.1139/T11-106.

Barbour SL, Hendry MJ, Wassenaar LI. 2012. In situ experiment to determine advective-diffusive controls on solute transport in a clay-rich aquitard. J. Contam. Hydrol. 131:79–88. doi: 10.1016/j.jconhyd.2011.12.002.

Boldt-Leppin BEJ, Jim Hendry M. 2003. Application of Harmonic Analysis of Water Levels to Determine Vertical Hydraulic Conductivities in Clay-Rich Aquitards. Ground Water 41:514–522. doi:10.1111/j.1745-6584.2003.tb02385.x.

Christiansen EA. 1992. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada: an update. Can. J. Earth Sci. 29:1767–1778. doi:10.1139/e92-139.

Christiansen EA. 1968. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada. Can. J. Earth Sci. 5:1167–1173. doi:10.1139/e68-114.

Christiansen EA, Sauer EK. 1998. Geotechnique of Saskatoon and Surrounding Area, Saskatchewan, Canada. In: Karrow PF, White EO, editors. Urban Geology of Canadian Cities. Special Pa. Geological Association of Canada. 42:117–145.

Clark MP, Fan Y, Lawrence DM, Adam JC, Bolster D, Gochis DJ, … Zeng X. 2015. Improving the representation of hydrologic processes in Earth System Models. Water Resour. Res. 51:5929-2956. doi:10.1002/2015WR017096

Cooper HH, Bredehoeft JD, Papadopoulos IS. 1967. Response of a finite-diameter well to an instantaneous charge of water. Water Resour. Res. 3:263–269.

Cummings DI, Russell HAJ, Sharpe DR. 2012. Buried-valley aquifers in the Canadian Prairies: geology, hydrogeology, and origin1Earth Science Sector (ESS) Contribution 20120131. Can. J. Earth Sci. 49:987–1004. doi:10.1139/e2012-041.

Cuthbert MO, Mackay R, Tellam JH, Thatcher KE. 2010. Combining unsaturated and saturated hydraulic observations to understand and estimate groundwater recharge through glacial till. J. Hydrol. 391:263–276. doi:10.1016/j.jhydrol.2010.07.025.

D’Astous AY, Ruland WW, Bruce JRG, Cherry JA, Gillham RW. 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia-area clay. Can. Geotech. J. 26:43–56. doi:10.1139/t89-005.

Ehlers J, Gibbard PL, Hughes PD. 2010. Quaternary glaciations - extent and chronology. Digital maps. Elsevier. [accessed 2019 Jan 8]. https://booksite.elsevier.com/9780444534477/digital_maps.php.

Fan Y. 2015. Groundwater in the Earth’s critical zone: Relevance to large-scale patterns and processes. Water Resour. Res. 51(5):3052–3069. doi:10.1002/2015WR017037

Ferris DM, Ferguson GAG, Potter G. 2019. Aggregate hydraulic conductivity data from site investigations in south-central Saskatchewan, Canada [Dataset]. Federated Research Data Repository. doi:10.20383/101.0140.

Fortin G, van der Kamp G, Cherry JA. 1991. Hydrogeology and hydrochemistry of an aquifer-aquitard system within glacial deposits, Saskatchewan, Canada. J. Hydrol. 126:265–292. doi:10.1016/0022-1694(91)90160-J.

Gleeson T, Smith L, Moosdorf N, Hartmann J, Dürr HH, Manning AH, … Jellinek AM. 2011. Mapping permeability over the surface of the Earth. Geophys. Res. Lett. 38(2):1-6. doi:10.1029/2010GL045565

Golder Associates. 2010. Potash One - The Legacy Project - Environmental Impact Statement. Saskatoon, SK.

Golder Associates. 2013a. Vale Kronau Project - Environmental Impact Statement. Regina, SK.

Golder Associates. 2013b. Milestone Potash Project - Environmental Impact Statement. Regina, SK.

Golder Associates. 2016. Yancoal Southey Project - Environmental Impact Statement. Saskatoon, SK.

Grisak GE, Cherry JA. 1975. Hydrologic Characteristics and Response of Fractured Till and Clay Confining a Shallow Aquifer. Can. Geotech. J. 12:23–43. doi:10.1139/t75-003.

Harrington GA, Hendry MJ, Robinson NI. 2007. Impact of permeable conduits on solute transport in aquitards: Mathematical models and their application. Water Resour. Res. 43:1-16, W05441. doi:10.1029/2005WR004144.

Hayashi M. 1996. Surface-subsurface transport cycle of chloride induced by wetland-focussed groundwater recharge. University of Waterloo, Ontario, Canada.

Hendry MJ. 1982. Hydraulic Conductivity of a Glacial Till in Alberta. Ground Water 20:162–169. doi:10.1111/j.1745-6584.1982.tb02744.x.

Hendry MJ. 1988. Hydrogeology of Clay Till in a Prairie Region of Canada. Ground Water 26:607–614. doi:10.1111/j.1745-6584.1988.tb00794.x.

Hiscock KM, Tabatabai Najafi M. 2011. Aquitard characteristics of clay-rich till deposits in East Anglia, Eastern England. J. Hydrol., 405(3):288–306. doi:10.1016/j.jhydrol.2011.05.025.

Houmark-Nielsen M. 2010. Extent, age and dynamics of Marine Isotope Stage 3 glaciations in the southwestern Baltic Basin. Boreas 39:343–359. doi:10.1111/j.1502-3885.2009.00136.x.

Hvorslev MJ. 1951. Time-lag and soil permeability in groundwater observations; Bulletin No.36. Vicksburg, Mississippi.

Jenks GF. 1967. The data model concept in statistical mapping. Int. Yearb. Cartogr. 7:186–190.

Jorgensen P, Hoffmann M, Kistrup JP, Bryde C, Bossi R, Villholth K. 2002. Preferential flow and pesticide transport in a clay-rich till: Field, laboratory, and modeling analysis. Water Resour. Res. 38:1246-1264. doi:10.1029/2001WR000494.

Kehew AE, Teller JT. 1994. History of late glacial runoff along the southwestern margin of the Laurentide Ice Sheet. Quat. Sci. Rev. 13:859–877. doi:10.1016/0277-3791(94)90006-X.

Keller CK, van der Kamp G, Cherry JA. 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. Can. Geotech. J. 23:229–240. doi:10.1139/t86-032.

Keller CK, van der Kamp G, Cherry JA. 1988. Hydrogeology of two Saskatchewan tills. I. Fractures, bulk permeability, and spatial variability of downward flow. J. Hydrol. 101:97–121. doi:10.1016/0022-1694(88)90030-3.

Keller CK, van der Kamp G, Cherry JA. 1989. A multiscale study of the permeability of a thick clayey till. Water Resour. Res. 25:2299–2317. doi:10.1029/WR025i011p02299.

Kelln CJ. 2001. Determination of detailed stable isotope profiles and hydrogeological conditions in a complex clay-rich aquitard, Saskatchewan, Canada. University of Saskatchewan, Saskatoon, Canada.

Kessler TC, Klint KES, Nilsson B, Bjerg PL. 2012. Characterization of sand lensed embedded in tills. Quat. Sci. Rev. 53:55–71. doi:10.1016/j.quascirev.2012.08.011.

MDH Engineered Solutions Corp. 2009. Regional and Detailed Hydrogeology of the Burr Project. Submitted as part of Burr Potash Project - Environmental Impact Statement. Saskatoon, SK.

MDH Engineered Solutions Corp. 2010a. Procedures for Regional Hydrogeological Mapping, M1890-1030109. Saskatoon, SK.

MDH Engineered Solutions Corp. 2010b. Mosaic Potash Esterhazy Stage 2 Expansion Project - Environmental Impact Statement. Saskatoon, SK.

MDH Engineered Solutions Corp. 2010c. Detailed Geotechnical and Hydrogeological Investigation for Jansen Project Tailings Management Area. Submitted as Annex 6-15 of Jansen Project Environmental Impact Statement. Saskatoon, SK.

MDH Engineered Solutions Corp. 2011. Hydrogeology Mapping of NTS Mapsheet Saskatoon 073B, M1890-1030109. Saskatoon, SK.

Mossop GD, Shetsen I, comp. 1994. Geological atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council.

Remenda VH, van der Kamp G, Cherry JA. 1996. Use of vertical profiles of δ18O to constrain estimates of hydraulic conductivity in a thick, unfractured aquitard. Water Resour. Res. 32:2979–2987. doi:10.1029/96WR01778.

Rutland WW, Cherry JA, Stan F. 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario. Ground Water 29:405–417. doi:10.1111/j.1745-6584.1991.tb00531.x.

Shaw RJ, Hendry MJ. 1998. Hydrogeology of a thick clay till and Cretaceous clay sequence, Saskatchewan, Canada. Can. Geotech. J. 35:1041–1052. doi:10.1139/t98-060.

Shaw RJ. 1997. Hydrogeology of a thick clay-rich till and Cretaceous bedrock clay sequence in Saskatchewan, Canada. University of Saskatchewan.

Sidle RC, Nilsson B, Hansen M, Fredericia J. 1998. Spatially varying hydraulic and solute transport characteristics of a fractured till determined by field trace tests, Funen, Denmark. Water Resour. Res. 34:2515–2527. doi:10.1029/98WR01735.

SNC-Lavalin Inc. 2018a. Hydrogeological Drilling, Instrumentation, and Testing Submitted as part of the Broadview Project – Environmental Impact Statement. Saskatoon, SK.

SNC-Lavalin Inc. 2018b. Hydrogeological Drilling, Instrumentation, and Testing. Submitted as part of the Project Albany – Environmental Impact Statement. Saskatoon, SK.

Tavenas F, Leblond P, Jean P, Leroueil S. 1983. The permeability of natural soft clays. Part I: Methods of laboratory measurement. Can. Geotech. J. 20:629–644. doi:10.1139/t83-072.

Trooien TP, Reichman GA. 1989. Hydraulic conductivity of till subsoil in North Dakota. International Winter Meeting - American Society of Agricultural Engineers. St. Joseph, MI: American Society of Agricultural Engineers. 333(5):1492-1496. doi: 10.13031/2013.31499

van der Kamp G. 1992. Evaluating the effects of fractures on solute transport through fractured clayey aquitards. In: 1992 Conference of the International Association of Hydrogeologists - Canadian National Chapter. Hamilton, Ontario. 468–476.

van der Kamp G. 2001. Methods for determining the in situ hydraulic conductivity of shallow aquitards - an overview. Hydrogeol. J. 9:5–16. doi:10.1007/s1004000001

4. Incorporating uncertainty into groundwater vulnerability assessments – A modified AVI method and case study of NTS map area 073B (Saskatoon)

4.1 Preface

The following manuscript chapter presents the culmination of my M.Sc. research program – the development of a method for incorporating and representing the uncertainty associated with the variability of input parameters into groundwater vulnerability assessments. This chapter draws on elements from Chapter 2, where the context and conceptual basis for this chapter was established, and on the characterization of hydrogeological properties and hydraulic conductivity of glacial tills aquitards which was presented in Chapter 3.

As an independent manuscript, this chapter represents a substantive contribution to the field of groundwater vulnerability assessments by investigating the representation of uncertainty and probability in deterministic, index-based calculations and provides insight into the parameter sensitivity of the process-based Aquifer Vulnerability Index method.

My role in this research and in preparing this manuscript was that of sole researcher and author. Dr. Grant Ferguson and Dr. Chris Hawkes provided valuable review and feedback throughout the conceptual development of this research project, and Dr. Grant Ferguson also provided valuable feedback during the late stages of the manuscript preparation. This manuscript has not been submitted as a candidate for peer review and publication. Dr. Ferguson and I may elect to further develop this manuscript concept for publication as a substantially revised manuscript in the future.

4.2 Abstract

The challenge of managing and protecting groundwater resources requires decision support tools that accurately present system complexity and the range of probable outcomes associated with different alternatives. However, the groundwater vulnerability assessments that policy makers rely on for decision support are often based on deterministic point estimates derived from averaged input parameters and do not provide any indication of the uncertainty or variation of the value. To incorporate the uncertainty resulting from the natural variability of input parameters into groundwater vulnerability assessments, we develop and demonstrate a modified Aquifer Vulnerability Index (AVI) method based on a statistically derived, depth-defined characterization of the hydraulic conductivity of Pleistocene-aged glacial till aquitards. This modified AVI method was used to produce three sets of depth-defined AVI groundwater vulnerability indices based on the range of probable hydraulic conductivity conditions, allowing for the pseudo-quantitative assessment of the uncertainty inherent in the deterministic groundwater vulnerability assessment. A final depth-defined AVI vulnerability map with an overlay indicating areas of elevated uncertainty was then produced. The results of the modified, depth-defined AVI method are compared with a classic AVI assessment, demonstrating the validity of the modified method in the study area and the impact of geological controls over groundwater vulnerability assessment results. This research demonstrates a methodology that can be used to incorporate uncertainty into deterministic, index-based vulnerability assessments and intuitively and effectively communicate the uncertainty to the end user of groundwater vulnerability assessments. The methods presented here are not limited to the AVI groundwater vulnerability assessment method, but can be applied to any deterministic vulnerability assessment method where a statistical characterization of the input parameters is possible, producing a pseudo-quantitative representation of the uncertainty associated with the natural variation of the input parameters.

4.3 Introduction

As demand for fresh water resources increases and changing climate and global water distributions stress already limited fresh groundwater reserves, the need for effective groundwater management and protection policy will increase. The challenge of protecting and managing groundwater resources is what is referred to as a “wicked problem” – a problem that is the result of complex interdependencies, difficult to define, unique, and that does not have solutions that are right/wrong, but better/worse [Patterson et al., 2013; Uusitalo et al., 2015]. Finding solutions to these wicked problems and developing consistent and defensible groundwater policy requires effective decision support tools that accurately communicate the system complexity and the range and probabilities of possible outcomes resulting from management decisions [Freeze et al., 1990; Uusitalo et al. 2015].

Groundwater vulnerability assessments and the associated vulnerability maps, which indicate a groundwater resource's relative susceptibility to contamination introduced at the land surface, are among the decision support tools available to guide land-use and groundwater management and protection policy. The adaptability of groundwater vulnerability assessments and the easy to understand, visual presentation of groundwater vulnerability maps makes these ideal decision support tools when applied and interpreted appropriately. However, most groundwater vulnerability assessments rely on deterministic, point estimates based averaged input parameters which are subjective or are subject to a high degree of uncertainty, and result in a single output value without any indication of the uncertainty or variation around this value. Except for statistical methods for assessing groundwater vulnerability, which are limited in application since these methods require a thorough quantification of known contamination incidents in the area of interest, conventional groundwater vulnerability assessments do not incorporate uncertainty directly.

Uncertainty defined in the simplest terms is a lack of exact knowledge [Uusitalo et al., 2015], and is present in all stages of the groundwater vulnerability assessment process. In groundwater vulnerability assessments uncertainty arises from the quality, distribution, and natural variation of the input data; the abstraction of the method of assessment; the discretization, interpolation, and generation of the vulnerability map; and the method and language of presenting the vulnerability assessment. To quantify and represent uncertainty, it can be helpful to identify several classes defined by the origin and nature of the uncertainty; aleatory uncertainty is associated with inherent randomness, epistemic uncertainty results from imperfect knowledge, and linguistic uncertainty is the result of the ambiguity and imprecision of language [Uusitalo et al., 2015].

Recent work has focused on the epistemic uncertainty associated with the interpolation of point groundwater vulnerability data through the application of common statistical methods such as indicator kriging, stochastic methods, multiple linear regression, and Monte Carlo simulation [Cooper et al., 2015; Llopis-Albert et al., 2014; Li et al., 2017], while Bojorquez-Tapia et al. [2009] have combined groundwater vulnerability mapping processes with the psychophysics' principle describing decision makers' perception of vulnerability classes to reduce the linguistic uncertainty inherent in index-based groundwater vulnerability assessments. Armengol et al. [2014] have introduced a method to separately analyze and represent the uncertainty associated with each of the input parameters depending on the type, quality, and quantity of the available data using a decision tree process. While offering innovative and valuable methods to quantify and represent the uncertainty associated with groundwater vulnerability assessments, these processes introduce significant computational complexity to the assessment process and lack broad applicability to other vulnerability assessment methods and hydrogeological conditions. In addition to these developments, there is a need and an opportunity for simple, intuitive, and adaptable methods of incorporating and representing uncertainty in groundwater vulnerability assessments.

The Aquifer Vulnerability Index (AVI) method was selected to examine a methodology for incorporating and representing the uncertainty associated with the natural variation of input parameters in groundwater vulnerability assessments. The AVI method is a deterministic groundwater vulnerability assessment method that assigns a vulnerability index based the hydraulic conductivity and thickness of the protective units overlying the aquifer of interest [Van Stempvoort et al., 1992]. However, the hydraulic conductivity, commonly assigned by hydrostratigraphic unit, can range by several orders of magnitude, and introduces considerable uncertainty in AVI results – an uncertainty which is not incorporated or represented in the resulting AVI groundwater vulnerability assessment. The deterministic, process-based AVI calculation, the minimal number of input parameters, and the natural variability of the primary input parameter makes the AVI method ideal for a study investigating the incorporation of uncertainty into groundwater vulnerability assessments.

In order to define and develop methodology for quantifying and presenting uncertainty in groundwater vulnerability assessments, our objective is 1) to develop and demonstrate a methodology for conducting a modified AVI assessment incorporating the uncertainty associated with the natural variability of the input data, and 2) to develop and demonstrate a methodology for displaying the results of the modified AVI assessment and the uncertainty associated with the assessment by means of a groundwater vulnerability map.

To achieve these objectives, a modified AVI method was developed based on statistically derived, depth-defined hydraulic conductivity distributions and demonstrated this method by a groundwater vulnerability assessment and comparative analysis. In the following paper, we consider the geological and hydrogeological factors influencing groundwater resource occurrence and vulnerability in the study area, and we review existing groundwater vulnerability mapping efforts in the region. The methodology for a classic AVI assessment as well as the modified, depth-defined AVI assessment is presented, facilitating a comparative analysis of the classic and modified groundwater vulnerability assessment methods.

Accommodating uncertainty in groundwater vulnerability assessments can facilitate a more effective interpretation of parametric and index-based groundwater vulnerability maps, particularly when assessing groundwater vulnerability in data-sparse regions. Incorporating this uncertainty represents a step towards developing and improving the decision support tools that are required to address the wicked problems associated with sustainable development in a world facing unprecedented environmental challenges.

4.4 Study area

The National Topographic System (NTS) map area 073B (Saskatoon) was chosen to develop and demonstrate a method for incorporating uncertainty into groundwater vulnerability assessments. This area was selected as it is representative of the topography, geology, and hydrogeology of the Interior Plains region of North America and the groundwater resources in this area are relatively well defined through publicly available academic and government hydrogeological investigations [Christiansen 1992; Christiansen and Sauer 1998; Keller et al., 1986; Keller et al., 1988; MDH Engineered Solutions Corp., 2011]. NTS map area 073B encompasses approximately 15,000 km^2 of the Interior Plains region of North America, and is located in Saskatchewan, Canada between 52° N to 53° N latitude and 106° W to 108° W longitude (Figure 4.1).

The topography is characteristic of the mostly flat-lying Interior Plains region, with elevations ranging from a low of 430 meters above sea level (masl) to a local high of 756 masl, and a general trend of gently decreasing elevation to the east and north [Mossop and Shetsen, 1994]. The regional topography is influenced by the erosion of the ancient Tyner and Battleford River valleys into the Upper Cretaceous Series shale, siltstone, and sandstone deposits during the late Cretaceous and Early Tertiary Period [Cummings et al., 2012]. Salt collapse structures, associated with the dissolution of Prairie Evaporite Formation, and Quaternary Period proglacial and glacial processes have further influenced the topographic and geological structure in the area, while fluvial and aeolian erosional processes continue to shape the local landscape [Christiansen, 1992; Christiansen and Schmid, 2005].

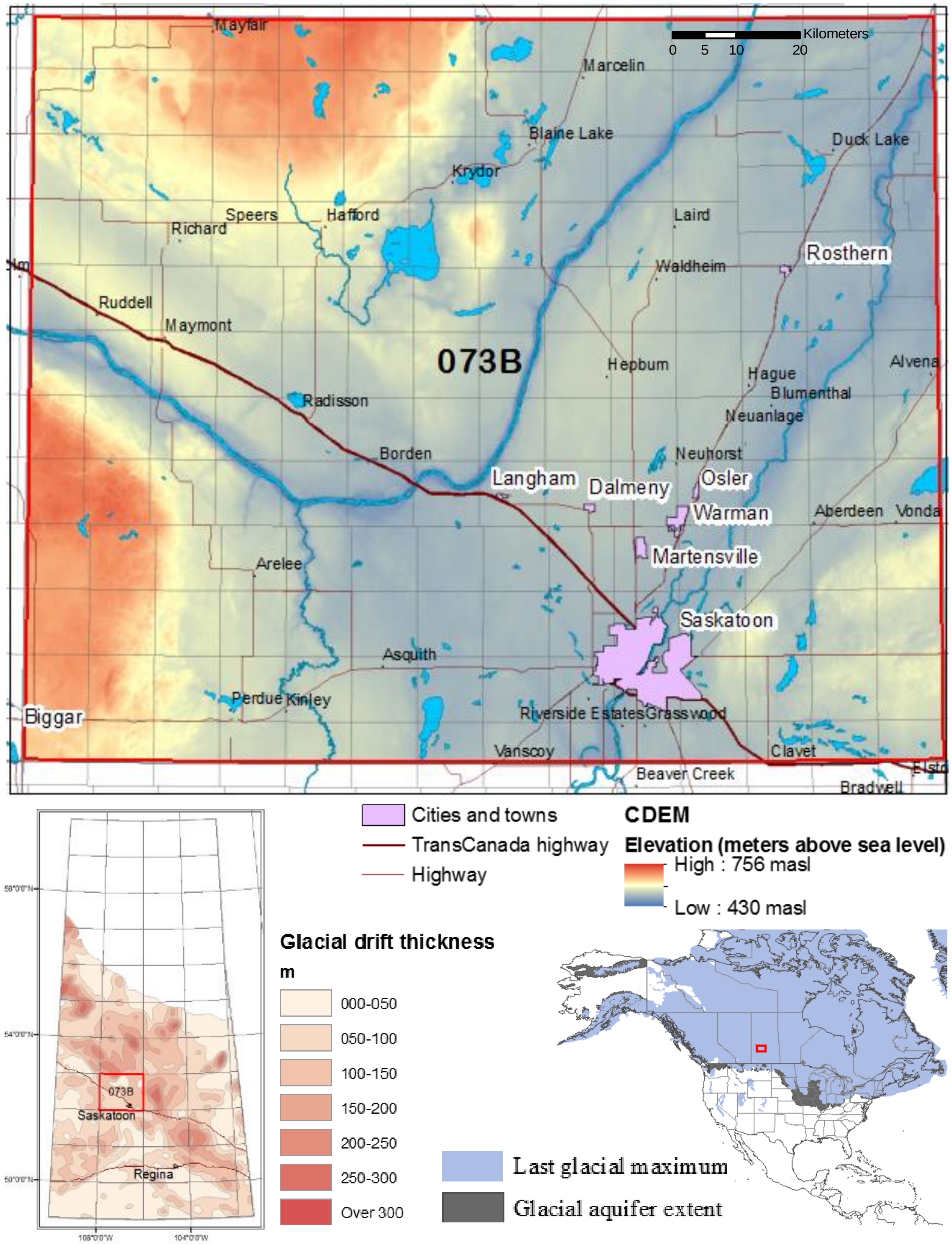
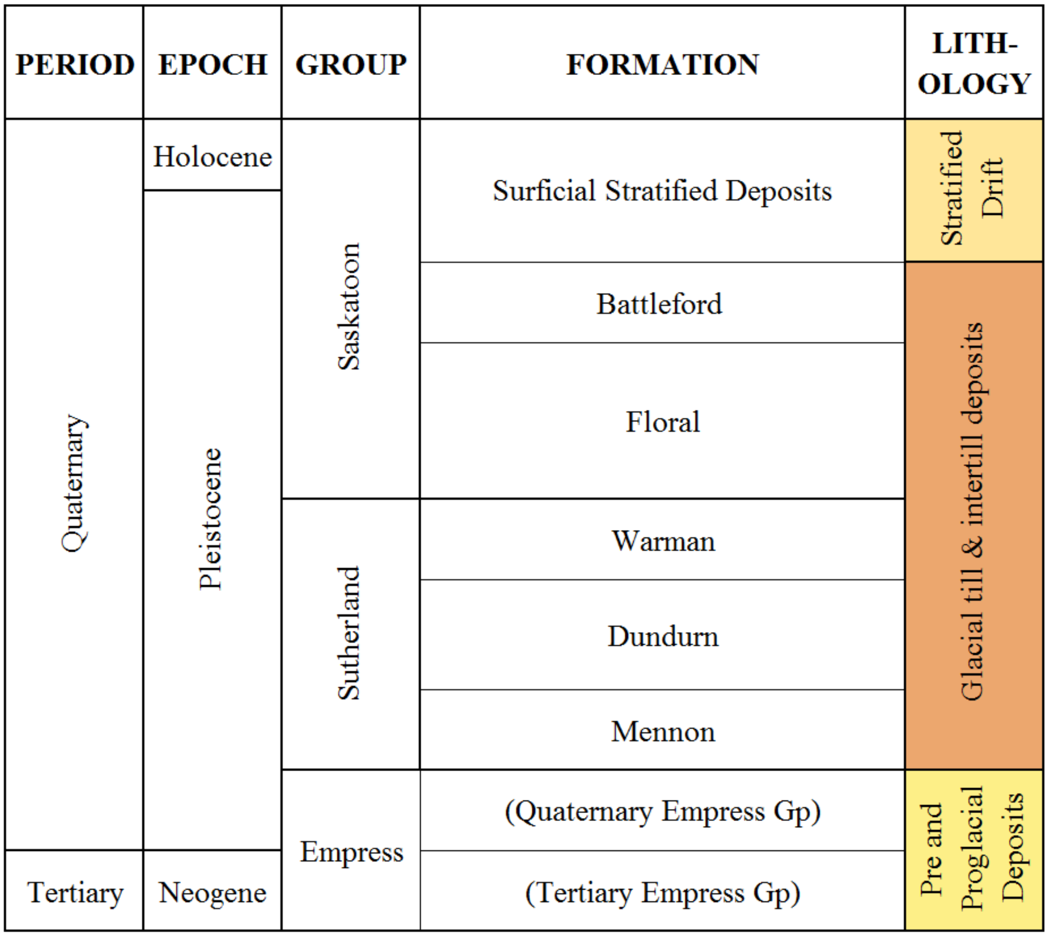


Figure 4.1 NTS map area 073B [Layers from Ehlers et al., 2010; Mossop and Shetsen, 1994]

The geology of the study area is characterized by thick, unconsolidated Pleistocene-aged glacial deposits which are commonly 50 to 120 m thick in the study area, but may vary in thickness from a few meters to over 300 meters, and in some cases may be absent altogether [MDH engineered Solutions Corp., 2011]. These Pleistocene-aged deposits overly the Upper Cretaceous bedrock and, where present, Tertiary-aged Empress Group buried valley fill, and may consist of Upper Empress Group pre and proglacial sands and gravels and the Sutherland Group and Saskatoon Group glacial and interglacial deposits (Figure 4.2) [Christiansen, 1968; Christiansen, 1992].



PERIOD	**EPOCH**	**GROUP**	**FORMATION**	**LITH-OLOGY**
Quaternary	Holocene	Saskatoon	Surficial Stratified Deposits	Stratified Drift
	Pleistocene		Battleford	Glacial till & intertill deposits
			Floral	
		Sutherland	Warman	
			Dundurn	
			Mennon	
		Empress	(Quaternary Empress Gp)	Pre and Proglacial Deposits
Tertiary	Neogene		(Tertiary Empress Gp)	

Figure 4.2 Simplified Quaternary Period stratigraphy of south-central Saskatchewan [after MDH Engineered Solutions Corp., 2010]

Bedrock in the study area is the Late Cretaceous Period interbedded shale, siltstone, and sandstone deposits of the Lea Park, Judith River, and Bearpaw Formations [MDH Engineered

Solutions Corp., 2011]. Intermittently present as buried valley fill are the Tertiary and Quaternary-aged Empress Group diamicton [Cummings et al., 2012]. The Empress Group deposits fill ancient buried valleys were incised into the bedrock during the uplift of the Rocky Mountains during the Late Cretaceous and Early Tertiary Period, forming the Tyner and Battleford buried valleys [Cummings et al., 2012].

Overlying the bedrock and Empress Group buried valley deposits are the Sutherland Group and Saskatoon Groups, consisting of glacial tills, intertill and intratill stratified deposits, and variable clay, silt, sand, gravel and coarser content [Christiansen, 1992; Christiansen and Sauer, 1998; MDH Engineered Solutions Corp., 2011]. The Sutherland Group consists of the Mennon, Dundurn, and Warman Formations and the Saskatoon Group consists of the Floral and Battleford Formation as well as surficial stratified deposits [Christiansen, 1968; Christiansen, 1992]. Each of these formations are further subdivided into hydrostratigraphic units, including low-permeability glacial till aquitards and permeable sand and gravel intertill aquifers [Christiansen, 1992; Maathuis, 2008].

The irregular geometry and variable lithology of the glacial deposits and the deeply incised interbedded shale, siltstone, and sandstone bedrock resulted in a system of local, shallow interglacial aquifers overlying intermittent regional buried valley and bedrock aquifers. The Judith River and Lea Park aquifers, marking the base of freshwater exploration, exist only in the southern half of the study area and are laterally discontinuous and highly mineralized, and are therefore not suitable for domestic or agricultural use without treatment [Ferris et al., 2017; Maathuis, 2008]. The Empress Group aquifers (Battleford Valley, Tyner Valley, and Meacham aquifers) are major, high-yield regional freshwater aquifers in Saskatchewan and the study area, while the discontinuous intertill aquifers (Fielding, Dalmeny, Tessier, and Forestry Farm aquifers) form locally important sources of water for municipalities, agriculture, and industry [Maathuis, 2008; MDH Engineered Solutions Corp., 2011]. Lateral groundwater flow in these aquifers is generally towards the North or South Saskatchewan River valleys where the water discharges as springs in the valley walls or percolates into subcroping bedrock aquifers [MDH Engineered Solutions Corp., 2011]. Although much of the fresh water demand in the study area is satisfied by surface water resources, the bedrock, buried valley, and intertill aquifers are of local and regional importance for municipal, agricultural, and industrial water supplies and form an integral part of the regional hydrological system [Maathuis, 2008; Peach and Wheater, 2014].

The shallow, freshwater aquifers in the study area are recharged primarily by downward percolation of precipitation from the surface through the overlying Pleistocene-aged glacial tills which influence groundwater movement and contaminant transport [Hendry, 1982; Keller et al., 1986; Keller et al., 1988]. The Pleistocene-aged glacial till aquitards exhibit evidence of a shallow, fractured active groundwater zone, extending to a depth of as much as 15 meters below ground level (mbgl) and a deeper, less active groundwater zone, regardless of lithostratigraphic unit[1]. The bulk hydraulic conductivity in this shallow, active groundwater zone can be 2 to 3 orders of magnitude greater than the hydraulic conductivity of tills in the deeper, less active groundwater zone[2], significantly increasing the rate of vertical groundwater flux and the vulnerability of the groundwater system to contamination introduced at the surface [Keller et al., 1988; Rutland et al., 1991].

4.4.1 Saskatchewan Water Security Agency's hydrogeological mapping program

In 2009, the Saskatchewan Water Security Agency (WSA) initiated a fourth-generation hydrogeological mapping program in Saskatchewan, which began with the mapping of NTS map area 073B (Saskatoon) as a pilot project to establish base hydrogeological mapping standards to be applied across south-central Saskatchewan. This pilot project resulted in the 2011 report *Hydrogeology Mapping of NTS Mapsheet Saskatoon 73B* [MDH Engineered Solutions Corp., 2011], which includes a series of aquifer vulnerability maps, and two reports detailing the hydrogeological mapping protocol for Saskatchewan [MDH Engineered Solutions Corp., 2010; Saskatchewan Research Council, 2010]. Notably, this project included the development of a geographic information system (GIS) database including digitized Water Well Driller's Report (WWDR) records, interpreted well logs with stratigraphic picks, and digitized aquifer boundaries [Water Security Agency, 2010]. The hydrogeological mapping protocol for Saskatchewan recommends the use of the Aquifer Vulnerability Index (AVI) method for mapping groundwater vulnerability, the WSA itself using a modified AVI method allowing for the vulnerability of multiple, stacked aquifers to be assessed and mapped [MDH Engineered Solutions Corp., 2010].

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[1] See Chapter 3; Sub-section 3.6.4

[2] See Chapter 3; Sub-section 3.5.2

4.5 The Aquifer Vulnerability Index (AVI) method

The Aquifer Vulnerability Index (AVI) method for mapping groundwater vulnerability, developed by Van Stempvoort et al. in 1992, is a common and popular method of assessing intrinsic groundwater vulnerability that has been widely applied around the world [Gogu and Dassargues, 2000; Luoma et al., 2017; Oke et al., 2016 Ronneseth et al., 1995; Vias et al., 2006]. The simplicity of the application and interpretation of the AVI method makes this method suitable for adaptation to accommodate local conditions [Luoma et al., 2017] and for comparative evaluations with other vulnerability assessment methods [Oke et al., 2016; Vias et al., 2006].

The AVI method quantifies groundwater vulnerability through two parameters – the thickness and hydraulic conductivity of each protective, low-permeability hydrogeological unit overlying the uppermost aquifer or groundwater-bearing unit – both of which can be derived from WWDRs which are freely accessible for the Canadian Prairie Provinces. Van Stempvoort et al. concluded that these two parameters adequately describe hydrogeological properties governing groundwater vulnerability in the Interior Plains region of North America, characterized by thick deposits of Pleistocene-aged glacial tills, although Van Stempvoort et al. also noted that other parameters such as topography, recharge, and catchment configuration should be included in site-specific investigations [Van Stempvoort et al., 1993].

The AVI method is based on hydraulic resistance, c (T), a theoretical factor which describes the resistance of an aquitard to vertical flow, and is calculated as

$$\boldsymbol{c} = \sum {}^{\boldsymbol{d_i}}\!/_{\boldsymbol{K_i}} \tag{4.1}$$

where d (L) is the thickness of sedimentary layer *i* above the uppermost, saturated aquifer surface, and K (L/T) is the corresponding estimated hydraulic conductivity of sedimentary layer *i*. Although hydraulic resistance has units of time, it should not be considered a travel time for water or contaminants, but is instead a process-based analogical relation that indicates relative groundwater vulnerability. Once calculated, the hydraulic resistance, c or Log(c), can be related to the qualitative AVI description (Table 4.1) and plotted [Van Stempvoort et al., 1992].

Table 4.1 AVI method hydraulic resistance and qualitative vulnerability codes [after MDH Engineered Solutions Corp., 2010]

c, Hydraulic Resistance (years)	$\text{Log}_{10}(c)$	AVI	Vulnerability Color Codes
0 to 10	< 1	1	very high
10 to 100	1 to 2	2	high
100 to 1,000	2 to 3	3	moderate
1,000 to 10,000	3 to 4	4	low
> 10,000	> 4	5	very low

The division of the overlying deposits into hydrogeological units first requires the uppermost saturated aquifer surface to be identified. Van Stempvoort et al. provide a practical definition of an aquifer as “any sand or gravel unit that has a saturated thickness of at least 0.6 m (2 ft), or is < 0.6 m, but has at least one water well installed.…[a]ny > 0.6 m sand or gravel unit deeper than 5 m below the surface is considered water saturated, unless there is direct evidence on the driller’s report to the contrary” [Van Stempvoort et al., 1992]. The thickness of the overlying units is then divided on the basis of the hydrostratigraphic rather than the lithological properties of the unit and a representative hydraulic conductivity is assigned to each unit. In practice, the definition of the uppermost saturated aquifer surface and of the overlying units is often dependent on the purpose of the assessment and the data available to the user [MDH Engineered Solutions Corp., 2010].

4.6 Methodology

For this study, both the classic AVI method and a modified, depth-defined AVI method were used to conduct a groundwater vulnerability assessment and develop groundwater vulnerability maps for the study area. By conducting a classic AVI assessment, the results of the modified, depth-defined method could be compared and analyzed. The WSA’s GIS borehole database [Water Security Agency, 2010] was used as the basis for both assessments. The borehole database includes records for 2755 boreholes, of which 1969 boreholes with detailed, reliable hydrostratigraphic picks were selected for this study. Each of the selected boreholes are associated with a precise spatial location and include the borehole elevation, total depth, stratigraphic picks for all hydrostratigraphic units, and identification of the completion horizon (if completed). This database was used to develop a spreadsheet-based AVI calculator, following the classic AVI and modified depth-defined methodology described below.

4.6.1 The classic AVI method

The classic AVI method is based on the division of the low-permeability sediments overlying the uppermost aquifer into effective hydrostratigraphic units. In the study area, hydrostratigraphic units are well defined, and published hydraulic conductivity estimates for these hydrostratigraphic units based on literature values, professional judgement, and experience were used (Table 4.2) [MDH Engineered Solutions Corp., 2010].

Table 4.2 Generalized hydraulic conductivity values for hydrostratigraphic units in south-central Saskatchewan [after MDH Engineered Solutions Corp., 2010]

Hydrostratigraphic Unit	**Hydraulic Conductivity (m/s)**
Saskatoon Gp, Battleford Till	1.0E-07
Saskatoon Gp, Upper Floral Till	1.0E-08
Saskatoon Gp, Lower Floral Till	1.0E-09
Sutherland Gp Till	1.0E-10
Bearpaw Formation Shale	1.0E-11

To calculate the classic AVI at each borehole the uppermost aquifer was identified as the first permeable hydrostratigraphic unit present in the stratigraphic succession that is below the water table – this hydrostratigraphic unit may or may not correspond to the identified completion horizon in the borehole. The hydraulic resistance for each of each of the low-permeability hydrostratigraphic units overlying the uppermost aquifer was calculated and summed to arrive at the overall hydraulic resistance for that point using Equation 4.1. The base 10 logarithm of the hydraulic resistance was taken to determine the AVI class.

4.6.2 The depth-defined AVI method

The modified AVI method presented here – the depth-defined AVI – was developed as a method for incorporating and representing the uncertainty associated with the natural variability observed in input data in groundwater vulnerability assessments. Incorporating this uncertainty required a characterization of the natural variability of the hydraulic conductivity of the Pleistocene-aged glacial tills. To characterize this natural variability, statistically derived depth-defined hydraulic conductivity estimates were prepared based on hydraulic conductivity test data collected from 15 sites across south-central Saskatchewan [Ferris et al., 2019].

Rather than associating hydraulic conductivity estimates with hydrostratigraphic units, hydraulic conductivity probability distributions were prepared for three depth intervals[3]: from 0 to 15 mbgl, from 15 mbgl to 23 mbgl, and for depths greater than 23 mbgl (Figure 4.3).

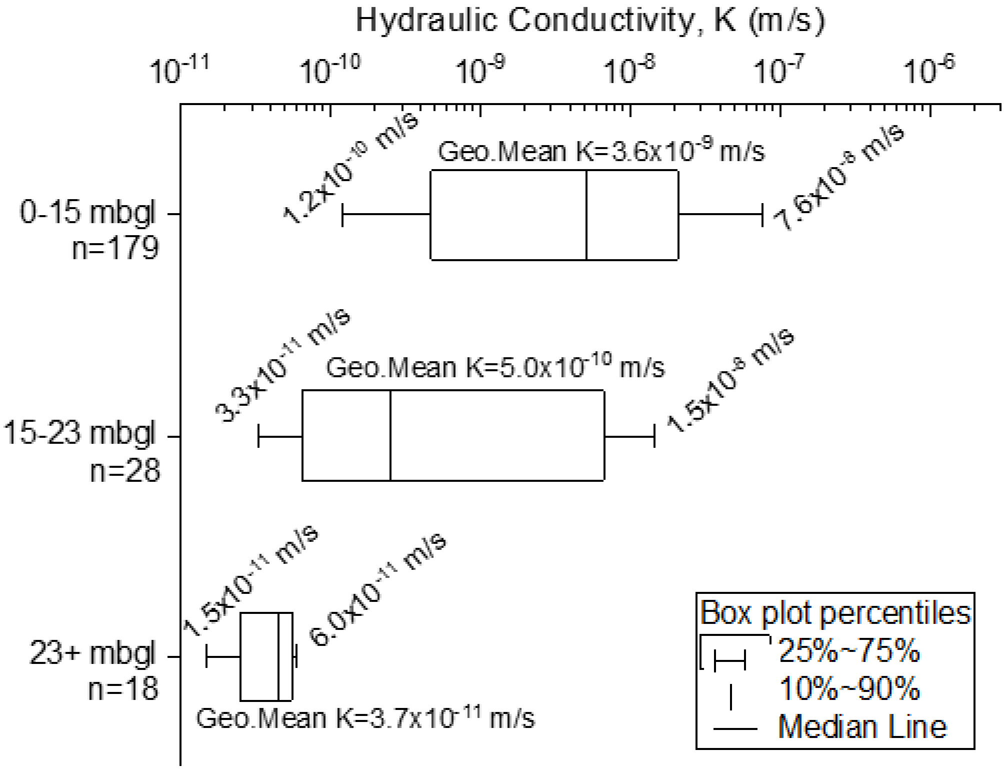

Figure 4.3 Box plot characterization of the hydraulic conductivity of Pleistocene-aged glacial tills

Three hydraulic conductivity estimates were calculated for each depth interval, each representing a different probability: the 10th percentile (P10), the geometric mean, and the 90th percentile (P90) (Table 4.3). These three estimates for each depth interval, representing optimistic (P10), expected (mean), and conservative (P90) groundwater vulnerability conditions, were then used as input data for the deterministic modified AVI method calculation.

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[3] See Chapter 3; Sub-section 3.6.2

Table 4.3 Depth-defined hydraulic conductivity estimates for associated probabilities

Hydraulic Conductivity (m/s)			
Depth	10th Percentile, P10 (Optimistic)	Geometric Mean (Expected)	90th Percentile, P90 (Conservative)
0-15 mbgl	1.2E-10	3.6E-09	7.6E-08
15-23 mbgl	3.3E-11	5.0E-10	1.5E-08
>23 mbgl	1.5E-11	3.7E-11	6.0E-11

Once the thickness of the low-permeability tills overlying the uppermost aquifer was determined for each point, the hydraulic resistance was calculated using one of the three sets of hydraulic conductivity estimates (P10, mean, or P90). The hydraulic resistance, c, for boreholes where the thickness of the low-permeability tills overlying the uppermost aquifer is 15 m or less is,

$$\boldsymbol{c_i} = \frac{\boldsymbol{z_i}}{\boldsymbol{K_{0-15\,mbgl}}} \tag{4.2}$$

for boreholes where the thickness of the low-permeability tills overlying the uppermost aquifer is greater than 15 m but less than 23 m the hydraulic resistance, c, is,

$$\mathbf{c}_{\boldsymbol{i}} = \frac{\mathbf{15}\,\boldsymbol{m}}{\boldsymbol{K_{0-15\,mbgl}}} + \frac{(\boldsymbol{z_i}-\mathbf{15})\,\boldsymbol{m}}{\boldsymbol{K_{15-23\,mbgl}}} \tag{4.3}$$

and for boreholes where the thickness of the low-permeability tills overlying the uppermost aquifer is greater than 23 m the hydraulic resistance, c, is,

$$\mathbf{c}_{\boldsymbol{i}} = \frac{\mathbf{15}\,\boldsymbol{m}}{\boldsymbol{K_{0-15\,mbgl}}} + \frac{(\mathbf{23}-\mathbf{15})\,\boldsymbol{m}}{\boldsymbol{K_{15-23\,mbgl}}} + \frac{(\boldsymbol{z_i}-\mathbf{23})\,\boldsymbol{m}}{\boldsymbol{K_{>23\,mbgl}}} \tag{4.4}$$

where z_i is the depth to the uppermost aquifer, and $K_{0\text{-}15\text{ mbgl}}$, $K_{15\text{-}23\text{ mbgl}}$, $K_{>23\text{ mbgl}}$ are the hydraulic conductivity values assigned to the depth intervals of 0 to 15 mbgl, 15 to 23 mbgl, and depth greater than 23 mbgl, respectively. The base 10 logarithm of the hydraulic resistance values was taken to arrive at the AVI. By this method, each point was associated with three AVI values, each representing a different likelihood scenario.

It should be emphasized that the probability associated with the input hydraulic conductivity data is not necessarily the statistical probability of the resulting AVI value – that is, the AVI derived from the P90 hydraulic conductivity estimate is not a statistically representative 90th percentile AVI value. Instead, the resulting AVI values; hereafter referred to as the P10

AVI, mean AVI, and P90 AVI; are relative indices indicative of the reasonably expected range of vulnerability conditions based on the statistical characterization of the input data.

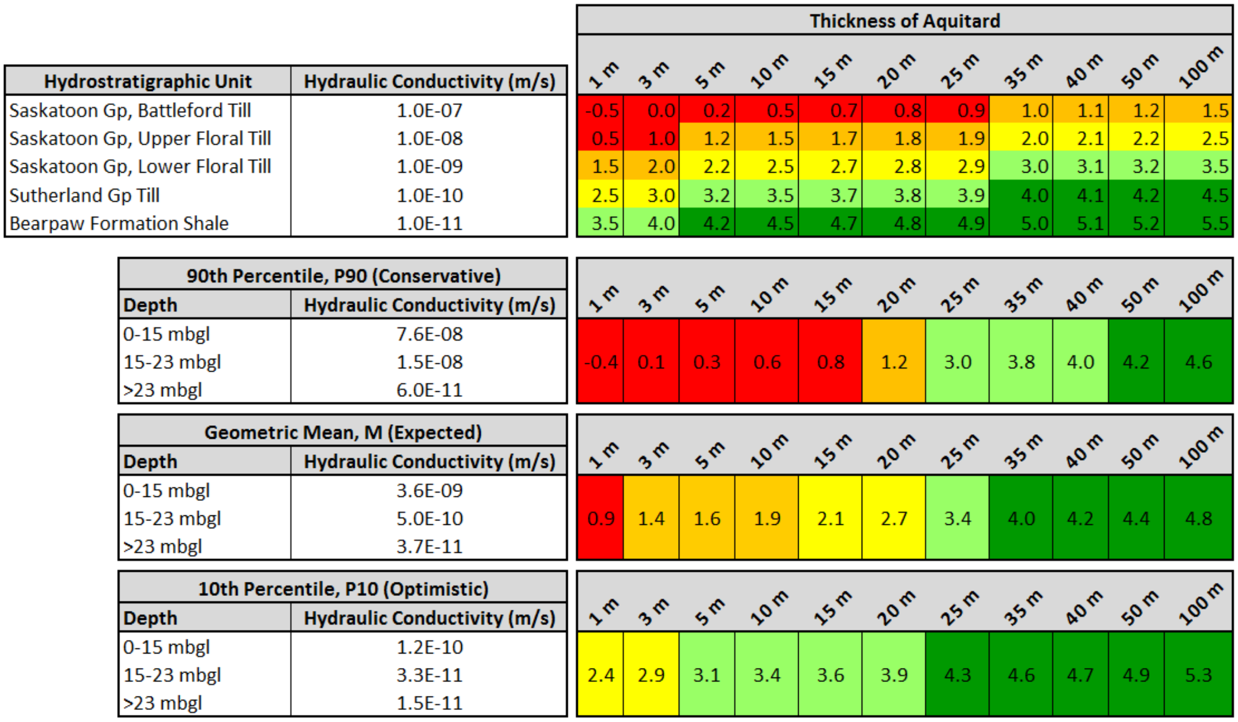
Comparing these cases provides a pseudo-quantitative measure of the uncertainty associated with the natural variation of the input parameter. To facilitate this comparison, the residual AVI was calculated as the difference between the mean AVI and the P90 AVI, quantifying the magnitude of the probable variability towards a lower AVI value. Although the residual between the P10 and P90 could be calculated to quantify the magnitude of the total probable variability, this value would serve little purpose in the evaluation of a groundwater vulnerability assessment, as the probability of optimistic conditions (P10 AVI) are not relevant for environmental and groundwater resource management and protection decisions.

4.6.3 Groundwater vulnerability maps

The classic and depth-defined AVI assessment results, as well as the comparative residuals, were compiled in a spreadsheet, and this spreadsheet was imported into the ArcGIS environment as a point (vector) geodatabase feature class where the borehole data was plotted as xy points. Using the spatial analyst tool in ArcGIS, 500 meter grid cell raster surfaces were generated from the point data by ordinary (spherical) kriging interpolation to produce AVI groundwater vulnerability and associated maps for the study area. A kriging variance map associated with the interpolation of the AVI raster was also produced using ArcGIS software.

4.7 Results

In addition to the AVI assessment for the study area, the general case for the depth-defined AVI method was compared with the classic AVI method. The general results of the classic AVI method with increasing unit thickness illustrates the significance of the identified hydrostratigraphic unit to the resulting AVI assessment (Figure 4.4). For example, a point where the Battleford Formation till is measured to a thickness exceeding 20 meters would be considered of very high vulnerability, whereas a point where the overlying deposits are identified as 5 meters of Sutherland Group till would be designated low vulnerability.



Hydrostratigraphic Unit	Hydraulic Conductivity (m/s)	1 m	3 m	5 m	10 m	15 m	20 m	25 m	35 m	40 m	50 m	100 m
		Thickness of Aquitard										
Saskatoon Gp, Battleford Till	1.0E-07	-0.5	0.0	0.2	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.5
Saskatoon Gp, Upper Floral Till	1.0E-08	0.5	1.0	1.2	1.5	1.7	1.8	1.9	2.0	2.1	2.2	2.5
Saskatoon Gp, Lower Floral Till	1.0E-09	1.5	2.0	2.2	2.5	2.7	2.8	2.9	3.0	3.1	3.2	3.5
Sutherland Gp Till	1.0E-10	2.5	3.0	3.2	3.5	3.7	3.8	3.9	4.0	4.1	4.2	4.5
Bearpaw Formation Shale	1.0E-11	3.5	4.0	4.2	4.5	4.7	4.8	4.9	5.0	5.1	5.2	5.5

90th Percentile, P90 (Conservative)	
Depth	**Hydraulic Conductivity (m/s)**
0-15 mbgl	7.6E-08
15-23 mbgl	1.5E-08
>23 mbgl	6.0E-11

1 m	3 m	5 m	10 m	15 m	20 m	25 m	35 m	40 m	50 m	100 m
-0.4	0.1	0.3	0.6	0.8	1.2	3.0	3.8	4.0	4.2	4.6

Geometric Mean, M (Expected)	
Depth	**Hydraulic Conductivity (m/s)**
0-15 mbgl	3.6E-09
15-23 mbgl	5.0E-10
>23 mbgl	3.7E-11

1 m	3 m	5 m	10 m	15 m	20 m	25 m	35 m	40 m	50 m	100 m
0.9	1.4	1.6	1.9	2.1	2.7	3.4	4.0	4.2	4.4	4.8

10th Percentile, P10 (Optimistic)	
Depth	**Hydraulic Conductivity (m/s)**
0-15 mbgl	1.2E-10
15-23 mbgl	3.3E-11
>23 mbgl	1.5E-11

1 m	3 m	5 m	10 m	15 m	20 m	25 m	35 m	40 m	50 m	100 m
2.4	2.9	3.1	3.4	3.6	3.9	4.3	4.6	4.7	4.9	5.3

Figure 4.4 General AVI results with depth; classic AVI results corresponding to identified hydrostratigraphic unit [after MDH Engineered Solutions Corp., 2010], and depth-defined AVI results corresponding to statistically-derived hydraulic conductivity estimates

The general results of the depth-defined AVI method provide an indication of the probable range of AVI values for any given depth. The mean, or expected, depth-defined AVI designates any point with less than 10 meters of overlying tills as high to very high vulnerability, while points with 15 to 25 meters of overlying tills are designated moderate vulnerability. In all cases, a point where the overlying tills exceed 25 meters would be designated as low or very low vulnerability. The P90, or conservative, depth-defined AVI shows that there is a high probability that any point with less than 25 meters of overlying tills may be of high or very high vulnerability. The depth-defined AVI indicates that it is where the thickness of the overlying tills is between 5 to 25 meters that the greatest variability, and therefore uncertainty, exists.

The depth to the first aquifer in meters below ground level was contoured as a raster map to provide a comparison for the groundwater vulnerability maps (Figure 4.5).

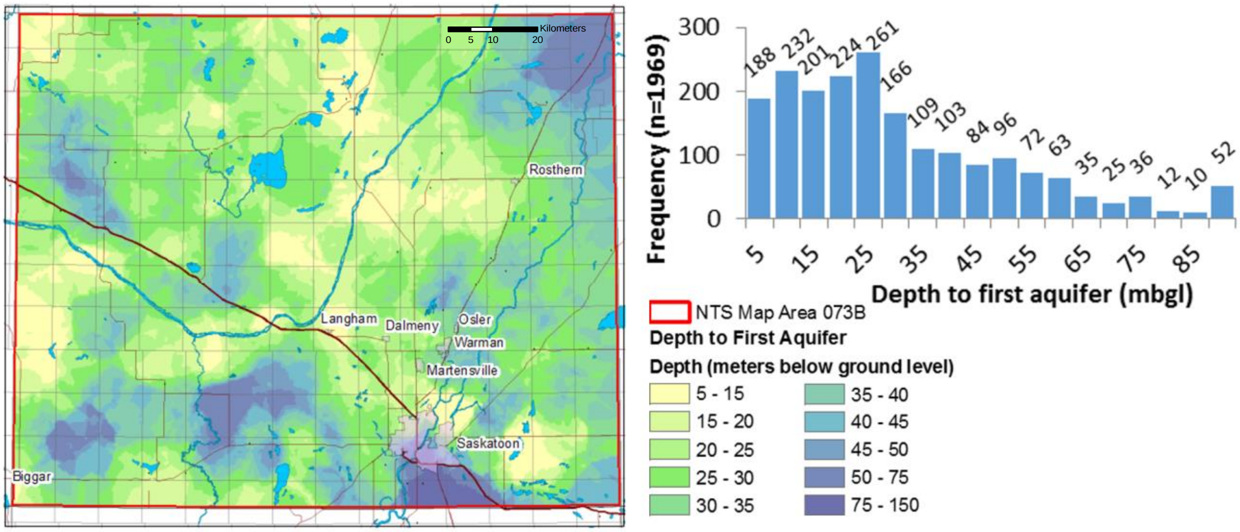


Figure 4.5 Depth to first aquifer raster map and frequency distribution

The depth to groundwater shown here is not the water table nor the piezometric surface, but is instead the depth of the first saturated, permeable unit (aquifer) beneath the water table. The depth to the first aquifer shown here may include topsoil, surficial stratified drift, as well as any permeable hydrostratigraphic units above the water table and does not correspond to the thickness of the low-permeability hydrostratigraphic units which contribute to the calculated hydraulic resistance in the AVI calculations.

4.7.1 Classic AVI groundwater vulnerability assessment

The spatial distribution of the classic AVI raster map (Figure 4.6) corresponds well with the depth to the first aquifer and with topographic elevation; areas of low vulnerability ratings (AVI class 3 to 5) occur in areas of low topographic elevation and high depth to first aquifer, while areas of high vulnerability ratings (AVI class 1 and 2) occur in areas of high elevation and shallow depth to first aquifer.

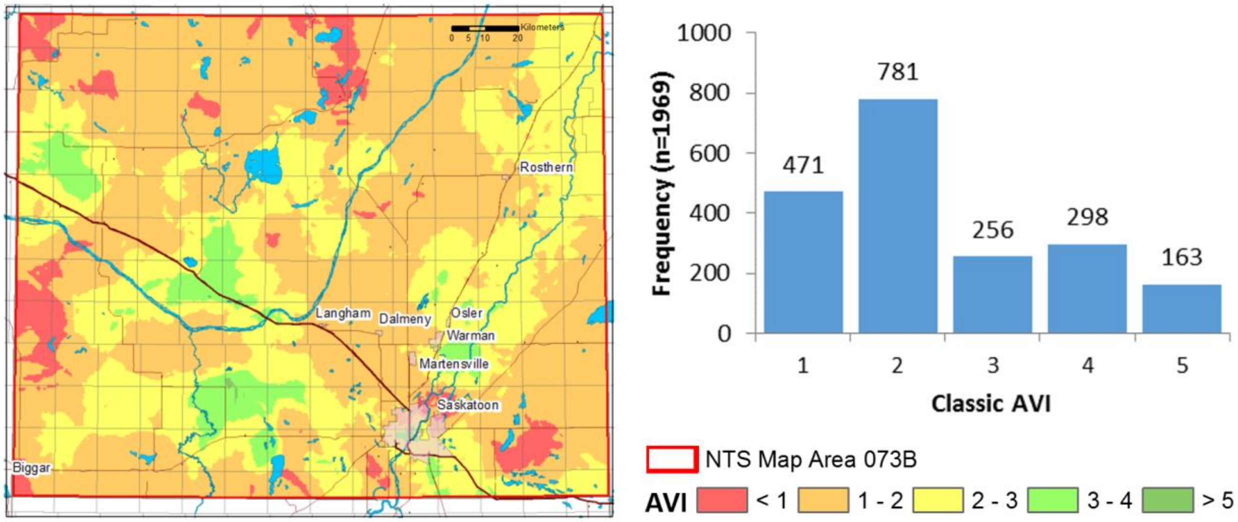


Figure 4.6 Classic AVI raster map and frequency distribution histogram

The frequency distribution of the classic AVI assessment is dominated by AVI classes 1 and 2 (very high and high vulnerability), accounting for 64 % of the boreholes assessed, with the remaining 36 % of boreholes are distributed across AVI classes 3 to 5. The classic AVI method indicates areas of very high vulnerability in five areas, notably to the immediate northwest and west of Saskatoon where Upper Floral Formation aquifers occurs at a shallow depth. Also notable is the moderate vulnerability rating for the South Saskatchewan River valley north of Saskatoon.

4.7.2 Mean depth-defined AVI groundwater vulnerability assessment

The spatial distribution of the mean depth-defined AVI assessment, representing expected conditions, also reflects topographic relief but corresponds most closely with the depth to first aquifer below ground level (Figure 4.7). The areas of low vulnerability ratings (AVI class 4 and 5) occur exclusively in areas where the depth to first aquifer is greater than 25 mbgl, and the areas of elevated vulnerability (AVI class 2) occur in areas of shallow depth to first aquifer.

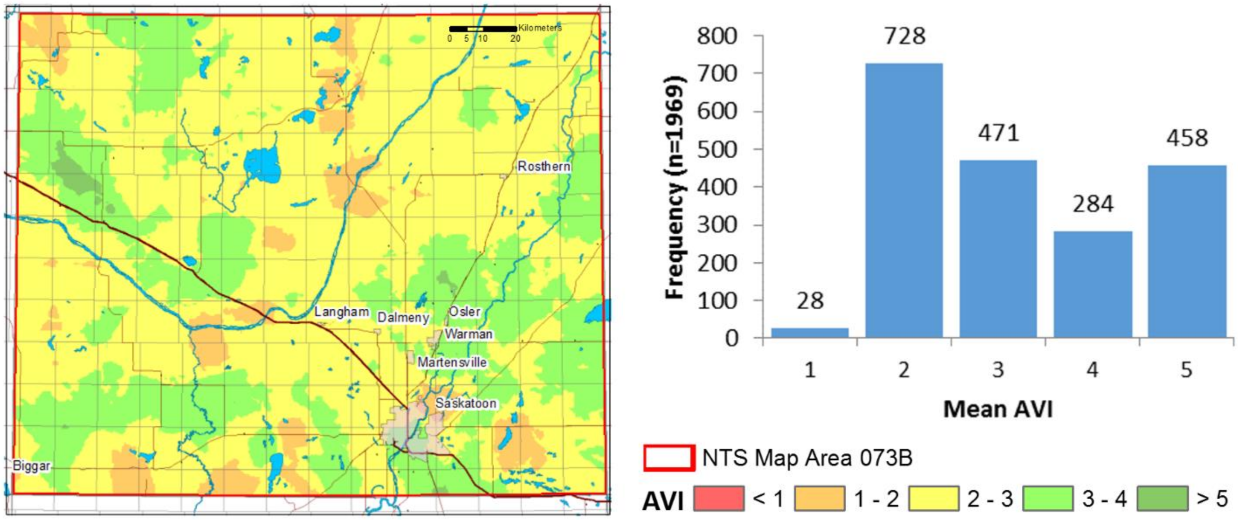
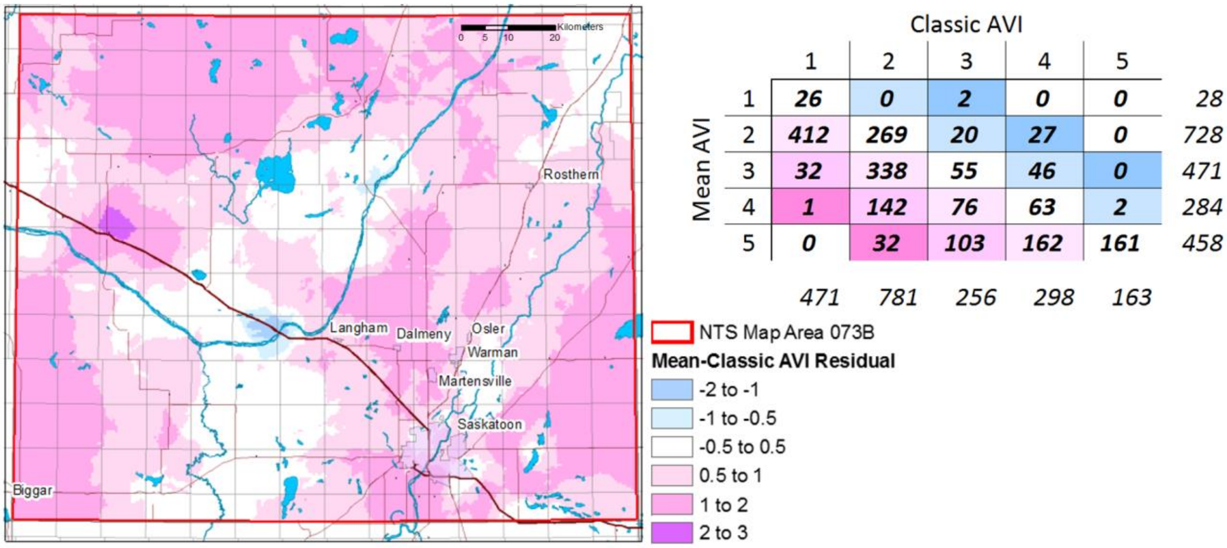


Figure 4.7 Mean depth-defined AVI raster map and frequency distribution

Like the classic AVI assessment, the mean AVI frequency distribution is also dominated by AVI class 2 (37 %), but only 1 % of the points are of AVI class 1, while 62 % of boreholes assessed are distributed across AVI classes 3 to 5. Notable areas of high vulnerability again include the areas to the immediate northwest and west of Saskatoon, and also include three areas along the North Saskatchewan River where thin deposits of low-permeability glacial tills overly Sutherland Group and bedrock aquifers.

4.7.3 Comparing depth-defined and classic AVI

Comparing the classic and mean AVI groundwater vulnerability raster maps and frequency distributions, the classic AVI predicts an overall lower AVI rating (higher vulnerability) than the mean depth-defined AVI. A raster map showing the difference of the mean AVI and classic AVI is shown below (Figure 4.8), where purple colours indicate areas where the mean AVI method predicts a higher AVI class (lower vulnerability) than the classic AVI.



	Classic AVI					
Mean AVI	1	2	3	4	5	
1	26	0	2	0	0	28
2	412	269	20	27	0	728
3	32	338	55	46	0	471
4	1	142	76	63	2	284
5	0	32	103	162	161	458
	471	781	256	298	163	

Figure 4.8 Mean AVI – classic AVI residual raster and comparison matrix

Comparing classic and mean AVI by borehole, only 29 % of points are in agreement, while 66 % of mean AVI points are of a higher class (lower vulnerability) than the classic AVI. Only 4 % of mean AVI points are of a lower class (higher vulnerability) than the classic AVI.

Although the AVI raster spatial distributions are generally similar, there are several notable difference. Due to the sensitivity of the classic AVI to the thickness of stratigraphic units, the classic AVI raster corresponds well with the topographic elevation, while the mean depth-defined AVI is closely correlated to the depth of the first aquifer below ground level. For boreholes where the entire stratigraphic succession is present in average, representative depths, the classic AVI and the mean AVI exhibit a similar AVI value. The points where the mean depth-defined AVI are 2-3 vulnerability classes greater than the classic AVI occur where unusually thick deposits of Battleford and Upper Floral Formation tills are found. These points occur where glacial drift is thickest, corresponding to areas of relatively higher elevation, in the north-west, the south-west, and the south-east corners of the study area. There are few, but notable, areas where the mean AVI is lower (indicating a greater vulnerability) than the classic AVI – these points are clustered along the North Saskatchewan River valley, and occur where the Saskatoon Group tills are thin or absent, and Sutherland Group tills are near the surface, overlying subcropping bedrock aquifers. Importantly, one such area is where the TransCanada highway crosses the North Saskatchewan River immediately to the west of Langham, Saskatchewan. Here, the Saskatoon Group tills area absent, and a thin layer of Sutherland Group tills overly the Lower Dundurn and Judith River aquifers. This area is designated mean AVI class 2 (high vulnerability) due to the thin depth of shallow overlying protective tills, but the classic AVI assessment designates this area class 4 (low vulnerability) due to the assumed low permeability of the Sutherland Group tills.

4.7.4 Variability of the depth-defined AVI method – P10 and P90 AVI

The P10 AVI raster map and frequency distribution (Figure 4.9) consists almost entirely of AVI class 4 and 5, and, as an optimistic case with little distribution or resolution between vulnerability classes, conveys very little useful information. It is notable, however, that the few cells of a moderate vulnerability (P10 AVI class 3) occur to the immediate north-west of Saskatoon, emphasizing the vulnerability of this location.

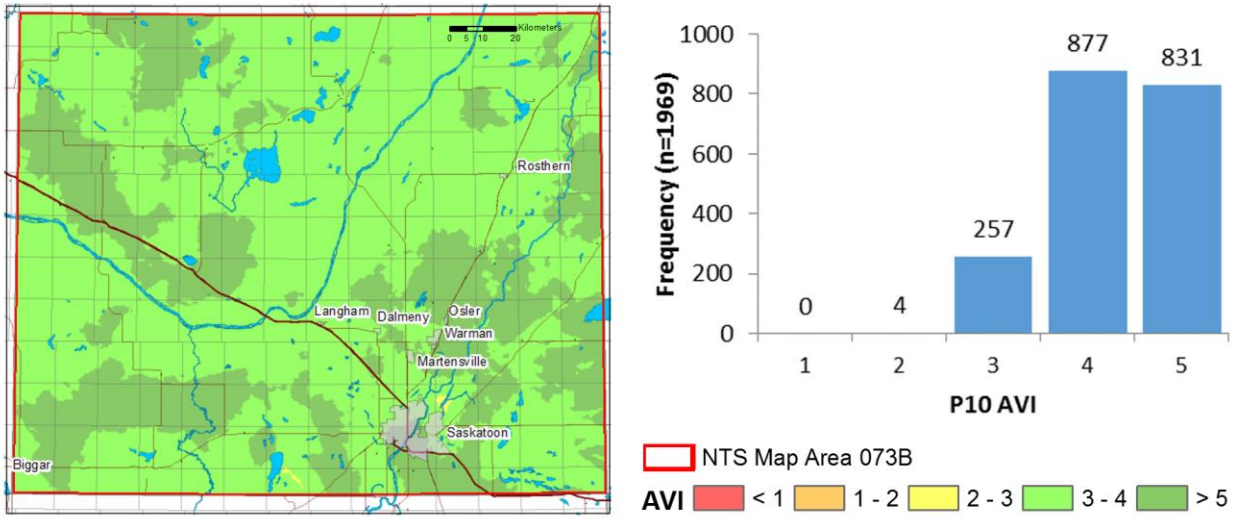


Figure 4.9 P10 depth-defined AVI raster map and frequency distribution

The P90 AVI raster map shows the greatest distribution of vulnerability classes of any of the cases (Figure 4.10). The spatial distribution of the very high vulnerability class (AVI class 1) in the P90 AVI raster map shows a very close correspondence with areas of shallow depth to the first aquifer below ground level, but the same correspondence is not observed in areas of high depth to the first aquifer. This indicates that the depth-defined AVI is highly sensitivity to changes of depth in areas characterized by thin overlying tills, but is insensitive to changes in depth in areas with thick overlying low-permeability units.

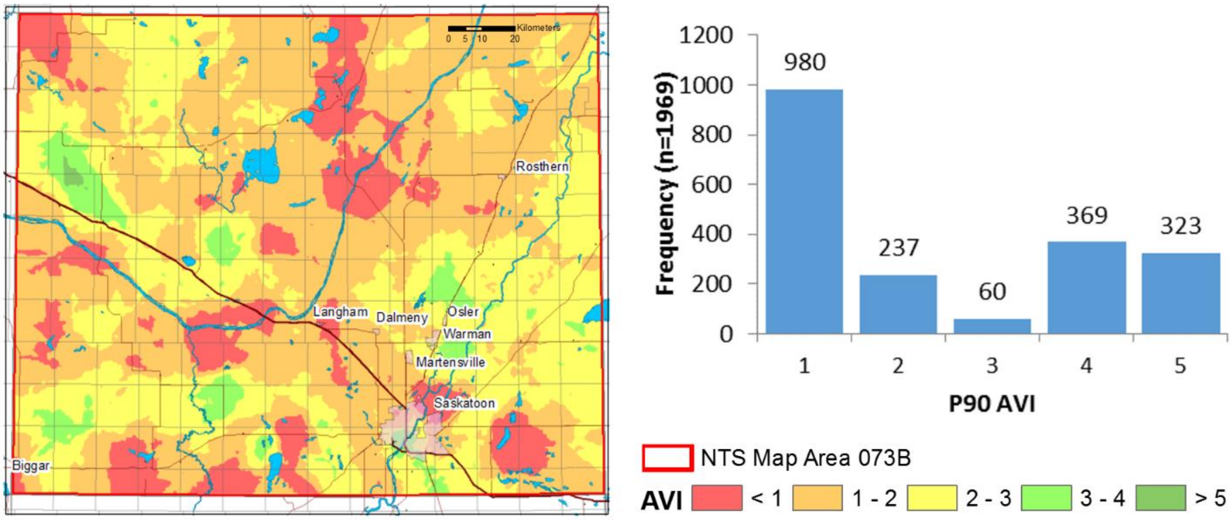


Figure 4.10 P90 depth-defined AVI raster map and frequency distribution

The P90 AVI case reflects a bimodal distribution, skewed heavily to AVI class 1 with 50 % of boreholes assessed. It is notable that for the P90 case, only 3 % of the boreholes assessed are AVI class 3, while 62 % are AVI class 1 or 2, and 35 % are AVI class 4 or 5; this is an artefact of the dramatic decrease in the P90 hydraulic conductivity at depths greater than 23 meters. It is notable that the areas designated low or very low vulnerability in the mean AVI assessment (mean AVI class 4 or 5) are all designated moderate, low, or very low in the P90 AVI assessment (P90 AVI class 3, 4, or 5) – this suggests that a low or very low vulnerability mean AVI designation is associated with low uncertainty.

4.7.5 Representing uncertainty – Mean-P90 AVI residual map

The residual AVI (difference between the mean AVI and the P90 AVI) quantifies the magnitude of the probable variability of the AVI value, and indicates those areas where the variability, and hence uncertainty, are greatest (Figure 4.11). The Mean-P90 AVI residual ranged from 0.2 to 1.4 AVI classes. As expected, the areas of greatest variability and therefore greatest uncertainty correspond to areas with the shallowest depth to first aquifer below ground level.

4.7.6 Kriging variance map

In addition to the uncertainty associated with the variability of the input parameters, the interpolation of point AVI values results in a spatial interpolation error that is represented by the kriging variance. The spatial distribution of the kriging variance is a function of the location of the data points, and is consistent between the various maps produced in this study, while the

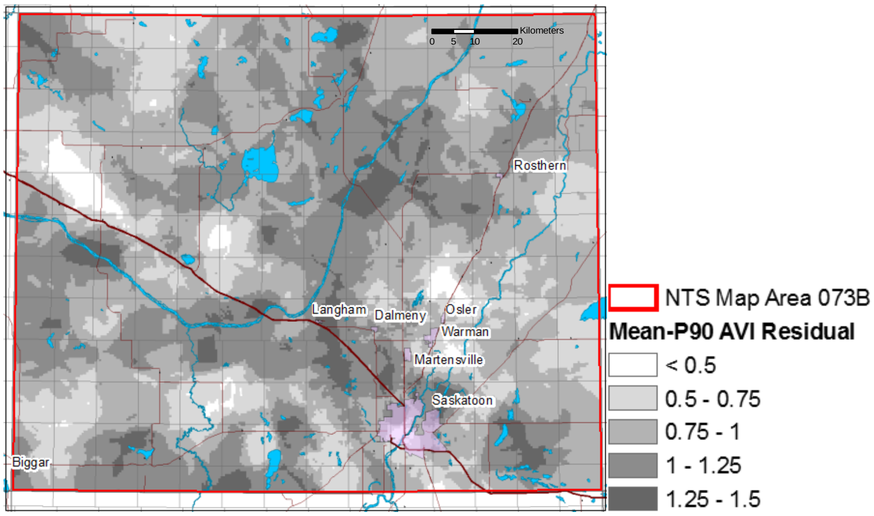


Figure 4.11 Mean-P90 AVI residual raster map and frequency distribution

magnitude of the kriging variance is derived from the relative values of the data being interpolated. The interpolation error represented by the kriging variance is independent of the uncertainty associated with the natural variability of the input data quantified by the mean-P90 AVI residual map, and is a separate source of uncertainty. The kriging variance of the mean AVI (Figure 4.12) shows the distribution of data points in the study area and the resulting representation of interpolation error.

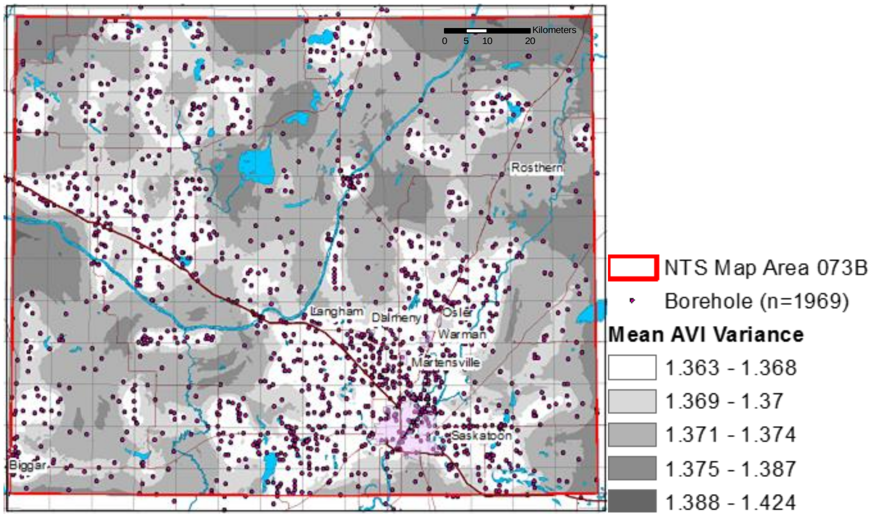


Figure 4.12 Mean AVI kriging variance representing interpolation error associated with point-to-raster conversion of data

4.7.7 Groundwater vulnerability map with uncertainty

To produce a final vulnerability map including uncertainty, the mean AVI raster map was used to indicate expected groundwater vulnerability conditions, with a hatched overlay indicating areas where there is an elevated uncertainty as indicated by a residual AVI greater than 1 (Figure 4.13).

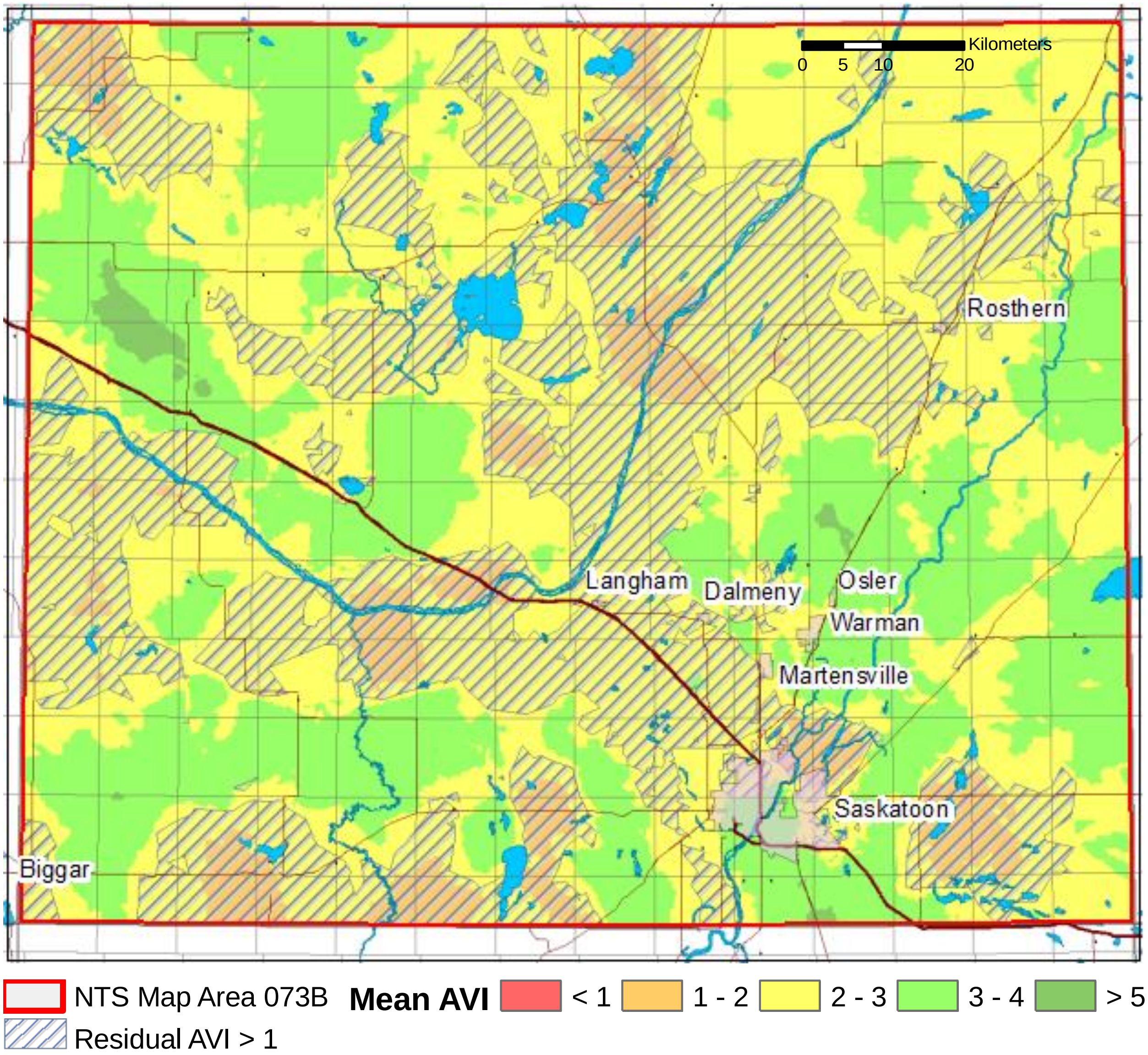


Figure 4.13 Groundwater vulnerability map for NTS map area 073B – Mean depth-defined AVI and uncertainty

The areas of elevated uncertainty encompass only areas of a mean AVI of class 3 or lower. All areas of mean AVI of class 4 or 5 (low and very low vulnerability) are excluded from the areas of elevated uncertainty. The principle areas of elevated uncertainty correspond to the modern North Saskatchewan River valley (corresponding to the broad pre-glacial Tyner and Battleford Valleys that cut into local bedrock millions of years ago), portions of Eagle Creek catchment basin, and areas to the immediate north-east and east of Saskatoon.

There are six areas of special concern, four of which are also designated by the classic AVI assessment as very high vulnerability (classic AVI class 1). These four areas are the areas to the immediate north-east and east of Saskatoon, as well as the areas at the north-west and north-central border of the study area. Although the areas of concern along the North Saskatchewan River and surrounding Eagle Creek were not identified as being of high or very high vulnerability by the classic AVI method, the extremely thin overlying low-permeability tills and the presence of shallow, locally and regionally important aquifers indicate that these areas are of particular concern to contamination introduced at ground surface.

4.8 Discussion

The modified AVI method developed here and the subsequent case study emphasizes the importance of understanding and accurately representing the hydrogeological controls over groundwater vulnerability. The AVI method, based entirely on the thickness and hydraulic conductivity of the protective low-permeability hydrogeological units overlying the aquifer of interest, was demonstrated to reflect depth to the first aquifer in meters below ground level and, to a lesser extent, the topographic elevation. Other factors, properties, and processes influencing groundwater vulnerability such as land use, distribution of recharge or discharge areas, and depth to the water table are not reflected in the resulting groundwater vulnerability assessment. The depth-defined AVI method is therefore suitable for assessing regional groundwater vulnerability in areas where groundwater vulnerability is dominated by the hydraulic protection afforded by thick overlying low-permeability hydrogeological units.

The depth-defined AVI method provides an improvement over the classic, hydrostratigraphically-defined AVI method by more accurately incorporating the effect of the shallow, fractured active groundwater zone common to Pleistocene-aged glacial tills. While the classic method of assigning hydraulic conductivity on the basis of hydrostratigraphic unit is effective, this method requires extensive interpretation of borehole logs to identify hydrostratigraphic units and robust data processing, increasing cost and required resources, and presenting the opportunity for additional ambiguity and error in the resulting vulnerability assessments. Importantly, as demonstrated in the case study analysis of the classic and depth-defined AVI methods, areas where hydrostratigraphic units are excessively thick, thin, or absent will result in irregular classic AVI groundwater vulnerability assessments.

The depth-defined AVI method also presents the opportunity to represent the uncertainty associated with the natural variability of the input parameter, hydraulic conductivity. Examining the residual AVI, calculated as the difference between the mean AVI and P90 AVI, both in the general case and in the case study, revealed the probable range of AVI values and therefore the uncertainty associated with the AVI groundwater vulnerability assessment. The residual AVI for the case study of NTS map area 073B (Saskatoon) not only revealed the areas subject to the greatest variability of probable vulnerability conditions, but also demonstrated that the greatest variability exists where the thickness of the overlying protective low-permeability units is between 5 and 25 m, accurately reflecting the increased variability observed in the hydraulic conductivity of shallow Pleistocene-aged glacial tills.

The combined groundwater vulnerability and uncertainty map, produced by overlaying a hatched area indicating a residual AVI greater than 1 on the mean, depth-defined AVI map, successfully and accurately presents hydrogeological complexity in an intuitive and aesthetic manner. Although the overlay is a simple addition to the groundwater vulnerability map, this addition introduces the concept of uncertainty to the vulnerability assessment. The use of the residual to quantify uncertainty is simple and easy to understand, facilitating the correct interpretation and application by the ultimate consumer of the vulnerability assessments. It should be noted, however, that the residual AVI is not a true measure of uncertainty, but is instead a pseudo-quantitative proxy of the uncertainty associated with the input parameters.

The method presented here for incorporating and representing the uncertainty associated with the natural variability of input parameters is not limited to hydraulic conductivity or to a single parameter. This method can be applied to any deterministic vulnerability assessment method to produce a pseudo-quantitative representation of the uncertainty associated with the variability of the input parameters, provided the input parameters can be represented by a probability distribution. A more precise representation of the uncertainty could be achieved by using a recognized statistical method such as Monte Carlo analysis in cases where more than one probability distribution is included. Furthermore, more complex methods of analysis or presentation could be applied depending on the application. For example, a probability map could be produced showing the probability of exceeding a specified groundwater vulnerability rating; however care to should be taken to ensure the added computation complexity and resources required is offset by an improvement in the accurate representation of the natural system to better support effective decision making and policy development.

4.9 Conclusion

The development of effective groundwater management and protection policies is a wicked problem that requires effective decision support tools that promote an accurate understanding of system complexity and the range of possible outcomes associated with policy and management decisions. Groundwater vulnerability assessments and vulnerability maps are one of the decision support tools that are used to find workable solutions to the groundwater management problems presented by a continuously increasing demand for fresh water and changing environmental conditions, but the lack of consideration for the uncertainty associated with these assessments limits the effectiveness of these tools. To address the pressing water security problems emerging today, new effective methods for incorporating and representing uncertainty in groundwater vulnerability assessments are required.

The modified, depth-defined AVI method presented here was developed to demonstrate the feasibility of quantifying and presenting the uncertainty associated with the natural variability of the input parameters of index-based groundwater vulnerability assessments. By eliminating the need to identify hydrostratigraphic units for each point of the vulnerability assessment, the depth-defined AVI method reduces the subjectivity and computational complexity associated with the hydrostratigraphic interpretation required for a classic AVI assessment, while more accurately incorporating the effect of the shallow, fractured active groundwater zone common to Pleistocene-aged glacial tills. Furthermore, this research demonstrates a methodology that can be used to incorporate uncertainty into deterministic, index-based vulnerability assessments, and intuitively and effectively communicate the uncertainty to the end user of the groundwater vulnerability assessments.

Finding effective solutions to the wicked problems of climate change, sustainable energy, and groundwater management and protection requires not only an accurate representation of complex natural systems and the range of possible outcomes resulting from our decisions, but also requires an understanding of what remains unknown. Effectively incorporating and representing the unknown into the decision support tools we develop can contribute to a shift in our understanding of the environmental system and our place in it, leading to a more sustainable future.

4.10 References

Armengol S, Sanchez-Vila X, Folch A. 2014. An approach to aquifer vulnerability including uncertainty in a spatial random function framework. J. Hydrol. 517:889–900. doi:10.1016/j.jhydrol.2014.06.016.

Bojórquez-Tapia LA, Cruz-Bello GM, Luna-González L, Juárez L, Ortiz-Pérez MA. 2009. V-DRASTIC: Using visualization to engage policymakers in groundwater vulnerability assessment. J. Hydrol. 373:242–255. doi:10.1016/j.jhydrol.2009.05.005.

Christiansen EA. 1968. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada. Can. J. Earth Sci. 5:1167–1173. doi:10.1139/e68-114.

Christiansen EA. 1992. Pleistocene stratigraphy of the Saskatoon area, Saskatchewan, Canada: an update. Can. J. Earth Sci. 29:1767–1778. doi:10.1139/e92-139.

Christiansen EA, Sauer EK. 1998. Geotechnique of Saskatoon and Surrounding Area, Saskatchewan, Canada. In: Karrow PF, White EO, editors. Urban Geology of Canadian Cities. Special Pa. Geological Association of Canada. 117–145.

Christiansen EA, Schmid BJ. 2005. Glacial Geology of Southern Saskatchewan. 1–29.

Cooper H, Zhang C, Selch D. 2015. Incorporating uncertainty of groundwater modeling in sea-level rise assessment: a case study in South Florida. Clim. Change 129:281–294. doi:10.1007/s10584-015-1334-1.

Cummings DI, Russell HAJ, Sharpe DR. 2012. Buried-valley aquifers in the Canadian Prairies: geology, hydrogeology, and origin1Earth Science Sector (ESS) Contribution 20120131. Can. J. Earth Sci. 49:987–1004. doi:10.1139/e2012-041.

Ehlers J, Gibbard PL, Hughes PD. 2010. Quaternary glaciations - extent and chronology. Digital maps. Elsevier. [accessed 2019 Jan 8]. https://booksite.elsevier.com/9780444534477/digital_maps.php.

Ferris DM, Ferguson G, Potter G. 2019. Aggregate hydraulic conductivity data from site investigations in south-central Saskatchewan, Canada [Dataset]. Federated Research Data Repository. doi:10.20383/101.0140.

Ferris DM, Lypka M, Ferguson G. 2017. Hydrogeology of the Judith River Formation in southwestern Saskatchewan, Canada. Hydrogeol. J. 25:1985–1995. doi:10.1007/s10040-017-1611-3.

Freeze RA, James B, Sperling T, Smith L, Massmann J. 1990. Hydrogeological Decision Analysis: 1. A Framework. Gr. Water. 28:738-766.

Gogu RC, Dassargues A. 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environ. Geol. 39:549–559. doi:10.1007/s002540050466.

Hendry MJ. 1982. Hydraulic Conductivity of a Glacial Till in Alberta. Ground Water 20:162–169. doi:10.1111/j.1745-6584.1982.tb02744.x.

Keller CK, van der Kamp G, Cherry JA. 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. Can. Geotech. J. 23:229–240. doi:10.1139/t86-032.

Keller CK, van der Kamp G, Cherry JA. 1988. Hydrogeology of two Saskatchewan tills. I. Fractures, bulk permeability, and spatial variability of downward flow. J. Hydrol. 101:97–121. doi:10.1016/0022-1694(88)90030-3.

Li F, Zhu J, Deng X, Zhao Y, Li S. 2018. Assessment and uncertainty analysis of groundwater risk. Environ. Res. 160:140–151. doi:/10.1016/j.envres.2017.09.030.

Llopis-Albert C, Palacios-Marqués D, Merigó JM. 2014. A coupled stochastic inverse-management framework for dealing with nonpoint agriculture pollution under groundwater parameter uncertainty. J. Hydrol. 511:10–16. doi:10.1016/j.jhydrol.2014.01.021.

Luoma S, Okkonen J, Korkka-Niemi K. 2017. Comparison of the AVI, modified SINTACS and GALDIT vulnerability methods under future climate-change scenarios for a shallow low-lying coastal aquifer in southern Finland. Hydrogeol. J. 25:203–222. doi:10.1007/s10040-016-1471-2.

Maathuis H. 2008. The Quality of Natural Groundwaters in Saskatchewan. Saskatchewan Research Council, Geology Division. 1-86.

MDH Engineered Solutions Corp. 2010. Procedures for Regional Hydrogeological Mapping, M1890-1030109. Saskatoon, SK.

MDH Engineered Solutions Corp. 2011. Hydrogeology Mapping of NTS Mapsheet Saskatoon 073B, M1890-1030109. Saskatoon, SK.

Mossop GD, Shetsen I, comp. 1994. Geological atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council.

Oke SA, Vermeulen D, Gomo M. 2016. Aquifer vulnerability assessment of the Dahomey Basin using the RTt method. Environ. Earth Sci. 75:964-971. doi:10.1007/s12665-016-5792-1.

Patterson JJ, Smith C, Bellamy J. 2013. Understanding enabling capacities for managing the 'wicked problem' of nonpoint source water pollution in catchments: A conceptual framework. J. Environ. Manage. 128:441–452. doi: 10.1016/j.jenvman.2013.05.033.

Peach D, Wheater H. 2014. Groundwater, Hydrogeology and Sustainability in Saskatchewan. Global Institute for Water Security. 1-54.

Ronneseth K, Wei M, Gallo M. 1995. Evaluating Methods of Aquifer Vulnerability Mapping for the Prevention of Groundwater Contamination in British Columbia. Ministry of Environment, British Columbia. 1-17.

Rutland WW, Cherry JA, Stan F. 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario. Ground Water 29:405–417. doi:10.1111/j.1745-6584.1991.tb00531.x.

Saskatchewan Research Council. 2010. Geology and Groundwater of Southern Saskatchwan Hydrogeological Mapping Protocol, SRC Report No. 12831-1E10. Saskatoon, SK.

Uusitalo L, Lehikoinen A, Helle I, Myrberg K. 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environ. Model. Softw. 63:24–31. doi: 10.1016/j.envsoft.2014.09.017.

Van Stempvoort D, Ewert L, Wassenaar L. 1992. AVI: A method for groundwater protection mapping in the prairie provinces of Canada: final report, March 31, 1992. Saskatoon, SK.

Van Stempvoort D, Ewert L, Wassenaar L. 1993. Aquifer Vulnerability Index: A GIS - compatible method for groundwater vulnerability mapping. Can. Water Resour. J. 18:25–37. doi:10.4296/cwrj1801025.

Vías JM, Andreo B, Perles MJ, Carrasco F, Vadillo I, Jiménez P. 2006. Proposed method for groundwater vulnerability mapping in carbonate (karstic) aquifers: the COP method. Hydrogeol. J. 14:912–925. doi:10.1007/s10040-006-0023-6.

Water Security Agency. 2010. Hydrogeological Mapping Database SWA M1890 073B. Regina, Sk.

5. Conclusion

Managing and protecting the world's groundwater resources requires an accurate understanding of the hydrogeological system as well as decision support tools that provide the information necessary to balance various competing interests. Groundwater vulnerability assessments are one of the decision support tools that are available to guide the development of informed, sustainable, and economic groundwater management and protection policies, including environmental impact assessments and land use planning for facilities or operations that may pose a risk to the hydrogeological system. The research presented in this manuscript-based thesis has been conducted to develop and improve groundwater vulnerability assessment and presentation methods, with the purpose of facilitating the most effective selection, application, and interpretation of groundwater vulnerability assessments. The research program was carried out in three phases, each presented in a separate manuscript chapter representing a substantive contribution to the field of hydrogeology, and culminating in the development of a modified AVI method for incorporating and representing the uncertainty associated with the variability of input parameters into deterministic, index-based intrinsic groundwater vulnerability assessments.

5.1 Review of manuscript chapter results

The first phase of the research, presented in Chapter 2 - *A review of the groundwater vulnerability concept and the state-of-the-art of groundwater vulnerability assessment methods*, involved the review and synthesis of literature, research, and conceptual models associated with groundwater vulnerability assessments. In this manuscript, the bewildering array of intrinsic groundwater vulnerability assessment methods resulting from the relative, non-measurable nature of the groundwater vulnerability concept and the variety of hydrogeological conditions and applications to which these methods are applied are systematically reviewed and a framework is presented that demystifies the selection, application, and interpretation of these assessment methods. As an independent manuscript, this work provides a valuable and accessible reference for academics, practicing hydrogeologists, and decision makers who work with vulnerability assessments, while as a thesis chapter, this work represents a thorough literature review and synthesis, establishing the context, conceptual basis, and need for the research presented in the following chapters.

To achieve the purpose of the overall research program by developing and demonstrating a method of incorporating the uncertainty associated with input parameters into groundwater vulnerability assessments, the second phase of the research program was to collect and analyze hydraulic conductivity data for Pleistocene-aged glacial tills to be used as the input data for a modified regional groundwater vulnerability assessment. This research is presented in Chapter 3 – *Regional characterization of the hydraulic conductivity of glacial till aquitards in Saskatchewan, Canada*. Based on the collection, aggregation, and analysis of hydraulic conductivity data of Pleistocene-aged glacial till aquitards collected from sites across the Interior Plains region of Saskatchewan, this manuscript includes substantive and significant original analysis and discussion. Among the notable results, the regional consistency of the observed central tendency and variability of the data, and the empirical evidence of a widespread shallow, fractured active groundwater zone in glacial tills are findings that are of interest to academics and practicing hydrogeologists across the Northern Hemisphere where Pleistocene-aged glacial tills influence shallow hydrogeological processes. In relation to the overall research program, the data and analysis presented in this manuscript chapter provides the statistical characterization of the hydraulic conductivity input data necessary to develop and demonstrate a method for incorporating uncertainty into groundwater vulnerability assessments.

The research program culminated in the third phase through the development and demonstration of a modified groundwater vulnerability assessment method that more accurately represents the hydrogeological conditions in south-central Saskatchewan by incorporating the uncertainty associated with the input parameters, and is presented in Chapter 4 – *Incorporating uncertainty in groundwater vulnerability assessments – A modified AVI method and case study of NTS map area 073B (Saskatoon)*. This manuscript lays the foundation for a thorough and meaningful evaluation of the methodology developed and presented to achieve the purpose of this research program by including a review of the geological and hydrogeological factors influencing the occurrence and vulnerability of groundwater resources in the study area, a summary of the existing local groundwater mapping program, and a review of the methodology for both the classic (original) Aquifer Vulnerability Index (AVI) method and a modified, depth-defined AVI method. Independently, this manuscript presents information of local interest through the description of the hydrogeological factors influencing groundwater occurrence and vulnerability in south-central Saskatchewan, as well as the presentation and analysis of the classic and depth-defined groundwater vulnerability assessments of NTS map area 073B (Saskatoon). This manuscript also has implications for a global audience by presenting a simple and intuitive method for incorporating and presenting uncertainty in deterministic groundwater vulnerability assessments. As part of the overall research program, this thesis chapter integrates the contextual basis and conceptual models presented in Chapter 2 with the statistically derived, depth-defined hydraulic conductivity frequency distributions developed from the research presented in Chapter 3 to achieve the purpose of the research program: to facilitate the most effective application and meaningful interpretation of groundwater vulnerability assessments by developing a method for incorporating and representing the uncertainty associated with the natural variation of input parameters into a deterministic, index-based groundwater vulnerability assessments.

5.2 Integrated results

The integrated results of the research presented in this manuscript-based thesis represents a meaningful contribution to the SFCCNI multi-disciplinary project investigating the issues related to the siting of a small modular nuclear reactor (SMNR). Preliminary site selection for a facility such as a SMNR or operations that pose a risk of contamination to groundwater resources are based on common factors that together are represented by intrinsic groundwater vulnerability, which is the focus of the research presented in this thesis. As a contribution to the SFCCNI project, this thesis provides:

1) A body of reference material, including conceptual figures and summary tables, that can facilitate the effective and appropriate selection, application, and interpretation of a groundwater vulnerability assessment method to be used for preliminary siting decisions;

2) A characterization and statistical analysis of the hydrogeological behaviour of the glacial till aquitards governing groundwater vulnerability in south-central Saskatchewan; and

3) A method for more accurately representing hydrogeological conditions in groundwater vulnerability assessments, and that can be used in conjunction with the hydraulic conductivity database and regional WWDR records to produce groundwater vulnerability maps for the preliminary site selection for a SMNR in Saskatchewan.

5.3 Future research opportunities

Managing and protecting groundwater resources in a sustainable and economic manner will require improvements in our understanding, representation, and communication of the hydrogeological system at all levels. The research presented in this manuscript-based thesis presents several opportunities for further developments in 1) data collection and analysis, 2) the abstraction of models that accurately represent relevant processes at the scale of interest, 3) methods for incorporating and presenting uncertainty in deterministic models, and 4) methods for effectively and meaningfully presenting hydrogeological models to policy makers and the general public.

The hydraulic conductivity database and associated analysis presented in Chapter 3 demonstrated that regionally significant trends in hydraulic processes and properties can be consistently observed and quantified in Pleistocene-aged glacial tills at sites separated by 10s to 100s of kilometers. Together with recent work by Kessler et al. [2012] characterizing sand lenses in glacial tills across the Northern Hemisphere, this work lays the foundation for efforts to further characterize and quantify the properties of these important hydrogeological units. As discussed in Chapter 3, there appears to be significant opportunity to characterize the depth and properties of the shallow, fractured active groundwater flow zone identified by Rutland et al. [1991] and supported by the findings of this thesis.

The demonstrated significance of the input parameters, the rating and weighting system, and the method of aggregating the parameters into the resulting model output presents an opportunity to examine popular methods of assessing groundwater vulnerability and compare these models with the real-world systems they are meant to simulate. A systematic approach to evaluating groundwater vulnerability assessment methods against observed field conditions may reveal important processes that may be neglected in the current model abstractions, leading to the development of groundwater vulnerability models that more accurately represent natural conditions.

As discussed in Chapter 2 and explored in Chapter 4, there are opportunities to further develop the inclusion and presentation of uncertainty in the deterministic models used to represent complex and dynamic natural hydrogeological systems. This area of research is being explored at various levels of complexity, from the pseudo-quantitative method presented here, to data and analysis intensive uncertainty analysis such as the Bayesian framework decision analysis reviewed by Freeze et al. [1990].

The final area of opportunity for future research discussed in relation to the findings presented here is the opportunity to examine methods for effectively communicating the results of hydrogeological and engineering analysis to policy makers and the general public. Decision support tools such as groundwater vulnerability assessments are produced by specialists in order to communicate information about complex systems in a way that allows informed, defensible decisions to be made. Efforts to incorporate uncertainty into decision support tools may lead to undesirable management decisions if the nature of the results and the underlying assumptions are not clearly communicated [Uusitalo et al., 2015]. The work of Bojorquez-Tapia et al. [2009] investigating the most effective ways of communicating the results of groundwater vulnerability assessments to the end user emphasizes that thought must be given not only to producing accurate results, but also to how those results will be perceived and used for the intended application.

Humanity is currently facing unprecedented challenges from an emerging energy crisis, rapidly growing population, disparities in wealth, and a changing climate and global water distribution. Finding solutions to these wicked problems will require new approaches for managing the Earth’s resources and a re-understanding of our place in the dynamic, integrated hydrological, ecological, climatic, and social systems. One small step in the right direction can be made by raising awareness and sensitizing decision makers and the general public to the sensitivity of groundwater resources to contamination, depletion, and the impact of changing global water distributions. These efforts not only assist in the development of sustainable groundwater management and protection policies, but promote ecological literacy and environmental awareness in society at large, shaping future generations and leading to lasting change well into the future.

5.4 References

Bojórquez-Tapia LA, Cruz-Bello GM, Luna-González L, Juárez L, Ortiz-Pérez MA. 2009. V-DRASTIC: Using visualization to engage policymakers in groundwater vulnerability assessment. J. Hydrol. 373:242–255. doi:10.1016/j.jhydrol.2009.05.005.

Freeze RA, James B, Sperling T, Smith L, Massmann J. 1990. Hydrogeological Decision Analysis: 1. A Framework. Ground Water 28:738–766.

Kessler TC, Klint KES, Nilsson B, Bjerg PL. 2012. Characterization of sand lenses embedded in tills. Quat. Sci. Rev. 53:55–71. doi:10.1016/j.quascirev.2012.08.011.

Rutland WW, Cherry JA, Stan F. 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario. Ground Water 29:405–417. doi:10.1111/j.1745-6584.1991.tb00531.x.

Uusitalo L, Lehikoinen A, Helle I, Myrberg K. 2015. An overview of methods to evaluate uncertainty of deterministic models in decision support. Environ. Model. Softw. 63:24–31. doi:10.1016/j.envsoft.2014.09.017.

Appendix A. Defining hydraulic conductivity depth intervals

The aggregate hydraulic conductivity data showed a clear pattern of decreasing central tendency and variability with depth. The relationship between hydraulic conductivity and depth was reflected most clearly in the in-situ data. To develop a depth-defined statistical characterization of the hydraulic conductivity of glacial till aquitards, the in-situ data set was divided into separate depth intervals. The data was divided into three depth-defined intervals to represent the shallow zone of elevated hydraulic conductivity and high variability (depth interval 1), the intermediate zone of transition characterized by decreasing central tendency and high variability of in-situ test data (depth interval 2), and the deep zone characterized by low hydraulic conductivity and low variability (depth interval 3). The depth intervals were defined using a novel statistical method based on the Jenks natural breaks classification method [*Jenks*, 1967]. This method involves several steps, and is intended to group data in such a way as to minimize the variability within each group, while maximizing the difference between the mean values of the depth-defined groups.

The variability within each depth-defined group was evaluated by calculating the sum of the square deviations from the class mean (SDCM) for each of the three depth-defined intervals as,

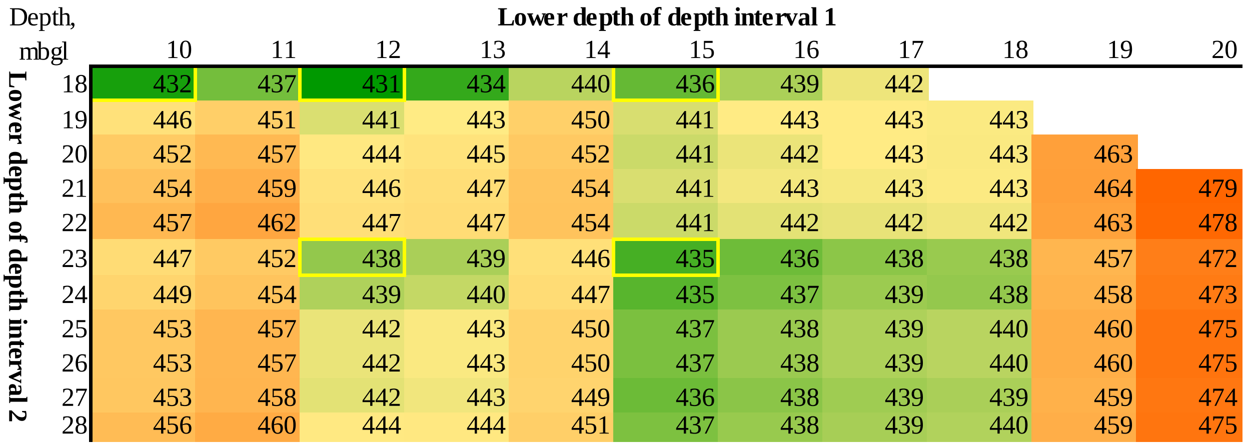
$$\boldsymbol{SDCM_{interval\,i} = \sum_{n=1}^{j}(x_n - x_{Mean})^2} \tag{A.1}$$

where *i* is the depth interval, and *j* is the number of data points in the depth interval, x_n is the negative log base 10 transformed hydraulic conductivity data, and x_{Mean} is the depth-class mean (arithmetic average) of the negative log base 10 transformed hydraulic conductivity data. The sum of the SDCM of the three depth-defined intervals was then calculated as,

$$\boldsymbol{\sum SDCM = SDCM_{interval\,1} + SDCM_{interval\,2} + SDCM_{interval\,3}} \tag{A.2}$$

The possible depth interval combinations, as defined by depth to the nearest meter, were arranged in a matrix, with the possible lower depth for the first depth interval arranged along the horizontal axis, and the lower depth for the second depth interval arranged vertically. The sum of

SDCM was then calculated for all combinations, and local minimum sum of SDCM were identified (identified in yellow-boxed cells in Figure A.1).



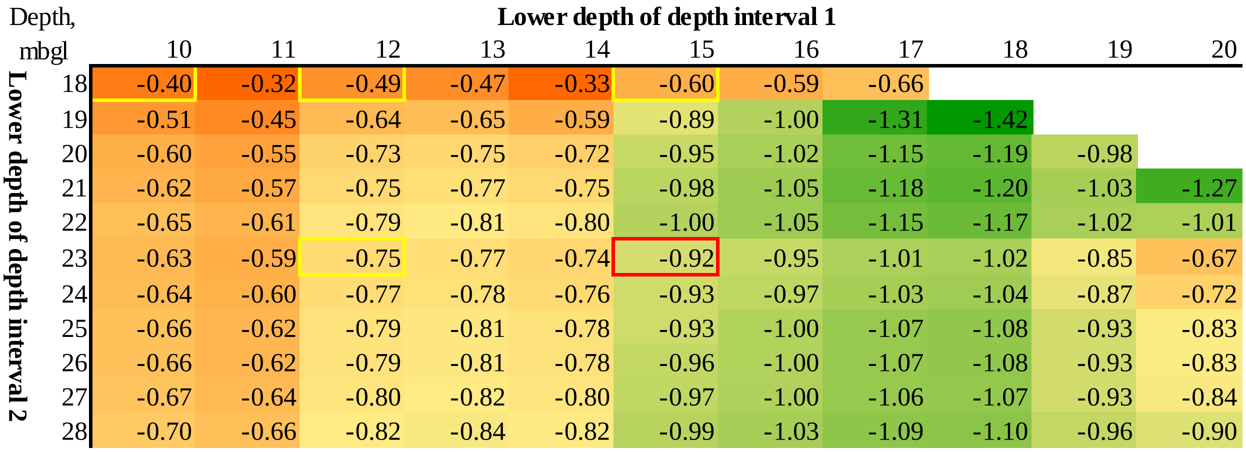
	Depth, mbgl	Lower depth of depth interval 1										
		10	11	12	13	14	15	16	17	18	19	20
Lower depth of depth interval 2	18	432	437	431	434	440	436	439	442			
	19	446	451	441	443	450	441	443	443	443		
	20	452	457	444	445	452	441	442	443	443	463	
	21	454	459	446	447	454	441	443	443	443	464	479
	22	457	462	447	447	454	441	442	442	442	463	478
	23	447	452	438	439	446	435	436	438	438	457	472
	24	449	454	439	440	447	435	437	439	438	458	473
	25	453	457	442	443	450	437	438	439	440	460	475
	26	453	457	442	443	450	437	438	439	440	460	475
	27	453	458	442	443	449	436	438	439	439	459	474
	28	456	460	444	444	451	437	438	439	440	459	475

Figure A.1 Sum of square deviations from the class mean (SDCM) matrix

The difference between the depth-class means (arithmetic averages) of the negative log base 10 transformed hydraulic conductivity data for the first and second depth interval was calculated as,

$$\boldsymbol{Difference\ between\ class\ means} = x_{\boldsymbol{Mean\ Interval\ 1}} - x_{\boldsymbol{Mean\ Interval\ 2}} \tag{A.3}$$

The possible depth interval combinations were again represented in a matrix, and the difference between the depth-class means was calculated for all combinations (Figure A.2).



	Depth, mbgl	Lower depth of depth interval 1										
		10	11	12	13	14	15	16	17	18	19	20
Lower depth of depth interval 2	18	-0.40	-0.32	-0.49	-0.47	-0.33	-0.60	-0.59	-0.66			
	19	-0.51	-0.45	-0.64	-0.65	-0.59	-0.89	-1.00	-1.31	-1.42		
	20	-0.60	-0.55	-0.73	-0.75	-0.72	-0.95	-1.02	-1.15	-1.19	-0.98	
	21	-0.62	-0.57	-0.75	-0.77	-0.75	-0.98	-1.05	-1.18	-1.20	-1.03	-1.27
	22	-0.65	-0.61	-0.79	-0.81	-0.80	-1.00	-1.05	-1.15	-1.17	-1.02	-1.01
	23	-0.63	-0.59	-0.75	-0.77	-0.74	-0.92	-0.95	-1.01	-1.02	-0.85	-0.67
	24	-0.64	-0.60	-0.77	-0.78	-0.76	-0.93	-0.97	-1.03	-1.04	-0.87	-0.72
	25	-0.66	-0.62	-0.79	-0.81	-0.78	-0.93	-1.00	-1.07	-1.08	-0.93	-0.83
	26	-0.66	-0.62	-0.79	-0.81	-0.78	-0.96	-1.00	-1.07	-1.08	-0.93	-0.83
	27	-0.67	-0.64	-0.80	-0.82	-0.80	-0.97	-1.00	-1.06	-1.07	-0.93	-0.84
	28	-0.70	-0.66	-0.82	-0.84	-0.82	-0.99	-1.03	-1.09	-1.10	-0.96	-0.90

Figure A.2 Difference between depth-class mean matrix

The matrices were compared to identify a combination that resulted in a local minimum sum of the SDCM and a local maximum difference between depth-class means. This method resulted in a first depth interval from 0 to 15 mbgl, a second depth interval from depths greater than 15 mbgl to 23 mbgl, and a third depth interval that includes all depths greater than 23 mbgl.

Appendix B. Statistical comparison of test group data

Establishing the similarity of the characteristics of the data samples collected by different test methods can allow inferences to be drawn regarding the hydraulic processes observed by various tests at different depth intervals. To compare the mean value of hydraulic conductivity data collected by different test groups within the same depth interval, a two-sample T-test was conducted.

For the statistical analysis and comparison of the hydraulic conductivity data, the negative log base 10 transformed hydraulic conductivity was used. It is noted that the log-transformed hydraulic conductivity data is not strictly normally distributed, and that the statistical analysis cannot therefore be considered rigorous statistical evidence. However, statistical methods still provide a reasonable method of comparison.

The two-sample t-Test assuming equal variances was conducted on the in-situ test (meter scale) and model (tens of meter scale) data for the first depth interval, from 0 to 15 mbgl. The similarity of the central tendency and distribution of the larger scale in-situ and model data is apparent, as is the difference of the small scale lab test from all other data (Figure B.1).

The descriptive statistics of the in-situ and model data for the first depth interval (Table B.1) and t-Test comparing the in-situ and modelled data (Table B.2) indicates that the difference between the mean values of the in-situ and model data is not significantly different from 0 at the 0.05 level of significance.

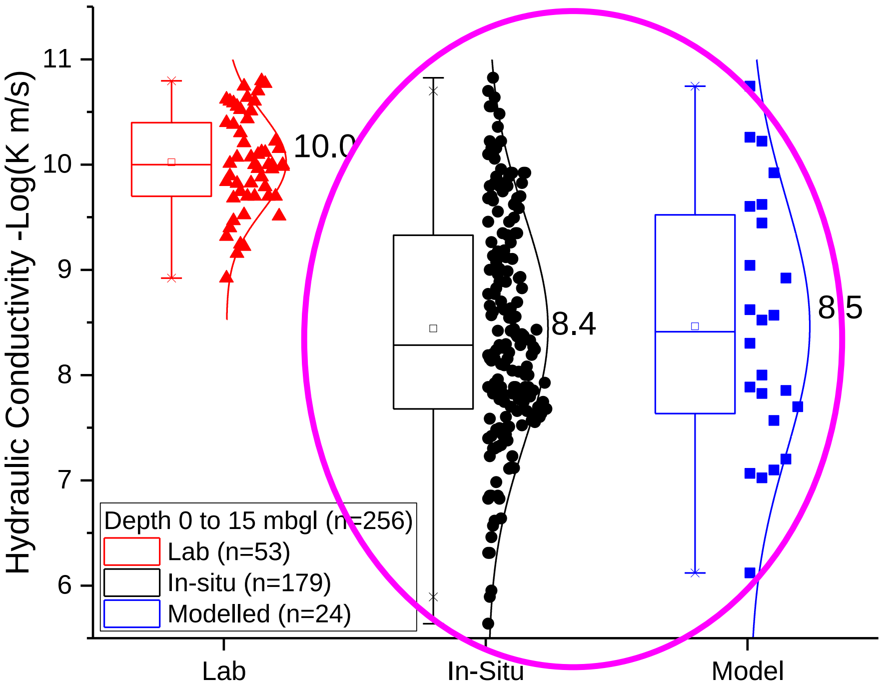


Figure B.1 Box-and-whisker plot for hydraulic conductivity data, sorted by test group, for the first depth interval, 0 to 15 mbgl

Table B.1 Statistics of in-situ and model data, 0 to 15 mbgl

	N	**Mean**	**SD**	**SE**	**Median**
In-situ	179	8.441	1.087	0.0812	8.284
Model	24	8.463	1.207	0.2465	8.411

Table B.2 Two-sample t-Test results comparing in-situ and model data, 0 to 15 mbgl

	t-statistic	**DF**	**Prob>|t|**
Equal variance assumed	-0.09195	201	0.926
Equal variance not assumed	-0.08482	28.22	0.933

The same analysis was conducted on the lab test (centimeter scale) and in-situ test (meter scale) data for the third depth interval, at depths greater than 23 mbgl. Here, the similarity of central tendency of the lab test and in-situ test data is apparent, and the central tendency and variability of both are significant lower than that of the model data at this depth interval (Figure B.2).

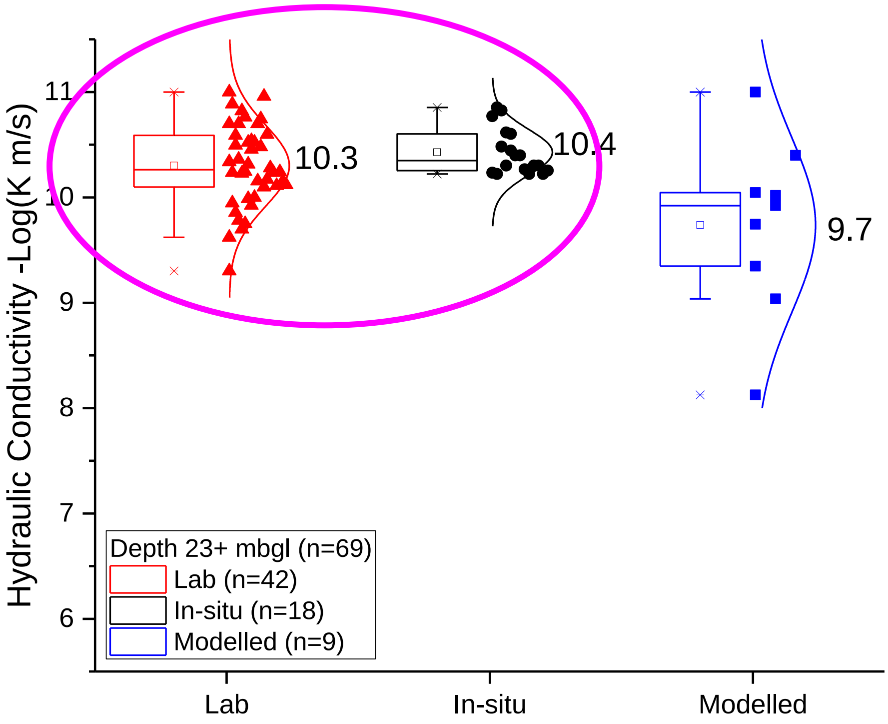


Figure B.2 Box-and-whisker plot for hydraulic conductivity data, sorted by test group, for the first depth interval, 23+ mbgl

Table B.3 Statistics of lab and in-situ data, 23+ mbgl

	N	Mean	SD	SE	Median
Lab	42	10.3	0.385	0.0594	10.262
In-situ	18	10.428	0.216	0.051	10.349

Table B.4 Two-sample t-Test results comparing lab and in-situ data, 23+ mbgl

	t-statistic	DF	Prob>|t|
Equal variance assumed	-1.315	58	0.193
Equal variance not assumed	-1.629	53.57	0.109

The descriptive statistics of the lab and in-situ data for the third depth interval (Table B.3) and t-Test comparing the lab and in-situ data (Table B.4) indicates that the difference between the mean values of the lab and in-situ data is not significantly different from 0 at the 0.05 level of significance

Appendix C. Correlation of in-situ data and test interval length

To investigate the relationship between the measured in-situ hydraulic conductivity and the length of the test interval, a linear fit analysis of the in-situ data for depths less than 15 mbgl was conducted using Origin 2017. Analysis included fit statistics including residual sum of squares, Pearson's r, and R-squared, as well as a residual analysis.

For the data set (n=141), the linear fit intercept was 4.355 +/- 0.5217 and the slope was 0.3394 +/- 0.0621 (Figure 3.7). The residual sum of squares was 89.61, Pearson's r was 0.4202, the R-squared was 0.1769 (P-value of 0.035), and the adjusted R-squared was 0.1709. The residual analysis is represented in the composite Figure C.1.

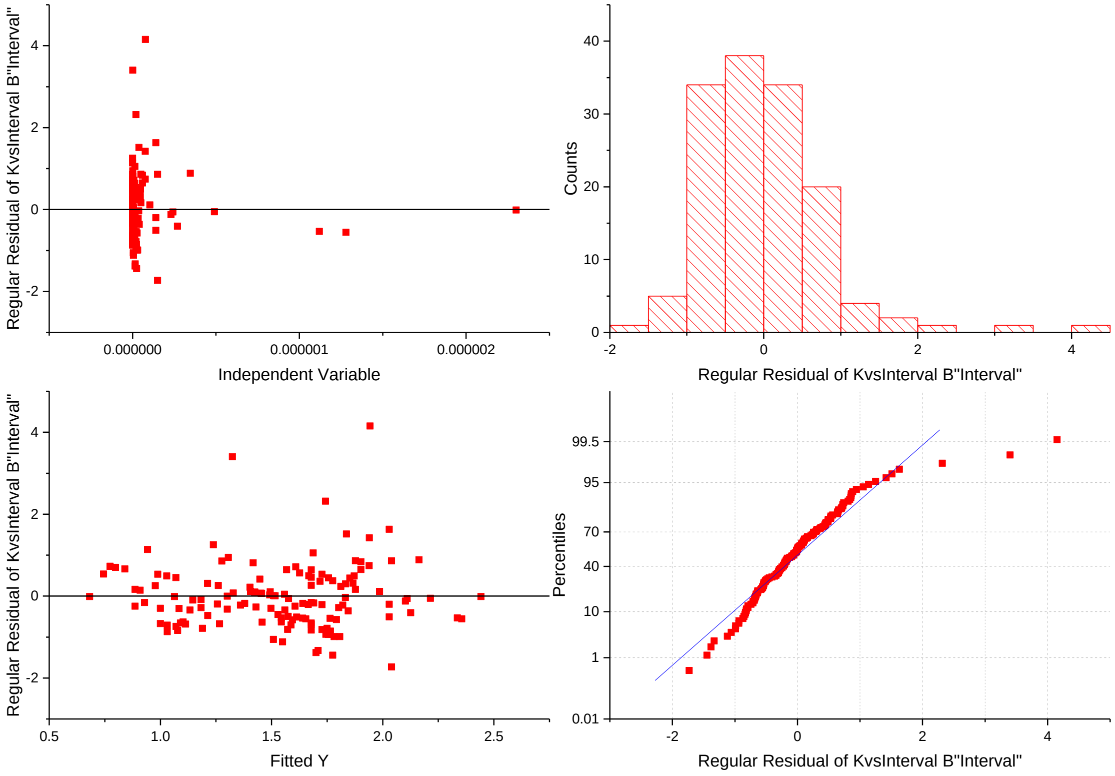


Figure C.1 Residual analysis of in-situ hydraulic conductivity and length of test interval at depths less than 15 mbgl

The R-squared of 0.1769 suggests that the length of the test interval influences the observed hydraulic conductivity, although this factor does not explain all of the observed variability.