PROPOSED AQUIFER VULNERABILITY ASSESSMENT INCORPORATING FRACTURED ROCK

PROPOSED AQUIFER VULNERABILITY ASSESSMENT INCORPORATING CHARACTERIZATION OF FRACTURED ROCK ENVIRONMENTS IN SOUTHERN ONTARIO

By

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Abstract

Much of southern Ontario relies on groundwater in fractured rock aquifers as a municipal drinking water source, thus the vulnerability of these sources is of importance from public health, economic, and environmental perspectives. Aquifer vulnerability assessments serve as visual communication tools useful in efficiently allocating resources for the establishment of new drinking water sources, hydrogeological characterization, and source water protection planning decisions. Examples of current vulnerability assessments include: DRASTIC, GOD, EPIK, AVI, COP and ISI. These vulnerability assessment methods either fail to quantitatively incorporate characteristics of fractured rock and preferential pathways, or they account for only heavily karstified areas; none are suited to the fractured rock formations in Ontario.

The goal of this work is to incorporate fractured rock characteristics in a new aquifer vulnerability assessment method using readily attainable quantitative data to produce an inexpensive and straightforward regional aquifer vulnerability map highlighting hydrogeological areas that are more fundamentally prone to contamination than others. This proposed method is applied to the Acton-Georgetown study area in southern Ontario, along with the AVI and DRASTIC methods for comparison. The AVI and DRASTIC vulnerability assessments yield very different results from each other, and the proposed method demonstrates the heavy influence that fractured rock has on the vulnerability of the study area. The heterogeneity of variables used in some of the methods created difficulty in the interpolation of point data, rendering the use of generalized spatial data more valuable. These results and the corresponding limitations and recommendations for future improvements are discussed in light of these conclusions.

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PSW	Public Supply Well
GUDI	Groundwater Under the Direct Influence of Surface Water
MOE	Ontario Ministry of the Environment
K	Hydraulic conductivity
OGS	Ontario Geological Survey
GIS	Geographic Information System
T	Transmissivity
S	Storativity
IDW	Inverse Distance Weighting
FR	Fractured rock rating

Declaration of Academic Achievement

This document consists of research conducted by the author, with assistance noted in the acknowledgements. Chapter 3 is being submitted for publication in a peer-reviewed journal. The thesis supervisors, Dr. Sarah Dickson and Dr. Yiping Guo, are also authors of this paper. They both offered knowledge and expertise, providing valuable input throughout each stage of research and writing processes.

Chapter 1

Introduction

1.1 Overview

Over 30% of the Canadian population relies on groundwater as a drinking water source for household consumption (Environment Canada 2013). Groundwater aquifers, particularly in rural areas, are often the only available water source within reasonable proximity to users. The raw quality of groundwater is almost always exceptional compared with surface water sources, due in large part to natural filtration processes and a lack of direct exposure to surface contamination.

Municipal treatment of raw drinking water is expensive, and because a cleaner source means less treatment is necessary, groundwater is regularly pursued as a cost-effective source for drinking water public supply wells (PSWs). When a new groundwater source is tapped in Ontario, it has potential to require the minimum treatment of disinfection alone; if it can be proven that the aquifer provides sufficiently naturally filtered groundwater (MOE 2006). This scenario would be ideal from an economic perspective, however groundwater that is not up to the MOE quality standards, called groundwater under the direct influence of surface water (GUDI), needs chemically assisted filtration in addition to disinfection before being distributed; a much more costly process (MOE 2006).

Unfortunately, current methods for classifying GUDI water lack an established or standardized scientific basis. The MOE currently considers a PSW to be categorized as GUDI if there is physical evidence of surface water contamination or organisms, e.g. unacceptable turbidity or pathogens like *Giardia* and *Cryptosporidium* (MOE 2001). In Ontario, a groundwater source with the potential to supply GUDI water is categorized as such, until there is proof that it is reliably not GUDI water, and therefore does not require chemically assisted filtration (MOE 2001). The following items must be presented in an engineering report, under the expertise of a hydrogeologist, in order to verify that the well in question is not a GUDI source: hydrogeological characterization, local surface water description, well integrity assessment, groundwater quality evaluation, and filtration requirements (MOE 2001). Other jurisdictions across Canada and the United States have similar policies for classifying GUDI water, often relying on controversial or non-/semi-quantitative and arbitrary measures like the mapped aquifer vulnerability assessments. These vulnerability evaluations lack measurable classification techniques, as descriptive terminology is often paired with arbitrary ranking systems. Ideally, an inexpensive, straightforward, and easy-to-read regional aquifer vulnerability map can be developed, and will adequately highlight hydrogeological areas that are fundamentally more prone to contamination.

To date, procedures measuring and mapping the susceptibility of aquifers to contamination were developed with porous media or karst geology in mind, and fail to adequately account for fractured bedrock groundwater sources such as those found in the greater Guelph/Waterloo region in southern Ontario. A study by Borchardt et al. (2007) looks specifically at microbial contamination and reveals that the ability of shale aquitards to protect groundwater has been overestimated. The exact manner in which these contaminants travelled through or around the confining bedrock layer is unknown, but the authors discuss the possibility of fractures and preferential pathways as modes of transport, and warn that even deep aquifers can be susceptible to severely unsafe types and amounts of pollutants (Borchardt et al. 2007). Fractures and other pathways offer the possibility for rapid transport of contaminants beyond bedrock layers. This has strong implications for the drinking water regulations that directly influence the 28.5% of Ontarians that rely on groundwater for consumption and daily use (Environment Canada 2013).

Discovering that bedrock is less protective than originally thought triggered insight into aquifer vulnerability assessments and how they are applied in various jurisdictions. Many attempts have been made to develop a systemic method for quantifying an aquifer's intrinsic susceptibility to contamination in various geographical and hydrogeological regions. These methods all suffer from being arbitrary or qualitative in nature and many lack consideration for preferential pathways and fractured rock environments.

1.2 Research Objectives

The objectives of this thesis are:

1. To provide an overview of current intrinsic aquifer vulnerability assessments;
2. To develop a new method for measuring intrinsic aquifer vulnerability that directly incorporates quantitative fractured bedrock characteristics applicable to the geology found in southern Ontario;
3. To apply this new method to a study area in the Acton-Georgetown study area in southern Ontario;
4. To compare and contrast this new vulnerability method with other previously developed methods.

1.3 Scope

This thesis contains three chapters beyond this introduction:

Chapter 2 contains a literature review outlining details of the study area, a review on fractured rock, and an outline of previously developed aquifer vulnerability assessments and their applicability to fractured rock aquifers.

Chapter 3, which has been submitted to a peer-reviewed journal for publication, outlines the development of the proposed groundwater vulnerability assessment method, results of application, comparison with other methods, and conclusions.

Chapter 4 provides a thorough discussion, expanding on the conclusions mentioned in Chapter 3, and providing more details about method development and implications.

Appendix A contains the figures relevant to the literature review in Chapter 2, while Appendix B provides supplementary information regarding the interpolated point data approach as discussed in Finding 4 of Chapter 4. The approach and data used to complete the proposed aquifer vulnerability assessment method are presented with full detail in Appendix C.

Chapter 2

Literature Review

This chapter will introduce the following topics that serve as a foundation for the research paper presented in Chapter 3:

1. Study Area: a thorough depiction of the stratigraphy and hydrogeology of the Acton-Georgetown region where aquifer vulnerability is being analyzed;
2. Fractured Rock: background on fractured bedrock aquifers and clarification of current field characterization techniques for conceptual understanding of fractured rock environments; and
3. Aquifer Vulnerability Analyses: an overview with examples of the more eminent previously developed methods, as well as insight into how fractured rock is addressed within these approaches.

2.1 Study Area

This study will focus on the bedrock aquifer systems in the communities of Acton and Georgetown, and the surrounding region just northeast of Guelph, Ontario. The site is located regionally on the map shown in Figure 2 of Chapter 3, and pictured locally in Figure A-1 of Appendix A. This section will explain key stratigraphic and hydrogeological details of the study area.

2.1.1 Boundaries & Hydrogeological Features

The study crosses many political boundaries, falling mostly within the Credit Valley Watershed, crossing into the Halton Region Watershed to the southeast, and the Grand River Watershed to the west and northwest. The study area is mostly within Halton Region, but overlaps with Wellington County to the west. In the southwest section of the study area, Halton Region meets Guelph/Eramosa, Erin, and Milton Townships. Major hydrological features that control groundwater movement in the watersheds pictured include the Silver

Creek, Black Creek, Credit River, Niagara Escarpment, and various moraines and buried bedrock valleys (AECOM & AquaResource 2012).

The Niagara Escarpment is a major topographical formation, splitting the study area in half: the west portion has a higher elevation, ranging around 350 – 450 metres above sea level (masl), and the east side has a lower elevation, from roughly 250 – 300 masl (AECOM & AquaResource 2012). In general, the western study area above the Escarpment has some rock outcrops as well as permeable formations and sporadic wetlands to promote recharge (AECOM & AquaResource 2012). Below the Escarpment, the eastern study area has many discharge zones, where groundwater flows into streams, springs, and other surface waters (AECOM & AquaResource 2012). The Escarpment itself serves as a large seepage face for water recharged in the west, discharging to the east (AECOM & AquaResource 2012).

All flow on a regional scale is bound southeast toward Lake Ontario. Surface topography is the dominant influence on shallow groundwater movement on a more local scale, flowing generally from northwest to southeast (AECOM & AquaResource 2012). Flow from the some high points in the very northwest portion of the study area redirects shallow groundwater slightly further northwest; some eventually flows further north away from the study area, and some flows south, and then east toward the Escarpment and Credit River (AECOM & AquaResource 2012).

Deeper groundwater flow follows bedrock topography, which mimics ground elevation closely (AECOM & AquaResource 2012). Much of the study area has overburden less than 25 m thick, with outcrops above the Escarpment where the overburden is absent (AECOM & AquaResource 2012). Overburden thicknesses from 25 - 50 m exist in the northwest corner of the study area and along the buried bedrock valleys that run from Acton to Georgetown and east, parallel to the Niagara Escarpment (AECOM & AquaResource 2012).

The buried bedrock valley is essentially a series of thalwegs or beds with thick overburden that strongly influences and redirects groundwater flow. These bedrock valleys are thought to be significant sources of groundwater recharge from the Gasport (Amabel) formation into the overburden (AECOM & AquaResource 2012). Seifert et al. (2008) stress the importance of including buried bedrock valley systems in a groundwater model, particularly because they may significantly influence groundwater vulnerability.

2.1.2 Stratigraphy

A general stratigraphic cross-section of the study area is shown in Figure A-2, and the uppermost bedrock formations that underlie the study area are pictured in Figure A-3. Below the Escarpment, the uppermost fractured rock layer is the Queenston shale formation, which is overlain primarily by Halton Till with intermittent patches of gravel and outwash sand (Credit Valley Conservation et al. 2002). The west half of the study area has much more complex bedrock system. The uppermost rock layers above the Escarpment are made up of either the Gasport/Goat Island or Guelph/Eramosa formations. The term "Amabel," although recently outdated, is still frequently used in literature and watershed studies, often referring to the unsubdivided Gasport and Goat Island formations (Brunton 2009). For the purposes of this thesis, the Goat Island, Gasport, Lockport, Amabel, and similar formations are said to fall within the "Amabel" family. Below the Amabel and Guelph/Eramosa is a thin layer of Fossil Hill/Cabot Head shale, which overlies Manitoulin/Whirlpool dolostone (Credit Valley Conservation et al. 2002). These layers are around 50 – 75 m deep, and below them is Queenston shale (AECOM & AquaResource 2012). Wentworth Till is the dominating overburden type above the Escarpment, also with gravel and outwash sand patches (Credit Valley Conservation et al. 2002).

The formations underlying the study area all contribute to groundwater flow, but within this study area, key groundwater transport is influenced heavily by the Guelph/Eramosa and Amabel formations (AECOM & AquaResource 2012). Areas of high groundwater flow are directly associated with increased weathering and fracturing (AECOM & AquaResource 2012). The bedrock topography above the Escarpment is noted as having enhanced fracturing; in locations near the Escarpment, fracturing has more influence on groundwater flow than porous media transport (AECOM & AquaResource 2012). The gradients associated with the discussed bedrock layers do not always cause expected pressure systems, as municipal well pumping can interrupt regular water levels (AECOM & AquaResource 2012).

2.2 Fractured Rock Review

In order to understand what makes fractured rock aquifers vulnerable, it is necessary to explore what is currently understood about fractured rock in existing literature and textbooks, and to clarify the terminology regarding preferential pathways and their role in the geology of southern Ontario. The following subsections will outline how fractured rock is defined in the academic world and the complexities of how it can be characterized in the field.

2.2.1 Terminology

A thorough understanding of fractures is required before characterization of fractured rock aquifers can begin. “Discontinuity” is the encompassing term for bedding planes, foliation, fractures, faults, and other geological breaks (Singhal & Gupta 2010). Use of the term “fractures” in this thesis encompasses all of these discontinuities.

Bedding planes are typically the dominating geological discontinuity contributing to groundwater flow (Singhal & Gupta 2010). Foliation can be thought of as bedrock being squished, causing parallel or near-parallel breaks that are perpendicular to stress directions, and can also be a large influence on groundwater flow (Singhal & Gupta 2010). Faults or shear zones are often a result of tectonic activity and shear movement; the term “fault” is also used to describe a larger fracture where movement along the fracture surface is significant and visible (Singhal & Gupta 2010). Fractures and joints, the key discontinuities studied here, are “planes along which stress has caused partial loss of cohesion in the rock” (Singhal & Gupta 2010). The components describing fractures are split up into the rock matrix, infillings (these may or may not be present), and the fracture network (Singhal & Gupta 2010).

2.1.2 Characterization & Vulnerability

There is a multitude of ways to measure and characterize fractured bedrock aquifers. Because of their complex structure and heterogeneity, it is often difficult to categorize properties of fractured rock without advanced site-specific conceptual modeling. This subsection will explore some known characterization techniques. It should be noted that not all of these parameters are necessarily of significant value on a regional scale.

Firstly, fractures can be organized by geometry. Single fractures can be classified by orientation, using dip direction relative to true North and strike angles, which can be visually represented with a rose diagram (Singhal & Gupta 2010). In nature, geological formations often cause systematic joints, where fractures are relatively evenly spaced and parallel (Singhal & Gupta 2010). Fracture spacing or frequency, fracture length, and fracture density are self-explanatory measures often organized into groups or sets (Singhal & Gupta 2010). These measures can be used to find fracture intensity or linear, areal, and volumetric fracture densities within each set (Singhal & Gupta 2010). These types of measurements are usually a function of lithology made under heavy assumptions, and they provide a numerical assignment to fracture presence (Singhal & Gupta 2010).

Fracture aperture is the term used to describe how wide, or how tight a fracture is. Dr. Kent Novakowski notes that fracture aperture is a very difficult feature to measure with any meaningful accuracy in the field, since it is immensely variable (personal communication, August 20, 2013). Because of this, an “equivalent aperture” is often used to describe the average aperture across a particular fracture or fracture network under a smooth, parallel plate fracture concept (Singhal & Gupta 2010). Variable aperture is caused by bumps, vugs and irregularities along fracture walls; a feature called the fracture’s asperity, which causes flow to decrease and dictates turbulence (Singhal & Gupta 2010). Infillings, the extra material between fractures, will also influence fluid flow, but quantitative field measurements of infillings are impractical (Singhal & Gupta 2010).

Connectivity is an important quality of the fracture network, often serving as a majorly dominating factor in groundwater transport. It is difficult to directly measure a single value for connectivity, because it is influenced by many overlapping fracture characteristics: fracture length, density, degree, conductivity, transmissivities, apertures, etc. (Singhal & Gupta 2010). Fractures can be microscopic or several metres long. When used in regional vulnerability assessments, fracture connectivity must be quantified on a larger scale. Even if many fractures are present, their termination mechanisms may prevent through-flow of water (Singhal & Gupta 2010). Conversely, it is entirely possible for fracture networks to be ultimately responsible for rapid movement of water from the surface into deep aquifers. Fracture termination is defined in three ways: blind, diffuse, and connecting (Singhal & Gupta 2010). As seen in Figure A-4, a 'blind' fracture ends without any connection to other fractures (B), 'connecting' fractures exist where multiple fractures meet (C), and 'diffuse' termination describes one fracture breaking off into multiple branches from a point (D) (Singhal & Gupta 2010).

Although there are many ways to characterize water flow through fractures and their overall connectedness, deciding the appropriate factors to use in vulnerability analyses is complex. As mentioned by Thornton & Wealthall (2008), fracture geometry, spatial and temporal variation in hydraulic properties, and transport mechanisms are imperative when developing a conceptual groundwater model and understanding dominating flow paths. Thornton & Wealthall (2008) found that contaminant flux within their study area was strongly influenced by transmissivity and water table fluctuations in the area, and that groundwater flux depends on fracture aperture and intensity (Thornton & Wealthall 2008). Recharge is the major influencer on water table fluctuations, and plays a key role in vulnerability analyses because major transport pathways will change as the water table moves (Thornton & Wealthall 2008).

Thornton & Wealthall (2008) raise a point brought forth in many studies: any combination of flow-inducing parameters can contribute to a primary, hydraulically significant zone. Highly fractured zones do not necessarily correlate to highly transmissive zones, and it takes a combination of hydraulic conductivity and interconnection to be hydraulically significant (Thornton & Wealthall 2008). It is possible to witness, within a highly fractured area, only a small set of fractures that actually contribute to groundwater flow (Thornton & Wealthall 2008). It is also possible that flow in karstified areas with many wide, open conduits can still be dominated by highly conductive interconnected bedding plane fracture features, completely independent of the karst network (Perrin et al. 2011).

There are many ways to numerically categorize fractured rock, but the heterogeneity of fracture networks makes these types of measurements very specific and only useful on a local or well-by-well basis. Overall, the literature suggests that the main qualities that will contribute to the vulnerability of an aquifer are:

1. The rate that water travels through fractures (flux), and
2. The fracture connectivity

Quantifying fracture connectivity is not straightforward. Various procedures discussed in the next subsection will outline current field methods used in southern Ontario that characterize fractured rock qualities.

2.2.3 Field Methods

The local fracture features mentioned previously all contribute to an overall fracture connectivity, but they fail to quantify a general, large-scale connectivity in a practical sense. A lengthy fracture with a large aperture may be capable of transmitting water and pollutants very rapidly, but if it is completely disconnected from the ground surface or any contaminant transport pathways, its contribution to the vulnerability of an underlying aquifer is minimal. This section examines field methods that are currently available and commonly used for fractured rock characterization, including the discussion of different approaches that have been taken in an attempt to quantify the connectivity of fractured rock aquifers.

Borehole Logs

In order to perform hydraulic testing on aquifers in either porous media or fractured rock, boreholes must be dug or drilled. This can be done in a variety of ways, but modern techniques provide reasonably preserved cores, which can be photographed and logged to identify the underlying lithological layers. Borehole logs in fractured rock are valuable in the detection of active fractures (West et al. 2005). In practice, rock cores are cracked or broken in the process of drilling; distinguishing between breaks that are natural versus mechanical fractures, and detecting which natural fractures actively transmit water can prove difficult (Kent Novakowski personal communication, August 22, 2013). Munn (2012) recommends drilling inclined boreholes rather than the traditional and more biased vertical approach. This way, highly angled fractures that are potentially key transport pathways are much less likely to be overlooked, and the approach is fair (Munn 2012).

Hydraulic Head Profiling

Completed on a single-borehole, hydraulic head profiling is a detailed approach to quantifying hydraulic connectivity from the ground surface to any point below. Multilevels measure how hydraulic head changes with depth, and inflection points in detailed head profiles serve as a numerical and visual representation of vertical hydraulic gradients (Meyer et al. 2008). These interfaces show a lack in vertical flow, representing reduced connectivity between sections or units that are separated by hydraulic head; these units do not necessarily match up with stratigraphic layers (Meyer et al. 2008). Because this approach pinpoints exact depths where vertical connectivity between hydrogeological layers changes, it is an extremely effective method for measuring vertical connectivity between any aquifer and the ground surface. Unfortunately, this technique and other borehole-scale tests are time-consuming, expensive, and not practical for classification of connectivity on a large scale.

Pumping Tests

Most textbooks and literature will propose transmissivity (*T*) and storativity (*S*) measurements as the two most prominent fractured rock features denoting aquifer connectivity. Several field tests are capable of measuring *T* and *S* on different scales. Pumping tests are common when a general understanding of fracture connectivity over a large region is required, as opposed to testing individual, isolated fractures (Le Borgne et al. 2006).

Pumping tests should run for at least 48 hours in fractured rock in order to achieve data that are readily analyzable. Analysis is typically done using type curves, but can be complicated since many variations of methods must be applied, as assumptions change under different physical conditions (Fetter 1994). The traditional approach by Theis for completely confined aquifers is often used as a baseline, but variations on conditions (e.g. leaky, unconfined aquifers) have led to many other pumping test analysis methods by Hantush, Jacob, Walton, etc. (Fetter 1994). In a pumping test analysis, choosing the correct analysis, or one that matches the physical groundwater conditions, is often the most challenging step. However, many different approaches will often lead to results on the same order of magnitude.

Pulse Interference Tests

Pulse interference testing also yields *T* and *S* measurements in fractured rock aquifers in a process similar to slug testing. Because the storativity in fractured rock is so small, the pressure change from slug insertion or removal into a source well can also be measured at response wells several metres away, given that a connection in the formation exists between the wells (Novakowski, personal communication August 22, 2013; Elmhirst 2011). Novakowski (1989) outlines type curve analysis methods and includes incorporation of well bore storage effects. Pulse interference tests are much less time consuming than pumping tests, and are relatively inexpensive (Elmhirst 2011).

2.2.4 Scale Effects

Fractured rock is heterogeneous in nature and, because of this, *T* and *S* measurements in fractured rock aquifers will vary at different scales (Elmhirst 2011). When performing hydraulic tests on a local scale in fractured rock, the rock matrix plays a more prominent role in groundwater flow than it would on a larger scale (Le Borgne et al. 2006). If larger sections of rock are tested, it is the preferential pathways or fractures that act as the major flow mechanism; thus, the transmissivity measured on a larger scale will be higher than the transmissivity measured on a smaller scale.

2.3 Vulnerability Assessments

2.3.1 Overview

A thorough understanding of hydrogeology in fractured rock aquifers can illustrate how easy it is for groundwater to become contaminated. This understanding is vital in groundwater/source water protection and remediation management, especially because public health is at risk. This research comes from a source-protection perspective, meaning it will focus on prevention of contamination rather than remediation of already-polluted water sources, avoiding the notoriously high costs associated with groundwater treatment and cleanup.

Current vulnerability assessments and management tools are used to designate the relative susceptibility of aquifers to contamination. Aquifer vulnerability in its most general sense is a dimensionless, inherent measure of the possibility that any anthropogenic contaminant will reach a groundwater source from the surface (Elçi 2012). It can also be measured as a contaminant-specific vulnerability; this is applied when an aquifer is already known to be contaminated, and incorporates mobility and chemical properties particular to the contaminant at hand (Elçi 2012). Specific vulnerability assessments are useful in remediation efforts, when specific contaminants are a known threat (e.g. nitrate). Intrinsic vulnerability is applicable to preventative measures and source protection, useful in drinking water source management.

The geological, physical, and chemical factors considered in aquifer vulnerability mapping are subject to the expertise and judgment of scientists, engineers, and governing protocols (Harter 2005). There currently exists a variety of vulnerability models, each employing its own set of hydrogeological elements and the relative importance of these elements (Harter 2005). In 1998, Robins emphasized the pivotal and complex role of recharge in an aquifer's overburden as a factor of vulnerability. Gogu and Dassargues (2000) also consider recharge, but claim that key parameters in an intrinsic vulnerability assessment should also include soil properties, topography, groundwater/surface water interactions, the underlying aquifer composition, and the structures of the saturated and unsaturated zones. In general, natural attenuation processes dictate how much and how quickly contaminants travel into aquifers (Gogu & Dassargues 2000).

Robins (1998) and Gogu & Dassargues (2000) emphasize that known vulnerability assessment methods tend to leave out effects of fracture networks and preferential flow paths. These effects must be adequately encompassed into vulnerability evaluations in order to achieve an accurate estimate of the risk of contamination in an aquifer. This is particularly evident in the example by Borchardt et al. (2007), where microbial contamination is found below a shale aquitard in a deep well; this is contrary to previous assumptions that confining layers prevent quick downward movement of contamination. Bias is a clear hindrance on the credibility of aquifer vulnerability tools, and the results have been criticized and questioned since vulnerability mapping came to be (Harter 2005). The majority of assessments described in the this section will often mention fracturing in a qualitative manner and assign arbitrary rankings based on descriptive media types, lacking up-to-date measurable fracture characterization techniques.

All current methods can be categorized into three groups: index and overlay, process-based computations, and statistical evaluations (Harter 2005). Index and overlay procedures for assessing aquifer vulnerability involve compiling pertinent hydrogeological factors, assigning weights to them, giving a final score based on a ranking process, then mapping these results over the watershed with Geographic Information Systems (GIS) (Harter 2005). Decision trees, matrices, and/or algorithms are often used in these methods to take sizable amounts of data and boil them down to a single, easy-to-read map. It has become essential to use GIS software in all index and overlay aquifer assessments to develop a final visual representation of vulnerability that can be meaningfully communicated. These maps serve as an inexpensive and practical decision-making instrument for watershed management and policy (Harter 2005).

Index and overlay methods necessitate collaboration between politicians, watershed managers, and scientists (Gogu & Dassargues 2000). Human communication is an important factor in the ratings and ranking of index and overlay parameters, as noted by Van Stempvoort et al. (1993). Although the collaboration of expert judgment is valuable in the creation of vulnerability assessment tools, it is a limiting factor when disagreements and bias occur. Indices based on biased and/or descriptive wording are common, and many are dependent on accurate transcription of logs and recorded data (Van Stempvoort et al. 1993). Weightings and choices of measured parameters in index and overlay methods are decided upon with expert opinions, and individual parameters are often strongly dependent on one another (Elçi 2012).

Computational simulations provide a much more thorough assessment of contamination potential in aquifers, but require intensive testing and data assembly. A three-dimensional approach allows for detailed modeling of groundwater flow and contaminant transport through multiple varying geologic layers over time (Harter 2005; Gogu & Dassargues 2000). From these simulations, it is not a direct vulnerability index or ranking outcome that is calculated, but rather transport times or contaminant concentrations, from which a sense of vulnerability can be determined (Harter 2005). The complexity of this type of method is much less user-friendly for water resource management and decision-making, the costs associated are high, and the results are often contaminant-specific.

The utilization of statistical methods to quantify vulnerability is similar to index and overlay except that statistics are applied alongside, or in place of expert judgment (Harter 2005). The use of statistics in aquifer vulnerability analysis can clarify the relationship between hydrogeological parameters and the pollution potential of groundwater, and offers uncertainty measures within the model (Harter 2005).

There clearly is no grand scheme for one standard vulnerability assessment; however, there is promise in the continual improvements that are made to existing techniques in an attempt to reduce subjectivity. The best approach to implement in a vulnerability assessment depends on the quality and quantity of data available (Elçi 2012). The focus of this research is to contribute a new, practical method that employs independent variables and up-to-date fractured rock characterization techniques discussed above, and to compare this new method to existing methods. Current index and overlay aquifer vulnerability assessments are summarized in Table 1 of Chapter 3, and the applicability of fractured rock within each one is outlined in the following subsection.

2.3.2 Vulnerability Assessment Examples

DRASTIC

DRASTIC is the popular American standard for assessing aquifer vulnerability using the following parameters: depth to water, net recharge, aquifer media, soil media, topography/slope, impact of vadose zone, and hydraulic conductivity of the aquifer (Aller et al. 1987). A single pollution potential, indicative of aquifer vulnerability, is calculated using the sum of all pre-assigned weights multiplied by the ratings of each parameter, where the weights have been ranked and assigned based on expert opinions (Aller et al. 1987). These parameters were decided upon largely for their field obtainability, as practicality was a prominent concern in the creation of DRASTIC (Aller et al. 1987). Field methods, particularly in fractured rock media, have improved since this method was developed.

Within the guidelines for using DRASTIC, it is made very clear that each analysis should be completed strictly on a case-by-case basis under skilled judgment, stating that “an inappropriate use of DRASTIC would be to specifically site a municipal well in a wellfield located in a fractured bedrock area” (Aller et al. 1987). This makes the application of DRASTIC or similar vulnerability assessments tricky for fractured bedrock aquifers in southern Ontario.

Within the DRASTIC procedure, fracturing can be considered within the aquifer media, impact of vadose zone, and hydraulic conductivity parameters (Aller et al. 1987). Aller et al. (1987) provide a chart for easy selection of the aquifer media rating based on media type, and fracturing is listed as a primary consideration; however, no measurements are specified to characterize fractured rock. This same idea follows for the impact of vadose zone factor (Aller et al. 1987). The authors briefly discuss how a higher degree of fracturing and interconnection between fractures should boost the rating of the vadose zone media factor, and therefore overall vulnerability (Aller et al. 1987). This approach is logical, but no quantitative methods for characterizing fractures are mentioned.

AVI

The AVI, which simply stands for Aquifer Vulnerability Index, is a less sophisticated, strictly numerical approach to mapping aquifer susceptibility that uses the sum of all lithological layer thicknesses divided by corresponding hydraulic conductivities for each respective layer (Van Stempvoort et al. 1993). This sum is equal to the total formation’s vertical resistivity to water flow into the aquifer, and this value is mapped to represent the vulnerability (Van Stempvoort et al. 1993). This approach assesses the vulnerability of only the “uppermost saturated” aquifer (Van Stempvoort et al. 1993). The two parameters involved are relatively easy to understand and measure, making AVI very applicable and quantifiable.

When hydraulic conductivity measures are not readily available, Van Stempvoort et al. (1993) recommend using estimates from texts; unfortunately the uncertainty revolving around these estimates is sizable. The conductivity estimates are often chosen based on media type using “fractured” as a descriptor for different sediment categories (Van Stempvoort et al. 1993). It is the intention in the AVI method that conductivity estimates are to be modified under the user's discretion with added information about the study area (Van Stempvoort et al. 1993). The authors mention the significance of fracture connectivity and suggest the depth below ground surface of fracture location is of little importance, under the assumption that fractures diminish downward (Van Stempvoort et al. 1993).

GOD

Seen as the British parallel to DRASTIC, the GOD vulnerability characterization technique is tuned to the sandstone and limestone bedrock aquifers of Great Britain (Harter 2005). GOD is an acronym for the method's procedure, which considers groundwater occurrence, overlaying layer lithology, and depth to groundwater as the factors determining contamination potential (Foster 1987). GOD is not a summation like DRASTIC; in GOD, all three parameters are multiplied together for a final vulnerability index (Gogu & Dassragues 2000).

The groundwater occurrence parameter depends on the user's judgment of the aquifer's confinement level. The groundwater occurrence rating is multiplied by the subsequent overlying lithology or rock formation rating only if the aquifer is unconfined, and the third step incorporates a depth to groundwater rating (Gogu & Dassragues 2000). The degree of fissuring is included qualitatively in the overlying lithology rating in Step II of the GOD method (Gogu & Dassragues 2000).

EPIK

EPIK is another acronym, short for the following vulnerability parameters: epikarst, protective cover, infiltration, and karst network (Doerfliger et al. 1999). Similar to DRASTIC, the EPIK method pre-assigns weights to each parameter and uses a summation of weight-rating products as a final index for susceptibility (Doerfliger et al. 1999). The numerical result in an EPIK vulnerability approach calculates a "protection factor," as the authors anticipated this vulnerability assessment to be utilized as a mode of defining karst protection zones

(Doerfliger et al. 1999). The procedure in EPIK is similar to DRASTIC, but tailored to karst-specific geology where runoff frequently enters groundwater almost immediately through swallow holes and other large, open conduits, bypassing infiltration (Doerfliger et al. 1999). For example, depth to water is considered one of the most heavily weighted factors in DRASTIC, but is included as only a subcategory of the EPIK method (Aller et al. 1987, Doerfliger et al. 1999).

The epikarst attribute is classified into subjective levels of karst presence, ranging from highly developed features, like sink holes and open channels, to nonexistent karst geology (Doerfliger et al. 1999). The described level of fracture development is what defines this parameter. The epikarst factor is measured with topographical maps and aerial photographs at various scales recommended by Doerfliger et al. (1999). The authors encourage further research into geophysics and tracer testing in an effort to conduct a more numerical assessment of epikarst development, but still use qualitative characterizations for rating the epikarst factor (Doerfliger et al. 1999).

Network development of karst features is implemented in the EPIK method to incorporate the connectivity of openings and channels providing direct flow routes to the underlying aquifer (Doerfliger et al. 1999). The aperture and orientation of channels is considered in hopes of identifying a valuable gauge of flow velocity, which in turn is directly responsible for vulnerability (Doerfliger et al. 1999). This network is characterized qualitatively as either a well-developed, a poorly-developed, or a mixed/fissured aquifer, and the authors suggest use of tracer tests to analyze discharge (Doerfliger et al. 1999).

Overall, EPIK's consideration for fracturing is extensive: fracture extent, size of conduits, and connectivity are all included (Doerfliger et al. 1999). These attributes are characterized qualitatively as mentioned above, despite the use of quantitative testing methods (Doerfliger et al. 1999).

COP

The concentration of flow, overlying layers, and precipitation are all incorporated into a vulnerability index in the COP method by Vías et al. (2006).

Each factor is ranked from five classes ranging from “very low” to “very high” and mapped (Vías et al. 2006). These scores are all combined accordingly to form a final COP index, also separated by the classes mentioned.

The “O” factor in COP uses these weighted media types, depths, and confining conditions of the soil and lithology for a starting “protection value” (Vías et al. 2006). This value is multiplied by the “C” score, which accounts for recharge conditions and their respective vulnerabilities (Vías et al. 2006). Ground areas where unsaturated media is bypassed, called swallow holes, are equally weighted with all other areas; the “C” score expresses the level to which these factors reduce the protection provided by the overlying layers (Vías et al. 2006). Karst is a heavy consideration in this step, as each surface feature is ranked on karst feature type and whether or not those features are permeable or impermeable (Vías et al. 2006). Vegetative cover in relation to topography is also considered in the “C” score and appears to be relatively unique to the COP method (Vías et al. 2006). The precipitation factor is defined by the quantity and temporal distribution of rainfall (Vías et al. 2006). It is mapped and multiplied with the “C” and “O” scores, applying a reduction in protection if rainfall levels are high or intense (Vías et al. 2006).

ISI

The Intrinsic Susceptibility Index (ISI) is the minimum standard set out by the Ontario Ministry of the Environment for vulnerability mapping as a groundwater source protection tool (MOE 2001). The ISI considers the depth from ground surface to water table, or thickness of confining layers, and hydraulic conductivity (MOE 2001). Each unit is assigned a ‘K-factor,’ similar to other index and overlay weightings, based on media type and hydraulic conductivity (MOE 2001). The thicknesses considered depend on how confined the most significant potential aquifer is (MOE 2001). The summation of each layer thickness multiplied by its K-factor yields a final ISI, assigned on a well-by-well basis and interpolated usually by kriging, then ranked as low, moderate, or high susceptibility (MOE 2001).

Although the hydraulic conductivity is used to quantitatively classify each material, the representative K-factors assigned do not directly coincide with magnitudes of hydraulic conductivities. The hydraulic conductivity of fractured or weathered rock in southern Ontario falls within a large range; in the study area alone, various rock formations range in hydraulic conductivity from $1x10^{-9}$ to $1x10^{-4}$ m/s (AECOM & AquaResource 2012). The K-factors assigned to fractured rock within the ISI guidelines do not represent this range of hydraulic conductivities (MOE 2001).

The ISI method is the only method to discuss a required level of certainty to be provided, and a depth-to-water-table map must be the “best available,” as decided by expert hydrogeologists (MOE 2001). Acknowledging that the water table is constantly changing, updates and a level of certainty in the water table depth used for the ISI ratings must be included (MOE 2001).

2.3.3 Application of Aquifer Vulnerability Maps

Inexpensive, simple guides to intrinsic hydrogeological contamination potential are important in groundwater/source water protection and remediation decisions, especially because public health is at risk. Often, the creators and users of vulnerability assessments come from diverse scientific backgrounds, thus the intentions and limitations of these tools must be made very clear. Final aquifer vulnerability maps are meant for use as a communication tool to bridge the gap between hydrogeological science and environmental management (Foster et al. 2013). In bridging this gap, there is a definite threat of misinterpretation or disagreements. Vulnerability assessment maps can be dangerous if used in the wrong context or misunderstood.

Experts often claim that vulnerability assessments are too general; noting the term “vulnerability” is vaguely defined and relative (Foster et al. 2013). The concept of aquifer “vulnerability” is criticized because contaminant attenuation and natural protective abilities of ground layers are complex and so many significant variables are at play (Foster et al. 2013). Index and overlay methods are said to represent an oversimplification of immensely complicated contaminant transport mechanisms, leaving out key details in groundwater transport that contribute to the full story (Foster et al. 2013). However, thorough hydrogeological models are also complicated and require a specific educational background in order to understand them. These models are often impractical in management and policy decisions because of their complexity and high expense. Index and overlay assessments are accessible to all involved with water resource management decisions (Foster et al. 2013). They act as a screening tool to effectively indicate areas for further assessment and allocate finances accordingly.

Foster et al. (2013) note that mapped vulnerability assessments indeed serve as an excellent first-step screening tactic used for selecting sites for more detailed future hydrogeological studies. The resulting key features (e.g. severely vulnerable areas) should be obvious, and the method itself should have definitive vulnerability categories and generally be kept as simple as possible; “[t]he more complex the vulnerability assessment procedure is, the more likely it is to obscure the obvious and make the subtle indistinguishable” (Foster et al. 2013). It is the authors’ intention to follow these suggestions with the aquifer vulnerability assessment method proposed in this thesis, and to provide a candid and comprehensive screening tool that is scientifically sound and useful in related water resource management decision-making. The proposed method is not meant to serve as a sound conceptual model for groundwater movement or contaminant transport, but rather as a management tool used to inform stakeholders and effectively direct resources for further research and development.

Chapter 3

Proposed method: incorporation of fractured rock in aquifer vulnerability assessments

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Keywords: vulnerability mapping, fractured rock, groundwater protection, Ontario

Abstract

Much of Ontario relies on fractured rock aquifers for municipal drinking water supplies. To protect these sources now and into the future, the Ontario Clean Water Act identifies the need to distinguish vulnerable aquifers. Aquifer vulnerability assessments are part of this process, and are useful in efficiently allocating resources for source water protection. Existing methods include DRASTIC, GOD, EPIK, AVI, COP and ISI. Some approaches do not consider risks posed by fractures, while others were developed for karstified regions; all are ill suited to the fractured formations found in much of North America. This work proposes a new vulnerability assessment method incorporating quantitative portions of existing methods together with fractured rock characteristics. The proposed method is applied to a study area in Acton-Georgetown; the DRASTIC and AVI methods are also applied for comparison. DRASTIC and AVI yield significantly different results from each other and from the proposed method. The proposed method demonstrates the heavy influence fractured rock has on vulnerability, highlighting the need for its inclusion in vulnerability assessments.

3.1 Introduction

More than 30% of Canadians rely on groundwater for their drinking water source, particularly in rural areas where aquifers may be the only source within reasonable proximity to users (Environment Canada 2013). Municipal treatment of raw drinking water is expensive, and the cost rises as the quality of the source water declines. Groundwater is pursued as a cost-effective source of drinking water as it is often less contaminated than surface water. Vulnerability assessment maps are a common first-step in the establishment of new drinking water sources, hydrogeological characterization, source water protection, and other water resource planning decisions (Ontario Ministry of the Environment (MOE) 2001).

Aquifer vulnerability in its most general sense is a dimensionless inherent measure of the possibility of any human-induced surficial contamination reaching a groundwater source (Elçi 2012). Current vulnerability assessment methods are used to designate relative scales of aquifer susceptibility to anthropogenic contamination. It can also be measured as a contaminant-specific vulnerability; this approach often applies when an aquifer is already known to be contaminated, and considers mobility and chemical properties that are unique to the contaminant at hand (Elçi 2012). *Specific* vulnerability is useful in situations where individual contaminants are a known threat, while *intrinsic* vulnerability is applicable to preventative efforts and source protection.

Common index and overlay procedures for assessing aquifer vulnerability involve compiling pertinent hydrogeological factors, assigning weights to each factor, determining a final score based on a ranking process, and mapping the results with Geographic Information Systems (GIS) (Harter 2005). The result is a single, easy-to-read, colour-coded map that visually represents areas of relative vulnerability within the study area. These maps serve as a valuable and practical decision-making tool for watershed management and policy (Harter 2005). Computational simulations and statistical methods can also be used to get a sense of aquifer vulnerability; however, these methods are more expensive and require rigorous testing and data assembly.

The geological, physical, and chemical factors considered in aquifer vulnerability mapping are subject to the expertise and judgment of engineers, scientists, and governing protocols (Harter 2005). There are a variety of existing index and overlay methods, each selecting its own set of hydrogeological information and the importance (i.e. weight) of this information (Harter 2005). Table 1 summarizes the common index and overlay methods, including the hydrogeological factors considered, the approach, and the context in which they were developed.

The index and overlay methods listed in Table 1 were developed with either porous media or karst geology in mind, and are not adequate for assessing the vulnerability of the fractured rock environments that southern Ontario relies on for drinking water. Both Robins (1998) and Gogu and Dassargues (2000) emphasize that these methods tend to neglect the effects of fracture networks and preferential flow paths. A study in deep sandstone wells by Borchardt et al. (2007) looks specifically at microbial contamination and reveals that the ability of bedrock aquitards to protect groundwater has been overestimated. The exact manner in which these contaminants travelled through or around the shale aquitard is unknown, but the authors discuss the possibility of fractures and other preferential pathways as modes of transport, and warn that even deep aquifers can be susceptible to severely unsafe types and amounts of pollutants (Borchardt et al. 2007). Fractures and other pathways offer the potential for rapid transport of contaminants beyond confining layers; this has strong implications for the drinking water regulations that directly influence the 28.5% of Ontarians who rely on groundwater for their domestic water supply (Environment Canada 2013).

Table 1 Aquifer vulnerability assessment method summary (Aller et al. 1987; Foster 1989; Doerfliger et al. 1999; Vías et al. 2006; Van Stempvoort et al. 1993; MOE 2001).

Method	Factors considered	Description
DRASTIC	Depth to water table Recharge Aquifer media Soil media Topography Impact of vadose zone Hydraulic conductivity	• Weights assigned to each factor • Ratings assigned to ranges within each factor (e.g. within "aquifer media" factor, shale is rated from 1-3, limestone is rated 5-9) • Final vulnerability is sum of all weights of each factor multiplied by associated ratings • Higher index corresponds to higher vulnerability
GOD	Groundwater occurrence Overlaying lithology Depth to water table	• Ratings assigned to each factor • Step-by-step flow chart approach, ratings act as modifiers • Higher final vulnerability index corresponds to higher vulnerability
EPIK	Epikarst Protective cover Infiltration conditions Karst network	• Ratings assigned to ranges within each factor • Final vulnerability is sum of all weights of each factor multiplied by associated ratings • Higher final vulnerability index corresponds to lower vulnerability
COP	Concentration of flow Overlying layers Precipitation	• Each factor assigned a "score," final index is product of each score • Scores calculated based on other indices with associated ratings (e.g. "P" score is composed of quantity and temporal distribution indices) • Indices are assigned ratings based on ranges • Higher COP index corresponds to lower vulnerability
AVI	Depth to water table Thickness of sedimentary layers Hydraulic conductivity	• No arbitrary weights or ratings assigned • Sedimentary layers above uppermost saturated aquifer surface are assigned a thickness and estimated hydraulic conductivity • Vulnerability is based on hydraulic resistance estimates, equal to the sum of all layer thicknesses divided by corresponding layer hydraulic conductivity • Higher hydraulic resistance corresponds to lower vulnerability
ISI	Depth to water table Thickness of sedimentary layers Hydraulic conductivity	• Vulnerability index is sum of thickness of each layer multiplied by a corresponding dimensionless "K factor" • K factor is an assigned rating based on geomaterial and range of hydraulic conductivity estimates • Index is calculated at each well and maps show interpolation between wells • Higher final vulnerability index corresponds to lower vulnerability

Groundwater experiences greater protection from anthropogenic activity in comparison to surface water sources, leading to the common belief that bedrock aquitards are capable of restricting the migration of pollutants into underlying aquifers. This feeds the notion that confined groundwater is safe from contamination- a notion that must be re-examined. Borchardt et al. (2007) emphasize the imperative role that fractured rock can have on the vulnerability of aquifers, and this must be accounted for when assessing the vulnerability of potential drinking water sources in Ontario. The goal of this paper is to incorporate fractured rock characteristics in a new aquifer vulnerability assessment method, hereafter referred to as the proposed method. This method uses readily attainable quantitative data to produce an inexpensive and straightforward regional aquifer vulnerability map, highlighting hydrogeological areas that are fundamentally more prone to contamination relative to others.

3.2 Method development

The intrinsic vulnerability assessment methods listed in Table 1 consider very similar hydrogeological properties, all of which support two independent concepts:

a) The vulnerability of an aquifer is related to the amount of available infiltration, which acts as a mechanism of transport for contaminants to migrate to the water table.
b) The vulnerability of an aquifer is related to the unsaturated layer(s) (above the water table), and its ability to attenuate or withhold contamination thus preventing or delaying the migration of contaminants to the water table.

The concepts described in (a) and (b) will hereafter be referred to as recharge availability and overburden factors, respectively, and form the basis for the proposed method. A flowchart of the proposed method is provided in Figure 1, and shows that recharge availability and overburden factors are considered with equal importance.

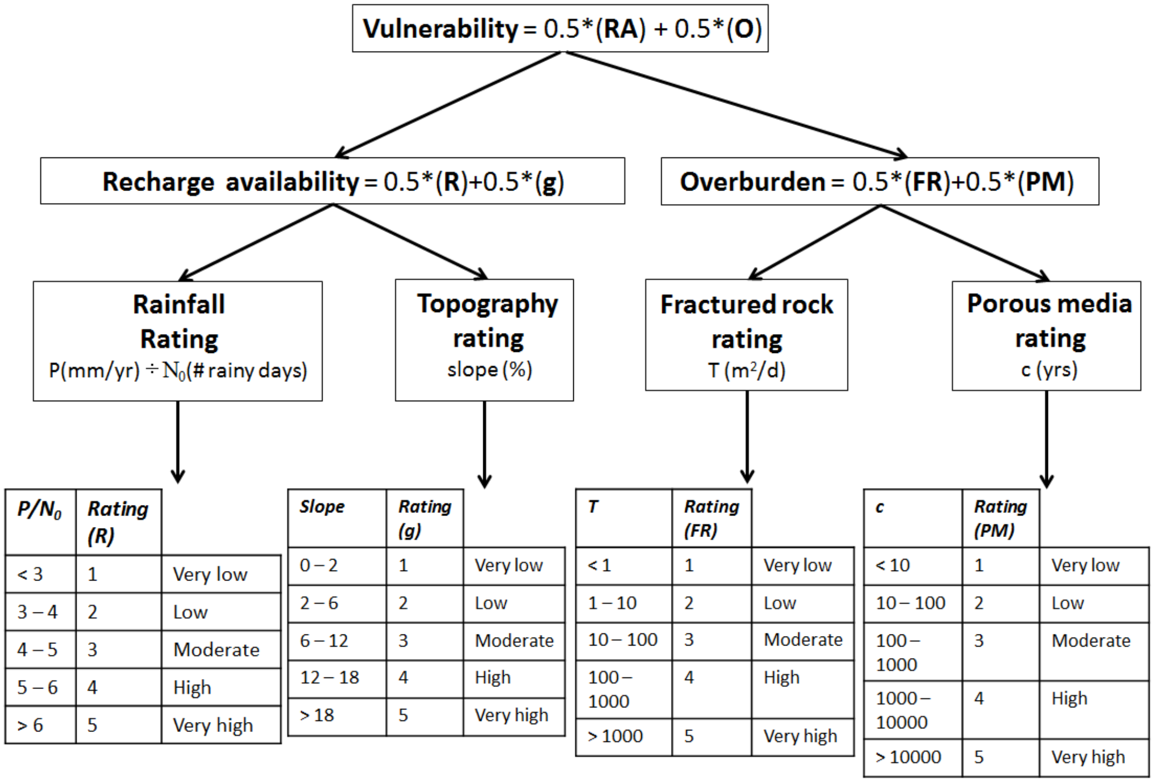

Figure 1 Proposed vulnerability assessment method, with variables recharge availability (RA), overburden (O), rainfall rating (R), topography rating (g), fractured rock rating (FR), and porous media rating (PM)

3.2.1 Recharge availability (RA)

Recharge typically refers to water penetrating the ground surface and reaching the water table; the amount of recharge is influenced by soil media, evapotranspiration, topography, infiltration, vegetative cover, runoff, precipitation, freeze/thaw conditions, soil permeability and porosity (Döll & Fiedler 2008; AquaResource Inc. 2008; USGS 2014; USGS 2013). These factors all affect aquifer vulnerability in the context of recharge availability, however many also influence vulnerability factors related to overburden. Therefore, proposed method considers only the amount of precipitation that is available to recharge the underlying aquifer, in the form of annual rainfall, average intensity, and topography. All of these measures are easily obtainable, and none are confounded with overburden factors.

Higher recharge availability corresponds to a greater opportunity for contaminant migration to the aquifer, and thus higher aquifer vulnerability; however, both DRASTIC and COP integrate the contrasting effects of dilution. Aller et al. (1987) and Vías et al. (2006) determine a threshold where the risk of increased transport of contaminants is outweighed by dilution; recharge values larger than this threshold act to decrease the vulnerability.

Rainfall Rating (R). In contrast to this, the proposed method emphasizes the protection of both drinking and source water, and therefore dilution is not considered; instead the goal is to determine the likelihood of contaminants reaching an aquifer, regardless of the concentration. The proposed method defines the rainfall rating as the annual rainfall, P (mm/yr), divided by the number of rainy days per year, (N_0), and uses this parameter as an indicator of the recharge availability, similar to the P factor in the COP method (Vías et al. 2006). The data required to calculate the rainfall rating are easily attained through Environment Canada's meteorological databases (Environment Canada 2014a). The rainfall rating is ranked according to average annual rainfall and rainy day data from 41 cities across Ontario (Environment Canada 2014b).

Snowmelt was considered for inclusion in the proposed model but not used. Simple models describing snowmelt exist, but none are applicable in the context of the proposed vulnerability assessment. Factors contributing to the intensity of a snowmelt, or the rate at which snow melts and infiltrates into the ground, are not easily defined by readily available data such as daily temperatures and snowfall. The proposed method is meant to be used as a first-step screening tool for aquifer vulnerability, and the incorporation of snowmelt would be appropriate at later stages of assessment, where thorough conceptual models of groundwater movement are required.

Topography Rating (g). The topography of the study area is as important as the rainfall intensity in terms of the risk of aquifer contamination due to recharge, and therefore both of these factors are given an equal weighting in the proposed method. The EPIK, COP and DRASTIC methods also emphasize the importance of land slope on relative portions of runoff and infiltration (Doerfliger et al. 1999; Vías et al. 2006; Aller et al. 1987). The topography rating in the proposed method implements the concept introduced in DRASTIC, where a slope of 0-2% is assumed to permit infiltration and a slope of 18% or larger will generally create runoff conditions (Aller et al. 1987). By accounting for the intensity and frequency of rainfall together with the site topography, the available recharge is spatially evaluated over the study site. It must be noted that this calculation (available recharge) remains independent of the overburden's counteraction to downward contaminant transport.

3.2.2 Overburden (O)

The overburden is defined as the layers between the ground surface and the water table. The ability of these layers to attenuate, retard, degrade, or otherwise impede contaminant migration to the water table is important in the assessment of aquifer vulnerability. Mechanisms of contaminant transport in subsurface environments include advection, dispersion, diffusion, adsorption and decay; however, the relative importance of each of these mechanisms differs in porous and fractured media (Singhal & Gupta 2010). Thus, these two types of media must be considered separately, yet weighted of equal importance, in the assessment of aquifer vulnerability.

Porous Media Rating (PM). The AVI method, developed by Van Stempvoort et al. (1993), suggests rating aquifer vulnerability using a hydraulic resistance calculation, representing the ability of overburden to resist downward movement of water. The resistivity of a layer, c_i, is defined as the thickness of the layer, d_i, divided by its hydraulic conductivity, K_i; the total resistivity (c) is simply the sum of the resistivities for each layer as follows (Van Stempvoort et al. 1993):

$$c = \Sigma(d_i / K_i) \tag{1}$$

The AVI approach is straightforward and quantitative, and therefore the same approach is used as the porous media rating in the proposed method. Equation (1) results in the least conductive hydrogeological layer governing vertical flow and the most conductive layer dictating horizontal flow. Vertical hydraulic conductivity must be used when applying this method as aquifer vulnerability is due to the downward migration of contaminants.

Fractured Media Rating (FR). The transmissivity (*T*) of fractured rock is related to hydraulic conductivity and aperture size; it is one way of characterizing fractured rock properties (Singhal & Gupta 2010). Transmissivity is indicative of the two key contributing aspects of fractured rock vulnerability on a regional scale: the water flux and the connectivity of the fracture network. Transmissivity is a widely used and well understood field parameter, thus it is used in the proposed method to indicate fractured rock vulnerability (Thornton & Wealthall 2008; Novakowski et al. 2000; Singhal & Gupta 2010). Transmissivity is known to vary with measurement scale; for example, pulse interference tests using 1-2m packer spacings will result in much smaller local *T* results than pumping tests with observation wells 10-20m apart (Elmhirst 2011; Le Borgne et al. 2006). The latter is a more appropriate, large-scale approach for measuring *T* in the proposed method. Table 2 gives Krásný's (1993) classification of transmissivity in fractured rock, upon which the proposed method's categorization of the fractured rock rating is based. The average transmissivities measured in rock formations across Ontario fit within these limits (Singer et al. 2003).

The final vulnerability index, *V*, as determined by the proposed method in Equation (2), is ranked on a five-point scale for simplicity, where final values are rounded conservatively, as shown in Table 3. This scale is used to avoid unnecessary complexities, as suggested by Foster et al. (2013).

$$V = 0.25(R + g + PM + FR) \qquad (2)$$

Table 2 Transmissivity classification (Krásný 1993)

T (m^2/d)	Description
< 0.1	Imperceptible
0.1 – 1	Very low
1 – 10	Low
10 – 100	Intermediate
100 – 1000	High
> 1000	Very high

Table 3 Proposed method vulnerability index classifications

Vulnerability Index	Class
1 – 1.49	Extremely Low
1.5 – 2.49	Low
2.5 – 3.49	Moderate
3.5 – 4.49	High
4.5 – 5	Extremely High

3.3 Application of proposed method

3.3.1 Study area

The proposed vulnerability assessment is applied to the bedrock aquifer systems in the Acton and Georgetown communities in the Town of Halton Hills, located in southern Ontario, Canada (Figure 2). The Acton and Georgetown communities make up the urban portion of the study area, with the remainder comprised of agricultural land, wetlands, forest, and quarries (CVC et al. 2002; 2011). The Niagara Escarpment is a significant geological feature running north/south along the study area, dividing the higher-elevation area to the west and lower elevation in the east (AECOM & AquaResource 2012). The west section above the Escarpment is underlain by Amabel/Gasport/Goat Island dolostone formations, with many outcrops as well as thicker, hummocky Wentworth till overburden serving as recharge areas (AECOM & AquaResource 2012). Buried bedrock valleys with thicker overburden are underlain by the Manitoulin and Whirlpool dolostone/shale formations along the Escarpment, while the east study area below the Escarpment is mostly Halton Till overlying Queenston shale (AECOM & AquaResource 2012). The area generally receives 850 – 900 mm/yr in precipitation (Environment Canada 2014). Georgetown draws drinking water from aquifers in the buried valley overburden deposits, while Acton takes some drinking water from overburden aquifers and some from the Gasport/Amabel rock formations (AECOM & AquaResource 2012).

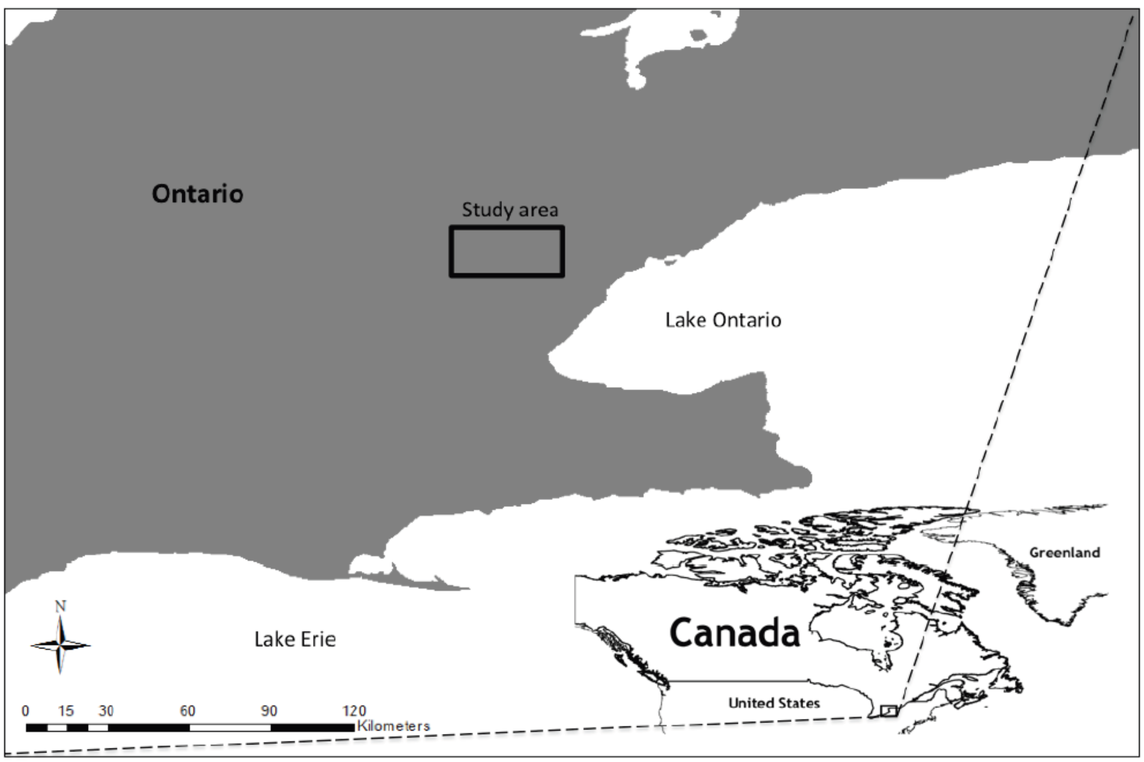

Figure 2 Geographical location of Acton-Georgetown study area

3.3.2 Proposed vulnerability assessment results

The results from the proposed aquifer vulnerability assessment method are shown in Figure 3, and were obtained using spatial and interpolated point data listed in Table 4. Transmissivity and hydraulic conductivity are estimated by formation type. The transmissivities reported for each formation span a significant range; therefore, both maximum and minimum vulnerability indices were calculated based on the 90th and 10th percentile transmissivity probabilities (T_{max}, T_{min}) for each rock unit, respectively. transmissivity probability (T_{max}), and minimum transmissivity probability (T_{min}) transmissivity probability (T_{max}), and minimum transmissivity probability (T_{min})

Table 4 Data used in vulnerability assessment maps.

Information	Source(s)	Use
Formation polygon data: primary surficial media	Ontario Geological Survey (2010)	Figures 3, 5, 8
Bedrock geology polygon data	Ontario Geological Survey (2011)	Figures 3, 5, 8
Climate normal data	Environment Canada (2014a)	Figures 3, 4
Ontario well records: depth to water table and depth to bedrock measurements	MOE (2014)	Figures 3, 5, 8
Ontario Base Map data: municipal boundaries, contours, and surface water segments	Government of Ontario (n.d.a)	Figure 2
	Government of Ontario (n.d.b)	Figures 3, 4, 5
	Government of Ontario (1998a)	Figures 3, 4, 5. 6, 8
	Government of Ontario (1998b)	Figures 3, 4, 5. 6, 8
Model estimates for horizontal hydraulic conductivity	Earth FX (2009), AquaResource Inc. (2009), Kassenaar & Wexler (2006), Dames & Moore (1995), Dames & Moore (1997), AMEC (2000), and Conestoga-Rovers & Associates Ltd (2000a,b; 2008a,b)	Figures 3, 5, 8
Transmissivity probability data	Singer et al. (2003)	Figures 3, 5
Borehole data	AECOM & AquaResource, Inc. (2012), AMEC (2001), Jagger Hims Limited (2005a; b), Dillon Consulting (2012), Stantec Consulting Ltd. (2014) & Gartner Lee Limited (2006)	Figure 6

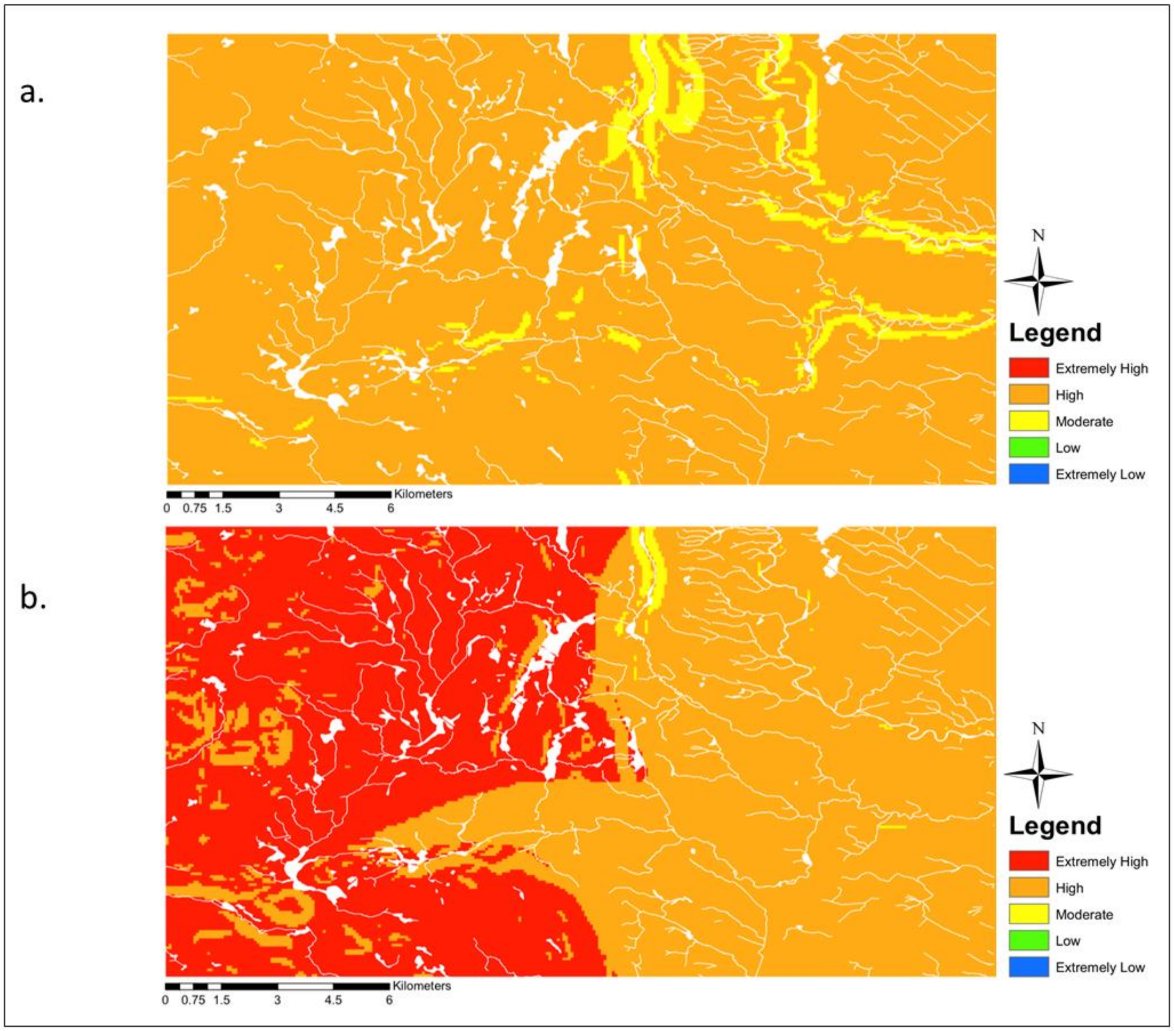

Figure 3 Aquifer vulnerability assessment results based on the proposed method showing (a) the minimum vulnerability (using T_{min}), and (b) the maximum vulnerability (using T_{max}). White areas represent rivers and water bodies, from Government of Ontario Base Data

The aquifer vulnerability maps generated using the proposed methodology indicate a high to extremely high vulnerability across the study area. In general, the high vulnerability throughout most of the study area is caused by intense rainfall, a relatively thin overburden, bedrock outcrops, and the fact that the water is relatively close to the ground surface (the interpolated depth to water surface never exceeds 35 metres (MOE 2014)). When T_{max} is applied, a clear boundary is seen between the Amabel/Gasport/Goat Island rock formations and the Manitoulin/Whirlpool/Queenston rock formations; this is a reflection of the difference in transmissivities between these units. The rainfall intensity varies minimally across the study area, and all values lie in the extremely high range of the rainfall rating.

A benefit to this proposed method is that the results can be broken down into separate maps, enabling the user to differentiate the location and associated cause for more vulnerable areas. This allows users to identify factors that drive higher vulnerability within a study area, and make informed decisions based on this information. Figure 4 shows the recharge availability ratings, while Figure 5 shows the overburden vulnerability for the study area. The vulnerability due to recharge availability is extremely high throughout most of the study area, with lower ratings only where topography provides larger slopes (and by extension better runoff conditions).. The overburden ratings span a large range, from low to extremely high; this is due to the large range of transmissivity probabilities documented by Singer et al. (2003). The split between fractured rock with a higher-*T* range and a lower-*T* range is visually distinct in the overburden rating as shown in Figure 5.

Climate normal data from Environment Canada (2014a) indicates high averages of roughly 700 mm of rainfall and 110 rainy days per year in the Acton-Georgetown area; these averages are very high compared with values throughout the rest of Ontario. The rainfall rating does not change across the entire study area; it is extremely high throughout. The index-and-overlay approach allows for sensitivity analysis on each input factor. The rainfall rating is masking the relative effects of all other factors in this case, but this layer could easily be removed from the vulnerability assessment so that the vulnerability due to the other factors can be considered.

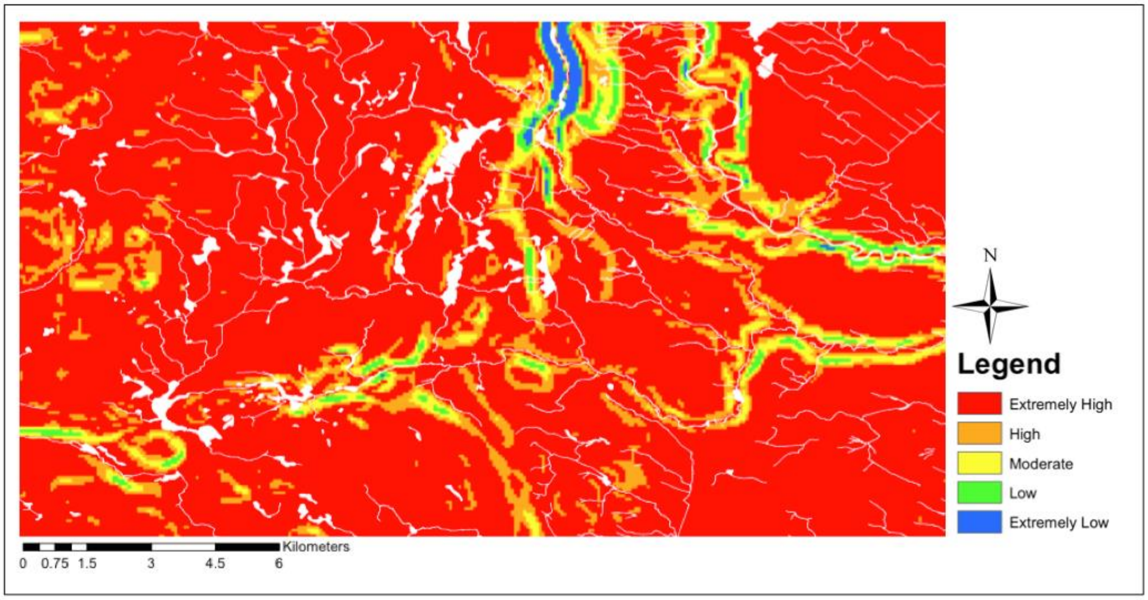

Figure 4 Recharge Availability ratings. White areas represent rivers and water bodies, from Government of Ontario Base Data (1998a;b). Contains information licensed under the Open Government License- Ontario

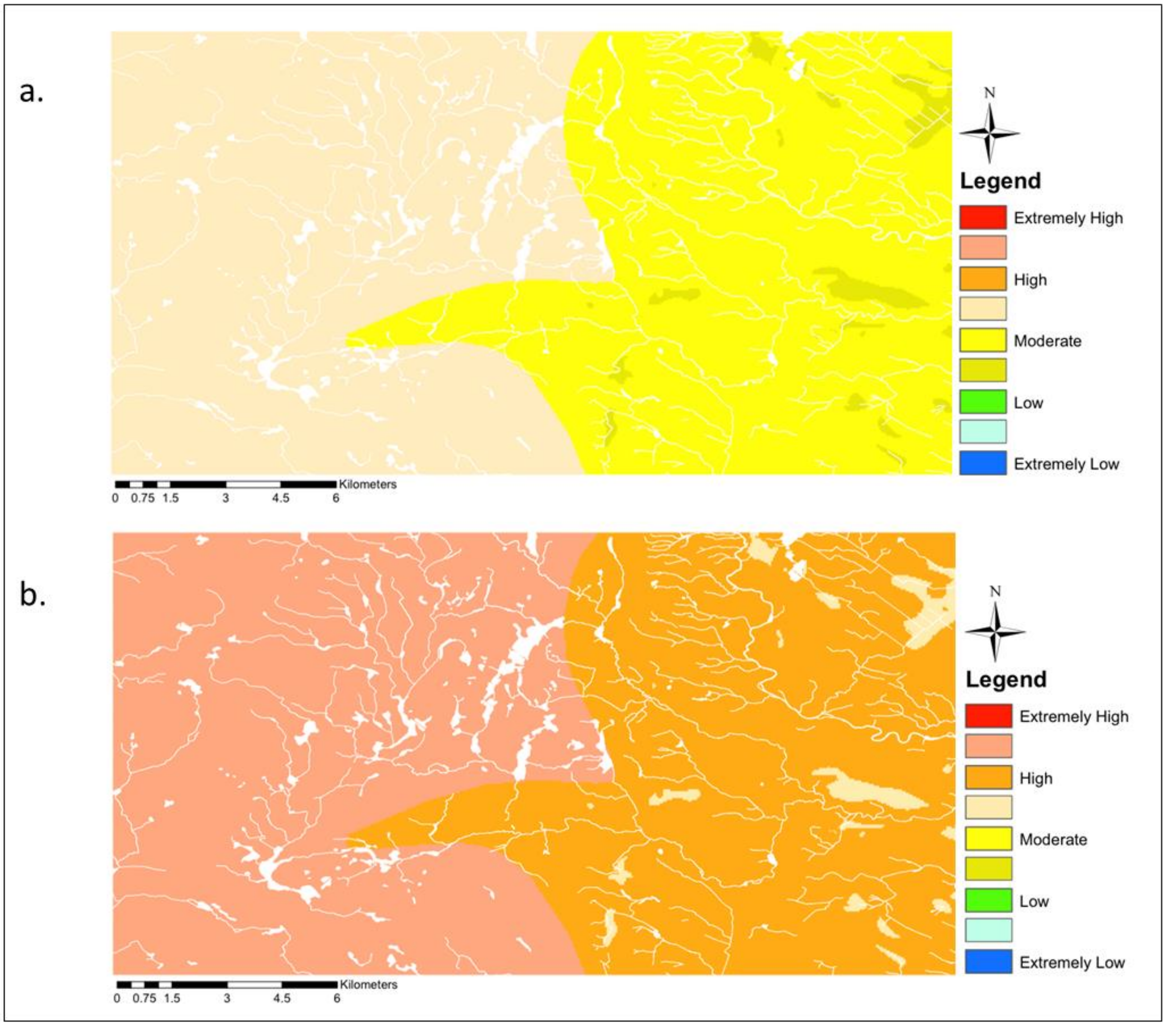

Figure 5 Overburden ratings based on (a) T_{min}, and (b) T_{max}. White areas represent rivers and water bodies, from Government of Ontario Base Data (1998a;b). Contains information licensed under the Open Government License-Ontario

3.4 Application of other methods & comparison

Two other vulnerability assessment methods, which are often used in North America, were also applied to the study area: AVI (Figure 6) and DRASTIC (Figure8). The AVI method employs a hydraulic resistance rating (Equation 1) calculated for each borehole, with results segregated into five levels of vulnerability. Hydraulic resistance borehole data for the Acton-Georgetown study area were obtained from borehole data in Table 4. The AVI method resulted in the majority of the study area being rated as extremely high vulnerability, with a small patch of high vulnerability where borehole data show thicker overburden. AVI calculates vulnerability based only on the protective cover of the water table (Van Stempvoort et al. 1993). However, the water table aquifer is often in the overburden throughout the study area, and therefore AVI cannot measure the vulnerability of any confined fractured rock aquifers.

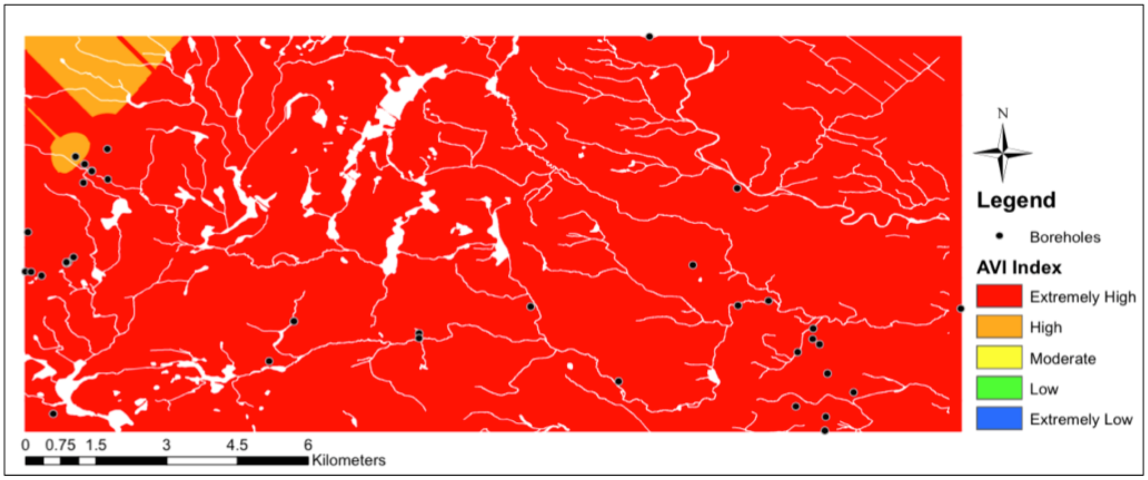

Figure 6 AVI vulnerability assessment method. White areas represent rivers and water bodies, from Government of Ontario Base Data (1998a;b). Contains information licensed under the Open Government License- Ontario

The authors of the AVI method measure vulnerability by interpolating point calculations of hydraulic resistance (Van Stempvoort et al. 1993). Kriging is used in the AVI method in Figure 6 because it is generally known as a "good interpolator" and it often provides the best and most easily analyzable results, or smallest errors in interpolation (Naoum & Tsanis 2004; Moradi et al. 2012; Gallichand et al. 1991). Point data from 48 boreholes is used to complete the AVI vulnerability assessment, while the proposed method uses spatial formation data. The point data used in the AVI method does not cover the entire study area presented in Figure 2; furthermore, the density of this point data does not represent the study area well. While interpolation works well for water level, bedrock depth, and contour data (Table 4), the semivariograms generated in ArcMap 10.2 suggest the resistivity data do not have a strong spatial correlation, and therefore the kriging method does not accurately predict measured resistivity values (Figure 7).

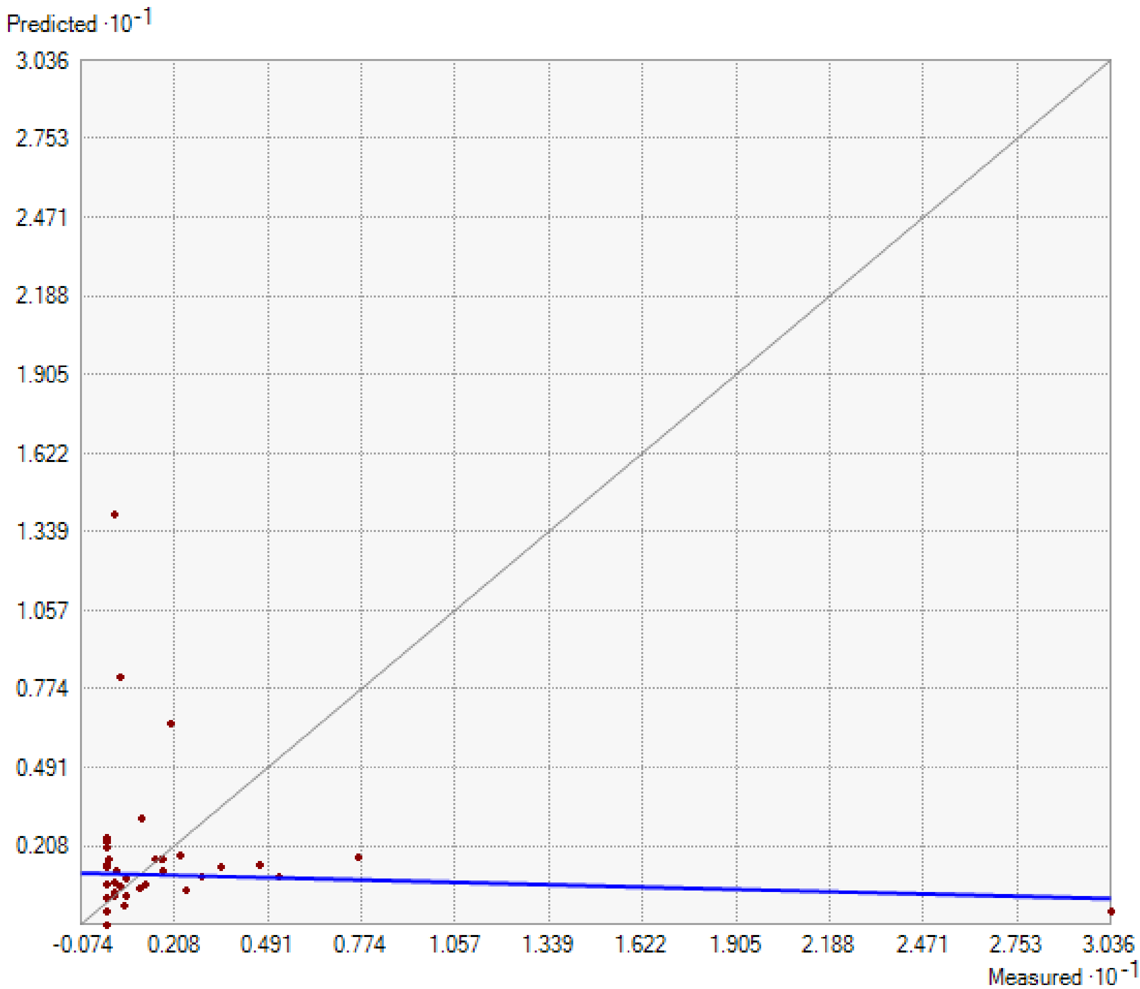

Figure 7 Predicted vs. measured resistivity values using kriging interpolation

The final DRASTIC vulnerability assessment has eight vulnerability categories, with indices under 80 representing the lowest vulnerability and indices over 200 representing the highest vulnerability (Aller et al. 1987). In the DRASTIC method, the depth to water table measurement can be replaced with the depth to the top of the aquifer where confining conditions exist (Aller et al. 1987). This was applied in the construction of Figure 8; the deeper of the two measurements was used in order to measure the vulnerability of aquifers in fractured rock formations rather than those in overburden.

This method shows areas of lower vulnerability on the east side of the study area where silt, clay, diamict, and till are the primary overburden media. High-vulnerability sections in the centre of the study area branching to the east correspond to gravelly/sandy overburden and bedrock outcrops. The patch of lower vulnerability in the top northwest corner and the bone-shaped section in the southwest side are highly influenced by the deeper water table and bedrock surface. Areas with the lowest vulnerability have similar patterns to sections with the deepest water tables/bedrock depths; areas with the highest vulnerability have the highest scores in all DRASTIC factors. Media type is a dominant feature in this assessment, used to develop the soil media, impact of vadose zone, hydraulic conductivity, and recharge ratings.

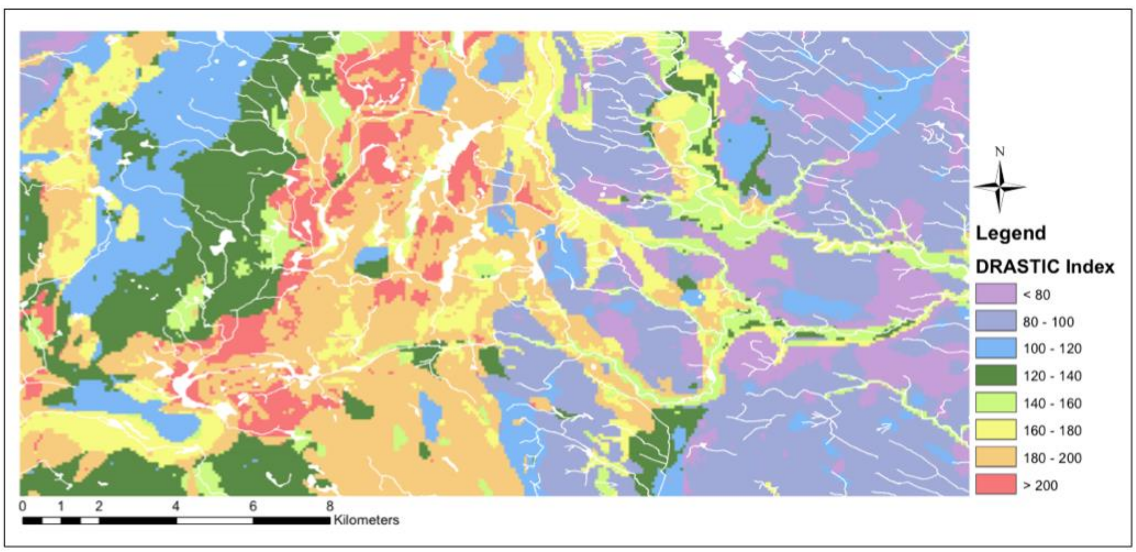

Figure 8 DRASTIC vulnerability assessment method. White areas represent rivers and water bodies, from Government of Ontario Base Data (1998a;b). Contains information licensed under the Open Government License- Ontario

The vulnerability ranges calculated by the proposed and AVI methods are similar in that they both show relatively high groundwater vulnerability across the entire study area, ranging almost entirely between high and extremely high ratings. However, the spatial distribution of high and extremely high vulnerability is very different between the two methods; while the AVI method shows most of the study area as extremely vulnerable, the proposed method indicates that the study area has mostly a high vulnerability with the lowest *T* estimates, and a split between high and extremely high vulnerability under the highest *T* estimates. In contrast to the AVI and proposed methods, the vulnerabilities calculated by DRASTIC span the full range of possible vulnerability ratings. Therefore, DRASTIC likely underestimates the vulnerability in certain parts of the study area while AVI may overestimate vulnerability.

3.5 Conclusions

The two previously developed vulnerability assessments (AVI and DRASTIC) yield very different results for the same study area. These assessments were both created for North American geology but produce conflicting vulnerability outcomes, making water resource decision-making processes difficult. The proposed method harmonizes key concepts from both DRASTIC and AVI methods, as well as other previously developed methods, and expands on them to directly incorporate fractured rock aquifers in a quantitative manner.

Fractured rock and porous media should be considered equally important when assessing overall intrinsic vulnerability. The proposed aquifer vulnerability assessment separates porous media and fractured rock when considering the characteristics of each that apply to vulnerability. This is a reflection of current literature and field approaches that recognize the need to model contaminant transport in fractured rock separately from contaminant transport in porous media.

When approaching methods on a well-by-well basis, interpolated vulnerability results prove to be statistically meaningless and visually impractical. Interpolated point data is appropriate for some aspects of vulnerability assessments where ample, homogeneous data is available, (i.e. elevation data); however, the interpolation of heterogeneous and scale-dependent factors (i.e. hydraulic conductivity and transmissivity) does not yield results that are statistically or visually valuable. In such cases, generalized spatial data are more useful than the interpolated results of sparse point data.

The AVI method uses only numerically measurable features (*K* and *d*), while DRASTIC uses arbitrary rankings of media type descriptions for three of seven factors considered. The results generated by the proposed vulnerability assessment use quantitative measurements or estimates, and independent inputs in an effort to reduce qualitative or arbitrary influences on vulnerability ratings.

The incorporation of quantitative fractured rock characterization is highly influential on vulnerability assessments, as seen in Figure 3. It is important to include fractured rock features when considering the vulnerability of groundwater, particularly in southern Ontario where drinking water is often supplied by fractured bedrock aquifers. The proposed method is the first to quantify vulnerability of fractured rock aquifers, which cannot be represented by porous media or karst geology models.

3.6 References

All references used in Chapter 3 are included in the final reference list that follows Chapter 4.

Chapter 4

Discussion & Conclusions

4.1 Discussion of Findings

The conclusions from this study are summarized at the end of Chapter 3. This chapter will thoroughly discuss details of each finding individually and provide additional details with supplementary data in Appendix B.

Finding 1: Two previously developed aquifer vulnerability assessments yield different results.

This is a fundamental issue with vulnerability assessments that has been demonstrated in previous work. In this study, AVI and DRASTIC were two sample assessments used over the same area in Figures 6 & 7. The AVI method indicates that the Acton-Georgetown area is extremely vulnerable for most of the study area, where DRASTIC suggests a higher percentage of lower-vulnerability areas. The spatial similarities between AVI and DRASTIC in Chapter 3 are slight.

VÍas et al. (2006) also compare AVI and DRASTIC results from two aquifers in Spain. The results between these two methods have a similar spatial distribution, but final index ratings are different. For one aquifer, DRASTIC shows roughly 80% of the area at a high vulnerability and 20% moderate, while AVI rates the same 80% of the study area as very high and 20% as low and very low vulnerability (VÍas et al. 2006). For the second aquifer, AVI splits the area into 75% high and 10% very high, while DRASTIC shows roughly the same 85% of the study area with moderate vulnerability (VÍas et al. 2006). VÍas et al. (2006) compare these results with their own COP method, which also shows a larger portion of both study areas having higher vulnerability than DRASTIC. Results from the COP, AVI, and the proposed method in VÍas et al. (2006) and Chapter 3 suggest that DRASTIC underestimates overall groundwater intrinsic vulnerability for large portions of all study areas.

The AVI method accounts for only the water table or unconfined aquifer in most of the Acton-Georgetown study area, whereas DRASTIC can also be applied to confined aquifers (Aller et al. 1987; Van Stempvoort et al. 1993). In many sections of the Acton-Georgetown study area, the water table is at a higher elevation than the bedrock surface. In this case, the AVI results indicate the vulnerability of the water table aquifer, and AVI is not able to assess the vulnerability of fractured rock aquifers in these areas. This is likely a key explanation for the large spatial variability between AVI and DRASTIC seen in the Acton-Georgetown study region, but spatial similarity seen in the study area in Spain used by VÍas et al. (2006).

Finding 2: The ability to incorporate fractured rock characteristics is highly influential on aquifer vulnerability assessments and important in the geology of southern Ontario.

The importance of including fractured rock features in aquifer vulnerability assessments for Ontario is discussed at length in Chapter 1, and is largely attributed to the fact that fractured rock aquifers serve as a drinking water source and contribute to local and regional flow systems that influence ecological and environmental stability.

The results of the proposed vulnerability assessment method in Figure 3 provide a visual indication of the influence that fractured rock can have on vulnerability assessments. In some instances, inclusion of transmissivity does not visually appear to heavily influence the study area's vulnerability, as is evident in Figure 3a, where topography is the key influence. However, the results in Figure 3b prove that the inclusion of transmissivity in aquifer vulnerability assessments can be a highly influential aspect of the final map.

Finding 3: Porous media and fractured rock characteristics should be considered equally important when assessing intrinsic aquifer vulnerability.

This finding is based on research done on the current vulnerability assessments discussed in Chapter 2. Multiple authors note the lack of proper incorporation of preferential pathways in current vulnerability assessments, and the methods themselves lack quantitative characterization techniques (Aller et al. 1987; Foster et al. 2013).

There are many previously developed methods that are effective for aquifers strictly in porous media. These methods work well for aquifers in porous media or overburden aquifers, as fractured rock does not need to be considered in this case. However, large parts of Ontario rely on groundwater that comes from aquifers in bedrock. If it is the vulnerability of these fractured rock aquifers that is being evaluated, bedrock characteristics that contribute to vulnerability are equally as important as the characteristics of any overlying porous media features. Just as transport through fractured rock is modeled differently than transport through porous media, fractured rock must be considered as a contributor to aquifer vulnerability separately from the porous media overburden layers.

Finding 4: Generalized spatial data are more useful than interpolated point data when conducting comprehensive and reasonably attainable aquifer vulnerability assessments.

There are many ways to create maps that represent the spatial distribution of certain hydrogeological features. Initially, *T, K, d,* and elevation data from boreholes within the study area were to be used to complete the proposed vulnerability assessment method. Common interpolation techniques used in similar GIS analyses include kriging and inverse-distance weighting (IDW) methods.

In the IDW method, interpolated points are estimated based on the value and distance of nearby points, under the idea that points closer together will be more closely related than points that are further apart (Naoum & Tsanis 2004). The kriging method assumes the data are normally distributed; kriging can be thought of as similar to the IDW method, but with a more complex weighting system that uses semivariance (Eckeskog 2006). Semivariance is a statistical function that quantifies the distance between pairs of two points, essentially testing the idea that closer points are spatially correlated (Eckeskog 2006). Semivariograms show the semivariance vs. distance between points. A semivariogram indicating significant spatial autocorrelation for a variable will generally increase exponentially when the distance between points is small and the values are similar, and then plateau as the distance increases and the values become unrelated (Eckeskog 2006).

Kriging is the most popular approach, generally known as a "good interpolator;" it often provides the best results with small errors compared to other interpolation methods (Naoum & Tsanis 2004; Moradi et al. 2012; Gallichand et al. 1991). Naoum & Tsanis (2004) note, "Although there are numerous articles [that] have been written that are concerned with spatial interpolation, there is little or no agreement among the authors on the superiority of some techniques over others."

Kriging was used to interpolate depth to bedrock and water table data. The point data for these parameters were densely distributed across the study area and provided practical results. Conversely, the T and c data were difficult to interpolate. Measured transmissivity data are only available for the Acton and surrounding area in roughly 14 boreholes, and measured resistivity data are only available for 48 boreholes across the whole study area. Therefore, multiple methods of interpolation for T and c were examined.

Geostatistical tools in ArcMap 10.2 provide quick visuals and error results from interpolated data. Results from three methods of interpolating T and c data are summarized in Tables B-1, B-2, and B-3 in Appendix B. These tables include the mean error, root mean square error (RMSE), root mean square standard error, and average standard error where applicable. The best result for each is bolded, as well as the overall best method. In all three cases, ordinary kriging is better suited than the IDW method and ordinary log kriging.

Although these results show the best method of interpolation, the errors for all methods are undesirably large. Figures B-1 and B-2 show semivariograms and Q-Q plots for hydraulic resistance (a), measured T_{min} (b), and measured T_{max} (c) data. Although Q-Q plots show that resistivity data are somewhat normally distributed, hydraulic resistance exhibits a weak spatial correlation and thus interpolation is not useful (Eckeskog 2006). There is not enough transmissivity data for corresponding semivariograms to be valuable, and the Q-Q plots indicate that kriging is not a valid model. This is also evident in the choppy appearance of the final interpolated maps that use ordinary kriging in Figure B-3.

If the proposed vulnerability assessment were to be completed using interpolated point data for *T* and *c*, it would require a larger amount of densely distributed sample points. This requires ample time and money, which negates the purpose of a simple vulnerability assessment that uses inexpensive and easily attainable data. It becomes clear that the small number of boreholes with measured *T* and *c* data across this study area cannot provide enough information to be valuable in a vulnerability assessment.

Instead of interpolated point data, free spatial geological information available from online databases is used. This is discussed fully in Appendix C.

Finding 5: The use of quantitative and independent factors is a valuable improvement to aquifer vulnerability assessments.

From a scientific perspective, it is more useful to have numerical values and measurable characteristics to quantify aquifer vulnerability. DRASTIC employs similar data sets or factors that are highly dependent on one another (i.e. topography, soil media, and recharge) and end up with vulnerability indexes based on overlays of re-used hydrogeological information. AVI uses strictly measurable factors that are independent of one another: layer thickness and hydraulic conductivity. In using fractured rock transmissivity, porous media hydraulic conductivity and layer thickness, elevations, and rainfall intensity data, the proposed method considers only independent factors that are quantifiable in field tests.

4.2 Recommendations & Limitations

One limitation to the work presented in this thesis is the manner in which field measurements are taken and the choice of data used for vulnerability assessments. Beyond standard human and equipment errors or biases, there are many different methods of extracting all hydrogeological data necessary. While topography and rainfall data are relatively straightforward to collect, water level information is highly variable. The water table changes, sometimes dramatically, throughout seasonal fluctuations and storm events or droughts. This is not accounted for in any of the vulnerability assessments completed in this thesis, however, fieldwork is typically done in the vulnerable seasons (i.e. spring, summer) meaning conservative measurements are often used. The ability to incorporate seasonality in a temporal vulnerability assessment is one recommended path for future research.

The proposed vulnerability assessment calculates average rainfall intensity with annual rainfall and a measure of the number of rainy days per year. Although this is still valuable, it is a coarse average over a long period of time, and denser data would be more valuable. Inclusion of a more detailed rainfall rating, using more frequent measurements, is a consideration for future applications of vulnerability assessments. Groundwater in fractured rock is most vulnerable in large events when preferential pathways fill and present opportunities for water and contamination to travel into new pathways. Inclusion of finer and more accurate rainfall intensity information may show more spatial variation and improve vulnerability assessment results. Water table fluctuations and extreme weather events will increase in importance regarding aquifer vulnerability assessments as climate change continues to inflict high-intensity events and higher frequencies of these events.

Snowmelt is another limitation to this research. The springtime presents the most vulnerable time for aquifers with large snowmelts. Larger fractures and highly connected fracture networks are more susceptible to significant recharge events and changes in the groundwater flow system (Foster et al. 2013). Simple models describing snowmelt exist, but none are applicable in the context of the proposed vulnerability assessment. Factors contributing to the intensity of a snowmelt, or the rate at which snow melts and infiltrates into the ground, are not easily defined by readily available data such as daily temperatures and snowfall. Snowmelt is unpredictable and highly influential in Ontario, and the ability to incorporate the amount of snowfall and the intensity of snowmelts in addition to rainfall is a highly recommended improvement to vulnerability assessments in this climate.

Another limitation involves discrepancies with measuring or estimating *T* values to be used within the aquifer vulnerability assessment. Chapter 2 introduces many different approaches to measuring transmissivity in the field and notes that regional *T* tests should be used (i.e. pumping tests). There are a variety of tools and methods used for conducting pumping tests. Open-hole tests will provide a good regional *T* measurement for the formations drilled, but the use of packers to isolate a formation on a small interval (e.g. 0.5 metres) will typically result in much smaller, local-*T* estimates. There is no explicit threshold to determine how large a packer spacing should be before it is considered a "regional" scale estimate. If standardized approaches improve consistency in transmissivity field measurements, this would serve as a valuable addition to future use of the proposed aquifer vulnerability assessment.

The choice in zones that are being tested within the formation will also affect *T* measurements. When aquifer tests are conducted in fractured rock in southern Ontario, the goal is often to find highly productive aquifers that can serve as a drinking water supply. This means high transmissivities are sought after, and reported results may not reflect the rock aquifers or hydrogeological formations as a whole.

The upper few metres of bedrock are often weathered and/or more highly fractured than the rest of the formation. Contact zones, where different formations meet, are also known for being more weathered. If water flows through them, these zones are highly productive and have high transmissivities. The upper weathered fractured rock sections and contact zones are rarely considered as separate from the rest of the formations, although they often only represent a small portion of the entire unit. For example, a high *T* measured in the upper weathered 3 metres of the Guelph formation would still represent a *T* measurement in this Guelph unit, even if the transmissivity averages are orders of magnitude lower throughout the next 60 metres of the formation. A recommendation for future work would be to account for, or properly communicate this discrepancy and ensure *T* measurements accurately represent the formations indicated.

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Appendix A: Figures in Literature Review

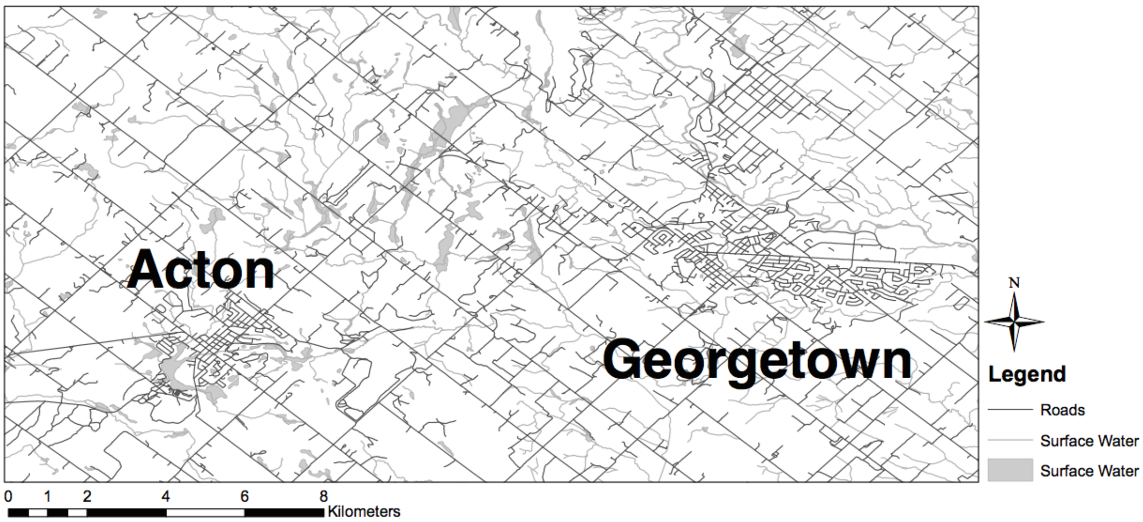


Figure A-1 Study area: roads and surface water on local scale, contains information licensed under the Open Government License- Ontario

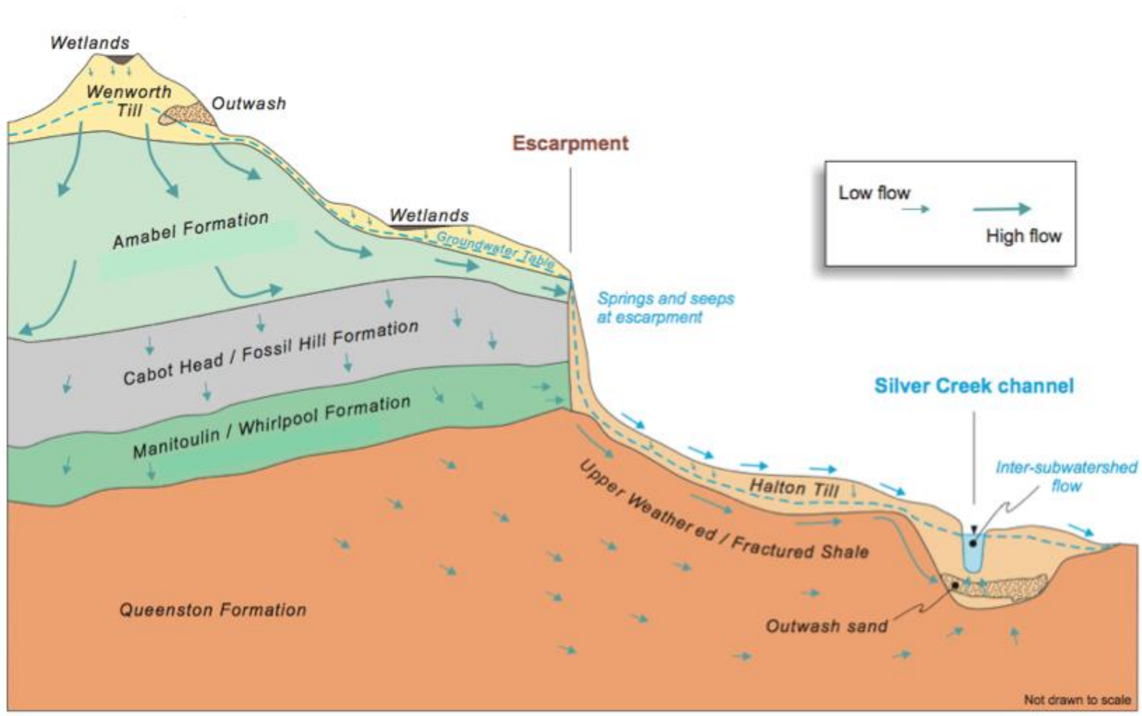


Figure A-2 Generalized stratigraphic west-to-east cross-section of study area (Modified from Credit Valley Conservation et al. 2001)

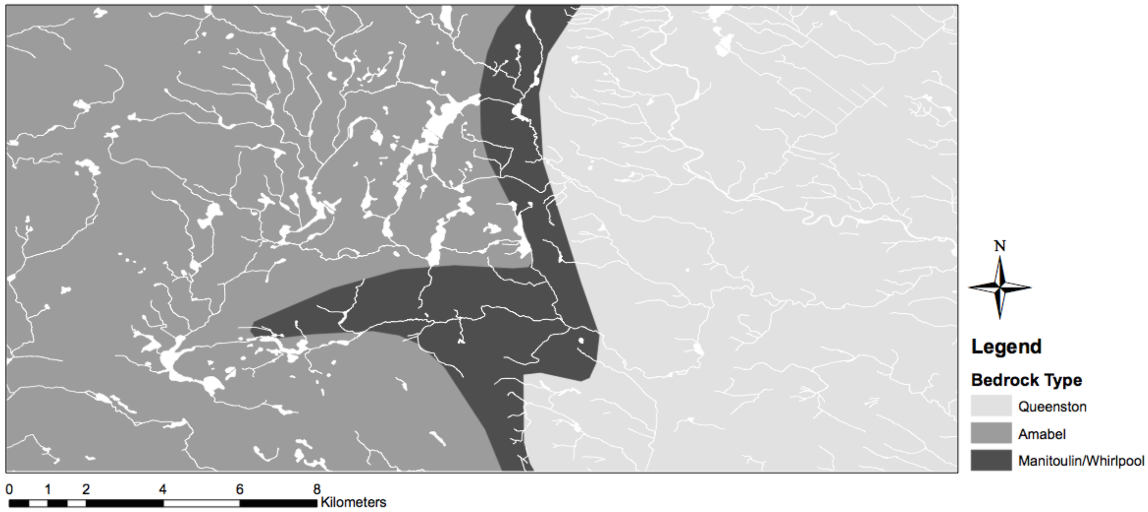


Figure A-3 Uppermost bedrock formation, contains information licensed under the Open Government License- Ontario

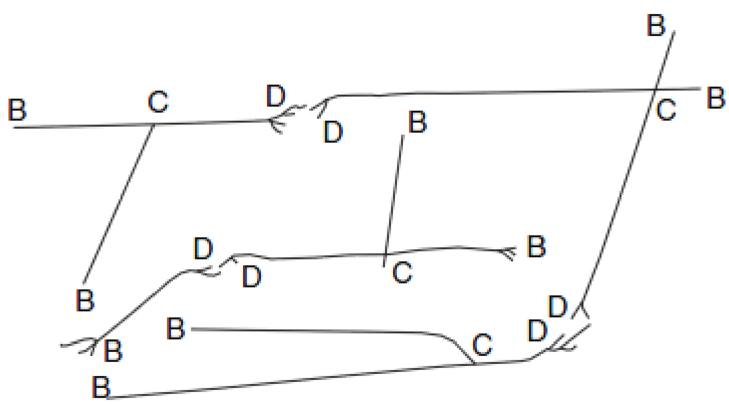


Figure A-4 Fracture termination types: B- blind, C- connecting, D- diffuse (Singhal & Gupta 2010)

Appendix B: Supplementary Interpolation Data

Table B-1 Interpolation error results for resistivity point data

Method	Mean error	RMSE	RMS standard error	Average standard error
IDW	-0.57	**5.38**		
Kriging - Ordinary	**-0.30**	5.96	**0.94**	**7.38**
Kriging - Ordinary Log	5.38	12.75	**0.37**	52487.22

Table B-2 Interpolation error results for minimum measured *T* point data

Method	Mean error	RMSE	RMS standard error	Average standard error
IDW	**138.89**	318.57		
Kriging - Ordinary	140.31	**260.42**	**0.61**	**539.94**
Kriging - Ordinary Log	111.51	300.28	0.39	5095.54

Table B-3 Interpolation error results for maximum measured *T* point data

Method	Mean error	RMSE	RMS standard error	Average standard error
IDW	194.32	454.03		
Kriging - Ordinary	190.49	352.67	**0.57**	**869.74**
Kriging - Ordinary Log	**153.84**	**306.80**	0.39	27373.20

a)

b)

c)

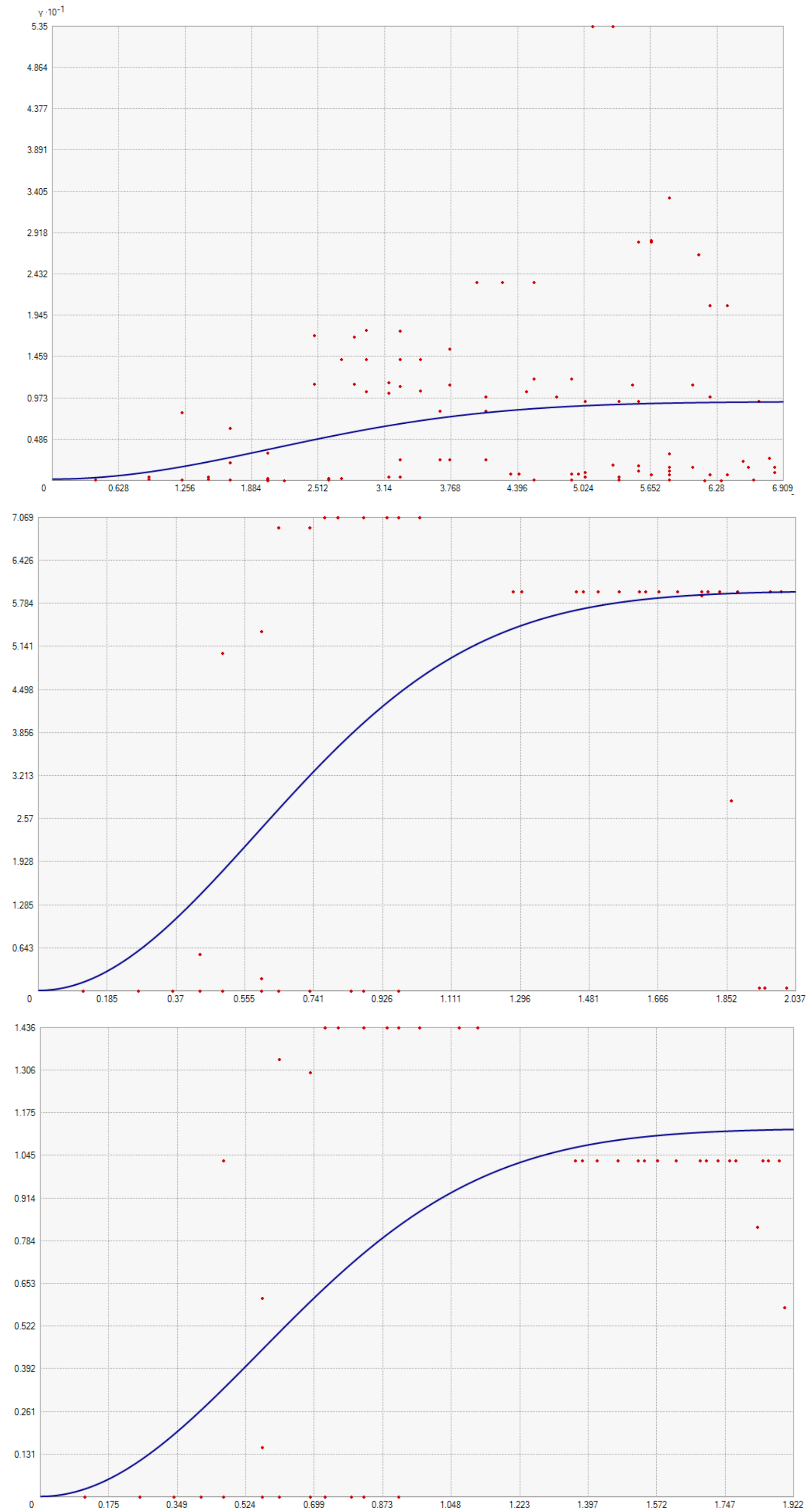
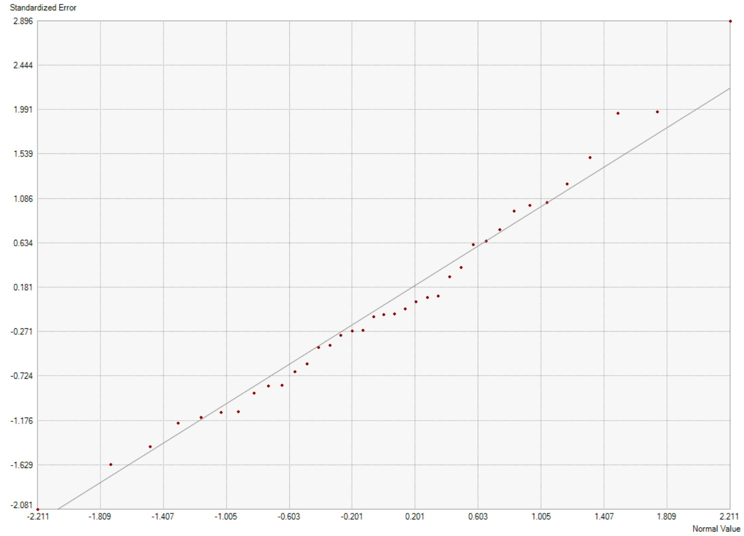
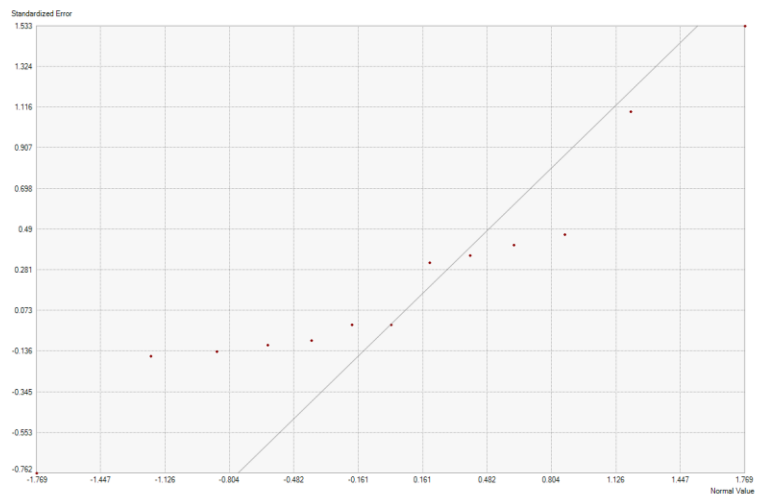


Figure B-1 Semivariograms for hydraulic resistance (a), minimum measured *T* (b), and maximum measured *T* (c); semivariance vs. distance between points

a)



b)



c)

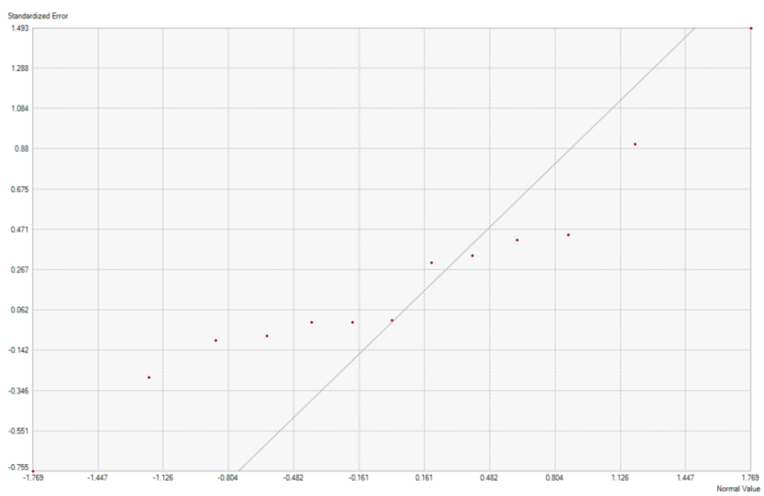
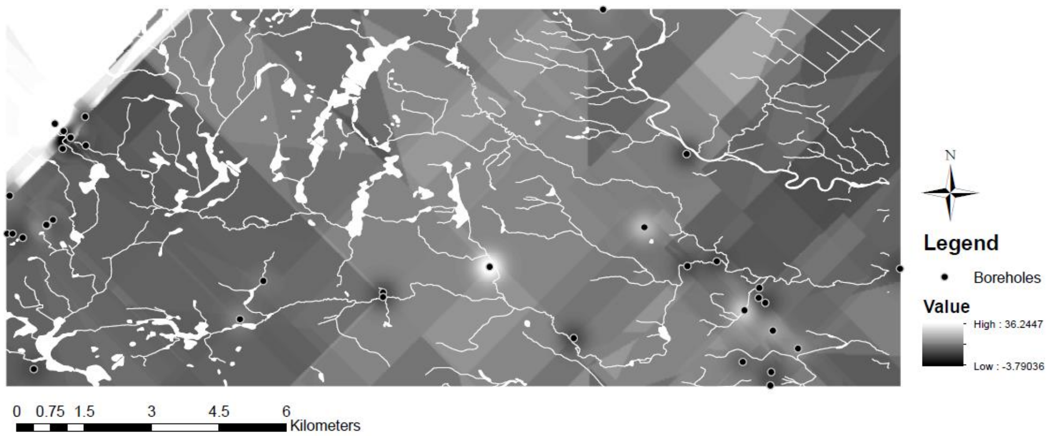
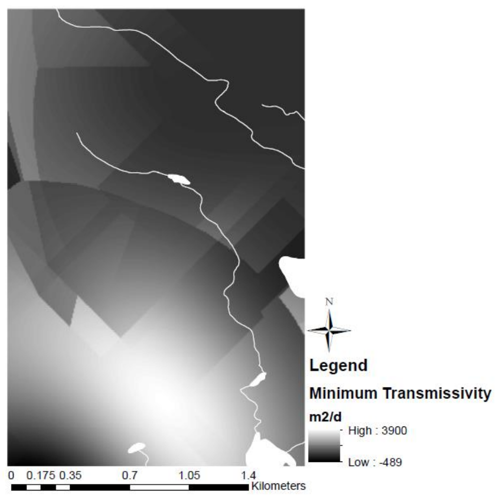


Figure B-2 Q-Q plots for hydraulic resistance (a), minimum measured *T* (b), and maximum measured *T* (c)

a)



b)



c)

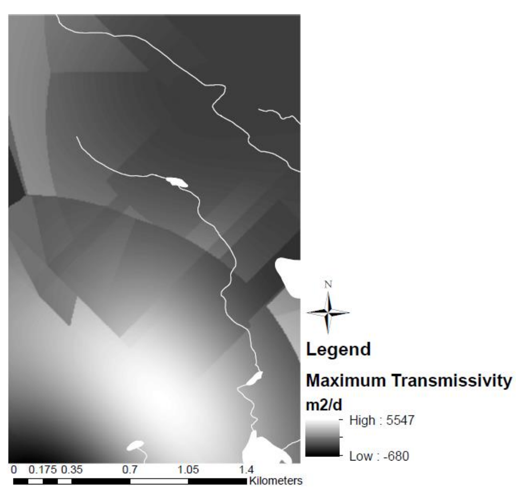


Figure B-3 Maps of hydraulic resistance (a), minimum measured T (b), and minimum measured T (c) interpolated with ordinary kriging, contains information licensed under the Open Government License- Ontario

Appendix C: Proposed Method Applied Data

The information in this appendix provides thorough details about data and methods used to compile the proposed vulnerability assessment.

Rainfall Information

The Rainfall rating in the proposed aquifer vulnerability assessment method uses Environment Canada (2014) climate normal data from 1981 to 2010. Two maps representing the number of rainy days and the annual rainfall in were created using point data from the following climate stations that surround the study area: Alliston Nelson, Ruskview, Albion Field Centre, Georgetown Wastewater Treatment Plant, and Orangeville Ministry of the Environment stations (Environment Canada 2014). These maps were interpolated with ordinary kriging, and both showed minimal spatial variability. The map of annual rainfall divided by the map of number of rainy days provided results that also had a very small range, leaving the entire study area at the same rating.

Topography Information

The Topography rating in the proposed aquifer vulnerability assessment method uses contour data from the Ontario Base Mapping Database (Government of Ontario n.d.b). Contours were converted to elevations, and slopes were calculated using the Geostatistical Analyst toolbox in ArcMap 10.2.

Porous Media Information

Information used to find Porous Media ratings in the proposed aquifer vulnerability assessment method come from the online database OGSEarth, well data from the MOE, and the estimated hydraulic conductivity values reported by AECOM & AquaResource 2012 in the Halton Hills Tier 3 Conceptual Model Report. Horizontal hydraulic conductivity estimates presented in the Tier 3 report are from models by Earth FX (2009), AquaResource Inc. (2009), Kassenaar & Wexler (2006), Dames & Moore (1995; 1997), AMEC (2000), and Conestoga-Rovers & Associates Ltd (2000a,b; 2008a,b). Vertical *K* values were calculated assuming vertical *K* is 10% of horizontal *K,* unless otherwise indicated by AECOM & AquaResource 2012. The geometric means of estimates for each porous media layer from all sources is in Table C-1. Surficial geology data, available through OGSEarth, splits the study area into primary surficial media types: Halton Till, Wentworth Till, clay/silt, organic deposits, sand, gravel, and sand/gravel, and bedrock outcrop areas (OGS 2010). Descriptions of porous media material are used to organize respective mean vertical *K* values into the appropriate dominating surficial media type. Estimates from Freeze & Cherry (1979) also influenced these estimates. Bedrock outcrops are automatically assigned a porous media rating of 5, since a lack of overburden provides no attenuation.

Table C-1 Vertical hydraulic conductivity geometric mean values (Earth FX 2009; AquaResource Inc. 2009; Kassenaar & Wexler 2006; Dames & Moore 1995; Dames & Moore 1997; AMEC 2000; Conestoga-Rovers & Associates Ltd 2000a,b & 2008a,b)

Material	***K* estimate (m/s)**
Halton Till	4.82×10^{-8}
Wentworth Till	2.36×10^{-7}
Gravel	1.19×10^{-3}
Sand	5.95×10^{-9}
Sand & gravel	1.19×10^{-4}
Organic deposits	6.49×10^{-4}

Thicknesses of porous media and water table depths were calculated using dense borehole data from Ontario Ministry of the Environment (2014). Point data for static water level and depth to bedrock were interpolated using ordinary kriging.

Fractured Rock Information

Information for the fractured rock rating in the proposed aquifer vulnerability assessment method comes from transmissivity probability data in a summary of Ontario's hydrogeological data by Singer et al. (2003). The following, taken directly from Singer et al. (2003), outlines how the authors use data from thousands of wells to determine transmissivity probabilities (transmissivity distributions for different formations tested in wells sampled throughout Ontario):

$$F = (100m)/(n+1)$$

where

F = the percentage of wells where transmissivities are less than the transmissivity of well of serial number m,

m = serial number of well arranged in ascending order of transmissivity, and

n = total number of wells.

Plotted, these transmissivity probabilities reveal a lognormal relationship for most formations tested, meaning the geometric mean values can be used to estimate the transmissivity.

Table C-2 summarizes transmissivities and their corresponding fractured rock ratings (*FR*). T_G is the geometric mean transmissivity, while T_{10} and T_{90} represent transmissivity values that do not exceed 10% and 90% of the wells, respectively (Singer et al. 2003). The authors deemed the Manitoulin/Whirlpool unimportant within the watershed (Singer et al. 2003). Singer et al. (1994) indicate a T_G of 4.0 m^2/d for the Manitoulin/Whirlpool formation; this mean was used, along with transmissivity-probability distribution trends for the Amabel-Lockport-Guelph formations, to approximate the 10th and 90th percentiles for the Manitoulin/Whirlpool units. The resulting FR ratings of the Guelph and Amabel family range from 2 to 4, while the Queenston and Manitoulin/Whirlpool ratings range from 1 to 3. The ranges calculated are then applied to the bedrock formation type, as determined by OGS data (Figure A-3).

Table C-2 Transmissivity data and corresponding fractured rock ratings for study area formations (Singer et al. 2003; 1994)

Formation	# Wells Sampled	T_{10} (m^2/d)	T_G (m^2/d)	T_{90} (m^2/d)	FR_{10}	FR_G	FR_{90}
Amabel	6516	1.54	15.5	134.8	2	3	4
Lockport (Gasport, Goat Island, Eramosa)	1662	1.69	20.6	141.0	2	3	4
Guelph	6072	1.37	12.05	104.90	2	3	4
Queenston	2505	0.47	2.66	27.95	1	2	3
Manitoulin	N/A	0.49	4.00	36.91	1	2	3