Compressed Air Energy Storage in Salt Caverns: Geomechanical Design Workflow, CAES Siting Study from a Geomechanics Perspective, and Deep Brine Disposal

by

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AUTHOR'S DECLARATION

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

The third chapter of the thesis, Siting Study for CAES in Canada: the Geomechanics Perspective, is a part of the report “First-Order Assessment of the Potential of Compressed Air Energy Storage in Salt Caverns across Canada”, which was sponsored by Natural Resources Canada (NRCan) and authored by Fraser Lord, Jai Duhan, Mina Lee, Logan Miller, Dipanjan Basu, Maurice Dusseault, and Arjun Tharumalingam. Majority of the content in the third chapter is researched and written by Jai Duhan, who was responsible for handling the geomechanics research area of the NRCan report. The non-geomechanical research areas written by other authors are briefly summarized; the reader is encouraged to read the full report for a detailed discussion on non-geomechanical research areas. Also, additional geomechanical research conducted by Jai Duhan, but not part of the NRCan report, is also added in this chapter; new sections include a discussion on second-order geomechanical parameters and a decision tree.

ABSTRACT

As agreed in the Paris Agreement, Canada is committed to combat climate change through reducing greenhouse gas (GHG) emissions and keeping the temperature rise well below 2° C above pre-industrial levels. One of the ways to achieve this goal is through replacing high GHG emitting electricity sources with renewables energy, such as wind and solar energy. However, due to their intermittent nature, wind and solar must be paired with energy storage to be a reliable source of electricity. Compressed air energy storage (CAES) in salt caverns is a well-demonstrated and effective grid-scale energy storage technology that can support large-scale integration of renewables. This thesis addresses on three major aspects of implementing CAES in Canada: I) geomechanical design workflow, II) CAES siting in salt caverns across Canada: a geomechanics perspective, and III) potential of deep brine disposal in southwestern Ontario.

Part I of the thesis discusses the geomechanical design workflow for CAES in salt caverns. The workflow includes tasks and design decisions that are executed from a CAES project's pre-feasibility period to end of operation period. The major sections of the workflow include geology, data collection and mechanical earth model, constitutive model: creep, geomechanical issues and cavern design decisions, and monitoring. The goal of this section is to identify and investigate high-level geological engineering tasks that should be considered when designing a salt cavern for CAES.

Part II of the thesis entails a comprehensive study on the siting of CAES plants in salt caverns across Canada. The objective of the study was to develop an evaluation methodology and use it to determine suitable sites for CAES based on geology, renewable energy potential, energy demand, and existing infrastructure. Multi-criteria analysis was utilized as a tool to compare and evaluate sites. Six criteria are used in the evaluation framework: 1) depth to salt strata, 2) salt strata thickness, 3) renewable energy potential, 4) energy demand, 5) proximity to existing natural gas infrastructure, and 6) proximity to existing electrical infrastructure. The study will be useful to the government in developing energy policies, drafting regulations, and utilized by the industry in deciding the location for front-end engineering and design (FEED) studies.

Part III of the thesis comprises of a study on the potential of deep brine disposal in southwestern Ontario. The aim of the study was to develop an evaluation methodology and investigate suitable sites for brine disposal in southwestern Ontario based on geological, geomechanical, and petrophysical parameters. A multi-criteria analysis evaluation system was developed based on relevant disposal parameters and applied to sites throughout southwestern Ontario. Criteria used in the study include permeability, porosity, depth, thickness, disposal formation lithology, and caprock lithology. The study will benefit industrial and academic readers to understand the parameters required for deep brine disposal and appreciate the availability of suitable locations for disposal in southwestern Ontario.

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To my parents,

for their love and endless support

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1) Introduction

The thesis is funded by Natural Sciences and Engineering Research Council of Canada (NSERC) and Natural Resources Canada (NRCan) with the main objective of minimizing the knowledge gap in implementing compressed air energy storage (CAES) technology in Canada. The three major research areas presented in the thesis are 1) geomechanical design workflow, 2) CAES siting in salt caverns across Canada: the geomechanics perspective, and 3) potential of deep brine disposal in southwestern Ontario.

1.1 Motivation

The world has realized the impact of greenhouse gas (GHG) emissions on climate change, which has affected natural and human systems across the globe (Figure 1). By October 2016, 159 countries agreed to the Paris Agreement that thrives to combat climate change through reducing GHG emissions and keeping the temperature rise well below 2° C above pre-industrial levels. Canada's commitment towards climate change aligns with the United Nation's plan for combating climate change through reducing greenhouse gas (GHG) emissions. Canada has committed to developing a low-carbon economy and reduce GHG emissions to 30% below 2005 levels by 2030. One of the ways to achieve this goal is by replacing high GHG emitting electricity generation sources with clean electricity generation sources. Canada's Mid-Century Strategy report highlights that electrification of end-use applications that utilize fossil fuel (e.g., vehicles, heating systems etc.) is crucial in mitigation of GHG emissions (Environment and Climate Change Canada, 2016). However, this will also mean that electricity demand will more than double by 2050, and this demand must be met by clean electricity. Examples of clean electricity generation sources are wind, solar, hydro, and nuclear power.

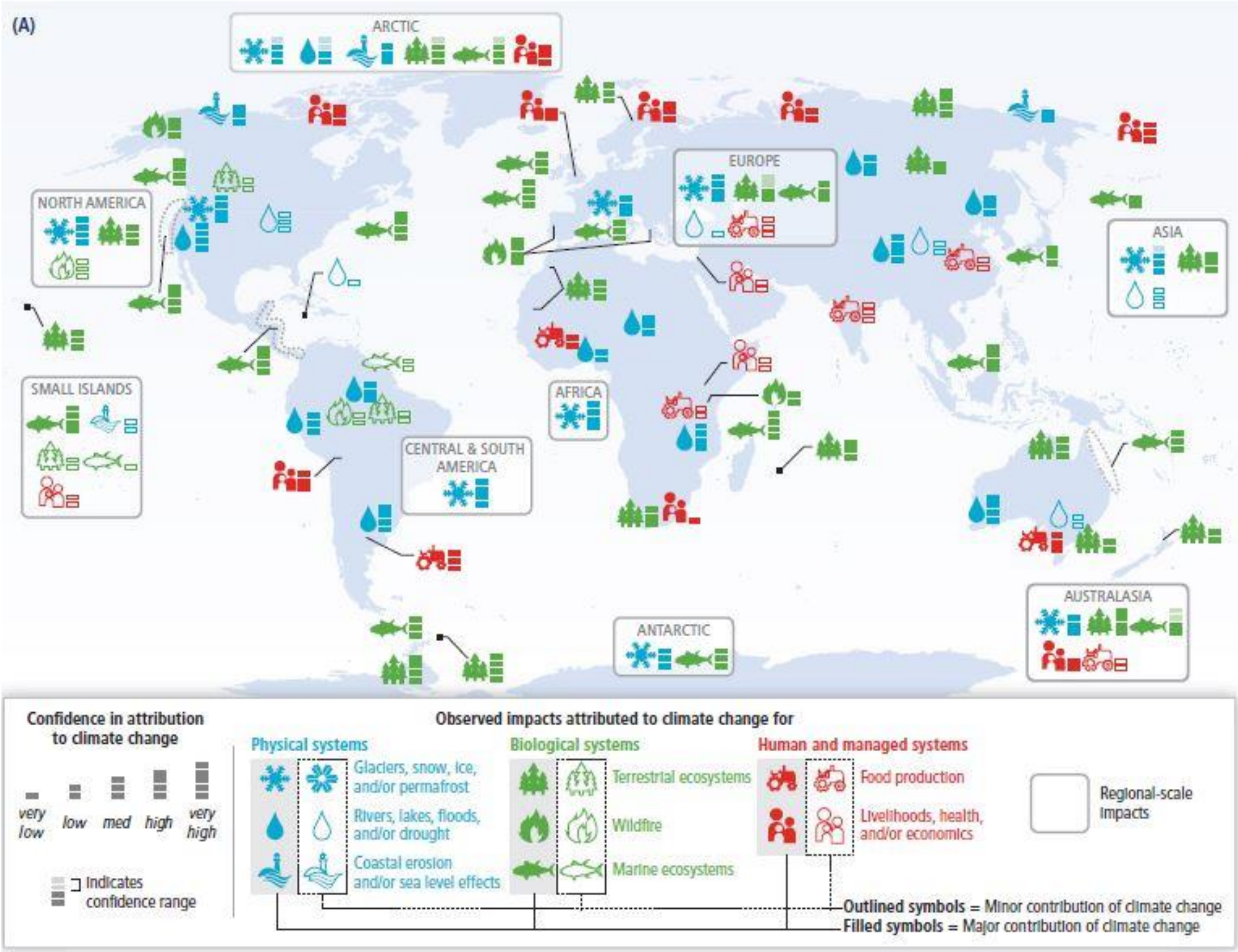

Figure 1: Impact of climate change across the globe (IPCC, 2014).

The provinces with the largest impact on Canadian economy, Alberta and Ontario, have created plans to meet Canada's GHG emission target by 2030. Ontario is leading the race in implementing clean energy; due to massive end to coal-based supply from 25 % of total electricity generation capacity in 2003 to coal-free generation in 2014, Ontario is the first jurisdiction in North America to fully eliminate coal-based electricity generation plants. The province has replaced coal with renewable sources such as wind and solar. Currently, Ontario has a generation capacity of 36,000 MW, out of which 11 % (3,983 MW) is wind and 1 % (380 MW) is solar. According to Ontario's 2013 Long-Term Energy Plan, Ontario is planning to extend the generation capacity from wind, solar and biofuels to 10,300 MW by 2021; most of which will come from wind and solar (Ministry of Energy, 2013). Alberta is also following the footsteps of Ontario to be coal-free by 2030. As of 2016, Alberta has a total installed generation capacity of 16,261 MW, out of which coal and wind make up 39 % (6,267 MW) and 9 % (1,491 MW), respectively, of the total generation capacity. Alberta has planned to be coal-free by 2030 and replace two-thirds of the existing coal generation capacity with renewable energy; at least, 5000 MW of renewable energy will be added by 2030 (Alberta Government, 2017).

The large-scale integration of wind and solar energy will require energy storage technology. Wind and solar are intermittent in nature; windmills will only generate electricity when the wind is blowing and solar sources will generate electricity when the sun is shining. Therefore, in order to be a reliable source of electricity, wind and solar sources will need to be paired with energy storage technologies. Energy storage technology will store electricity during low demand periods and put it back on the grid during high demand periods. In fact, it can even be said that the large-scale integration of wind and solar is largely dependent on the ability to store energy.

One of the well-demonstrated and effective energy storage technology is compressed air energy storage (CAES) in salt caverns. Even though other storage technologies exist, CAES and pumped hydro storage (PHS) are the only two technologies capable of storing grid scale (> 50 MW) electricity. Deployment of PHS requires 1) a large hydraulic head difference between upper reservoir and lower reservoir, and 2) large volumes of water. Due to these two requirements, PHS is infeasible in certain locations such as southwestern Ontario. CAES also has few advantages over PHS in terms of high energy density, small surface footprint, low-risk construction, and no devastating failure that could affect human life. In comparison to flywheels, super-capacitors, and batteries, CAES is much inexpensive ($/kWh) and has the largest storage capacity.

Apart from assisting with wind and solar integration, CAES can also provide benefits through arbitrage, load levelling, peak shaving, and curtailment reduction. In the report, “Unleashing the value of energy: A case study of fuel-free, compressed air energy storage for the Ontario Power System”, Andrew Ford (2015) discussed that fuel-free CAES can provide Ontario with a value of $7.2 billion over 20 years through 8 months per year of wind integration and 4 months per year of load levelling/combustion turbine (CT) displacement. Wind integration and load levelling/CT displacement would provide values of $ 4.7 billion and $ 2.5 billion, respectively.

1.2 Background on the CAES Technology

The general goal of CAES is to store energy generated at one time, generally during low demand period, and use it later, usually during high demand period. Similar to PHS, CAES is a mechanical form of energy storage; however, instead of pumping water from a higher elevation to lower elevation, CAES technology utilizes the elastic potential of air to store it as compressed air. The main components of CAES technology are the compressor, thermal energy storage (only applicable for Adiabatic CAES), compressed air storage vessel, turbine, and generator (Figure 2). The concept behind a conventional CAES is to 1) use surplus power to compress ambient air, 2) extract heat during compression and store it in thermal energy storage (only applicable for Adiabatic CAES), 3) store compressed air in the storage vessel, 4) release and pre-heat the stored compressed air in the heat exchanger before being directed into the turbine-generator to produce high-cost electricity, and 5) release electricity back to the grid.

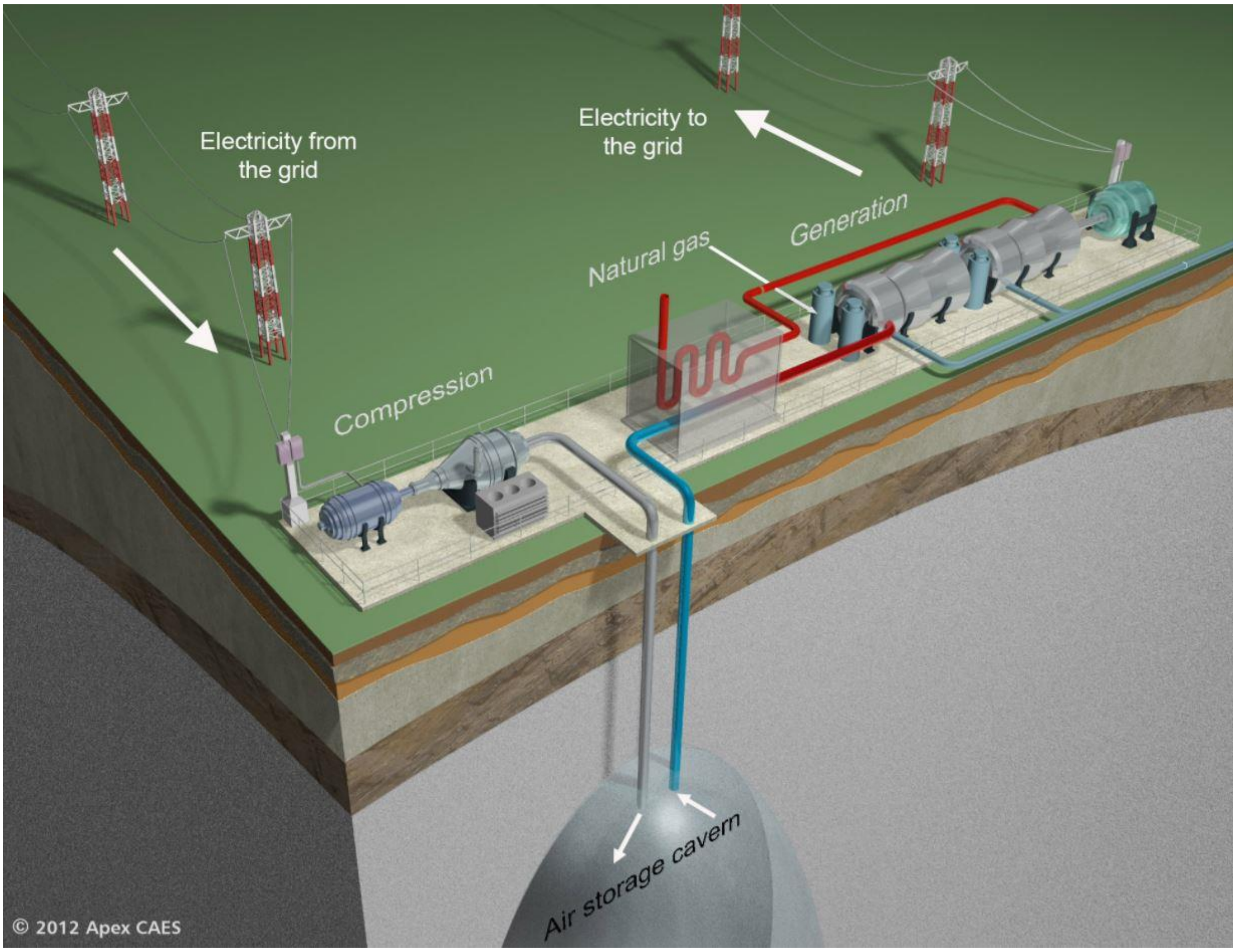

Figure 2: Components of a CAES facility (Apex CAES, 2017).

Two types of CAES technologies exist: Conventional (fuel-fired) CAES and Adiabatic (fuel-free) CAES. Compression of ambient air to high storage pressure generates strong heat that is either wasted away using cooler or stored in thermal energy storage (TES). During the expansion stage, it is required to pre-heat the compressed air before entering the turbine-generator for electricity generation. The main difference between the two CAES technologies is the process of pre-heating the compressed air in the expansion stage. In conventional CAES, heat extracted during the compression stage is wasted away in the atmosphere and natural gas is used to re-heat the compressed air in the expansion stage. Whereas, in adiabatic CAES, heat extracted during the compression stage is stored as thermal energy storage (TES) and later used to re-heat compressed air in the expansion stage. Reusing the heat increases the efficiency of CAES up to 70% as compared to the 40-50 % efficiency of conventional CAES. In addition, Adiabatic CAES has zero carbon emission because it does not use natural gas in the expansion stage.

Various aboveground and underground storage options exist to store compressed air at high pressure. Examples of aboveground options are surface steel vessels, underwater balloons, and a network of hollow steel pipes. Underground options include salt caverns, hard rock mines, and aquifers. For grid-scale energy storage, there is no doubt that underground storage options are much more advantageous than the aboveground storage options. The capital cost of aboveground storage is almost double than that of underground storage. Furthermore, the surface footprint of underground options is much lower than that of aboveground options.

Within the underground storage options, salt caverns are feasible for grid-scale storage due to suitable storage properties of rock salt such as impermeability, high strength, and ease of creation. The impermeable nature of rock salt matrix prevents compressed air from leaking and affecting efficiency. The high strength of rock salt enables pressurizing and cycling compressed air at desirable rates without cavern collapse. Generating salt caverns through solution mining is a proven technique as it has been extensively utilized in the past to create storage caverns for fossil fuels. Where rock salt is not present, aquifers can be utilized as a storage reservoir; however, a disadvantage in using aquifers is the slow flow rate that occurs due to the presence of water in the pore space. This limits the efficiency of the CAES system in aquifers as compared to salt caverns.

Two grid-scale CAES facilities exist in the present day: Huntorf Plant in Germany, and McIntosh Plant in Alabama, United States. Huntorf plant, commissioned in 1978, is the world's first CAES plant and has a peak generating capacity of 290 MW for 3 hours. The facility utilizes two underground salt caverns with volumes of 140,000 m^3 and 170,000 m^3, resulting in the total volume of 310,000 m^3. The caverns are typically operated between 4.3 MPa to 7.0 MPa and have a maximum extraction rate of 1.5 MPa/hr (Crotogino et al., 2001). The McIntosh plant was commissioned in 1991 and has a peak generating capacity of 110 MW for 26 hours. The facility utilizes a single 460 m deep cavern with the volume of 560,670 m^3; the cavern has maximum height and diameter of 230 m and 72 m, respectively (PowerSouth Energy Cooperative, 2014). The facility typically operates between 4.5 MPa to 7.6 MPa. Apart from these large-scale CAES plants, a few CAES projects are either operating at small scale or are in development stage. Some of these projects include: Hydrostar's 0.7 MW underwater CAES project in Toronto, Ontario; Hydrostar's 1.75 MW CAES project in Goderich, Ontario; Apex Bethel Energy Center's 317 MW CAES project in Tennessee Colony, Texas; Gaelectric's 330 MW CAES project in Northern Ireland; and RWE Power's ADELE Adiabatic CAES project in Germany.

1.3 Research Topics in the Thesis

The research is divided into three major studies: geomechanics design workflow (chapter 2), CAES siting in salt caverns across Canada: the geomechanics perspective (chapter 3), and potential of deep brine disposal in southwestern Ontario (chapter 4). Even though these studies can be read independently, they complement and build on each other. Two of these studies, CAES siting in salt caverns across Canada and deep brine disposal potential in southwestern Ontario, are funded and published as open reports by Natural Resources Canada (NRCan). A detailed introduction on these topics is presented at the start of each chapter, and a very brief introduction is presented below.

The chapter on "geomechanical design workflow" includes all the major geological engineering steps that are undertaken before the start of the project to during operations. Some major sections in the workflow include geology, data collection and mechanical earth model, constitutive model: creep, geomechanical issues and cavern design decisions, and monitoring. The goal of this section is to identify and investigate high-level geological engineering tasks that should be considered when designing a salt cavern for CAES.

The section on "CAES siting in salt caverns across Canada: the geomechanics perspective" was funded and published by NRCan with a goal to understand the suitable areas for implementing CAES in Canada. The main objective of the study was to develop an evaluation methodology and use it to determine suitable sites for CAES based on geology, renewable energy potential, energy demand, and existing infrastructure. Multi-criteria analysis was utilized as a tool to compare and evaluate sites. The study will be useful to the government in developing energy policies, drafting regulations, and utilized by the industry in deciding the location for front-end engineering and design (FEED) studies.

One of the major limitations of implementing CAES in salt caverns is the issue of brine disposal. A large quantity of brine, approximately 6-7 m^3 of brine per 1 m^3 of salt, is generated during solution mining. The brine must be properly disposed to avoid environmental issues. The last chapter, potential of deep brine disposal in southwestern Ontario, was funded and published by NRCan to investigate the suitability of deep brine disposal in southwestern Ontario. The main objective of the study was to develop an evaluation methodology that would evaluate and compare sites based on geological, geomechanical, and petrophysical parameters. Multi-criteria analysis was adopted as a decision-making methodology, which uses scoring and weighting scheme to evaluate sites. The study will benefit industrial and academic readers to appreciate those parameters required for deep brine disposal and educate on the suitable locations for disposal in southwestern Ontario.

2) Part I - Geomechanical Design Workflow

The underground storage portion of the CAES facility is a complex component that involves multiple research fields such as geology and geomechanics. A comprehensive understanding of the geology and geomechanics principles is vital because they have major impact on siting, sizing, and designing a CAES facility; for example, energy output (MWh) of the CAES facility is limited by cavern air storage pressures and storage size, which are dependent on depth and thickness of salt strata. In this part, a geomechanical design workflow is created to understand the geology and geomechanics tasks that must be executed from a CAES project's pre-feasibility period to end of operation period. The main sections in the geomechanical design workflow are geology, data collection and mechanical earth model, constitutive model: creep, geomechanical issues and cavern design decisions, and monitoring. Figure 3 displays the geomechanical design workflow of a CAES project, and a detailed description of the main tasks is provided in the subsequent sections.

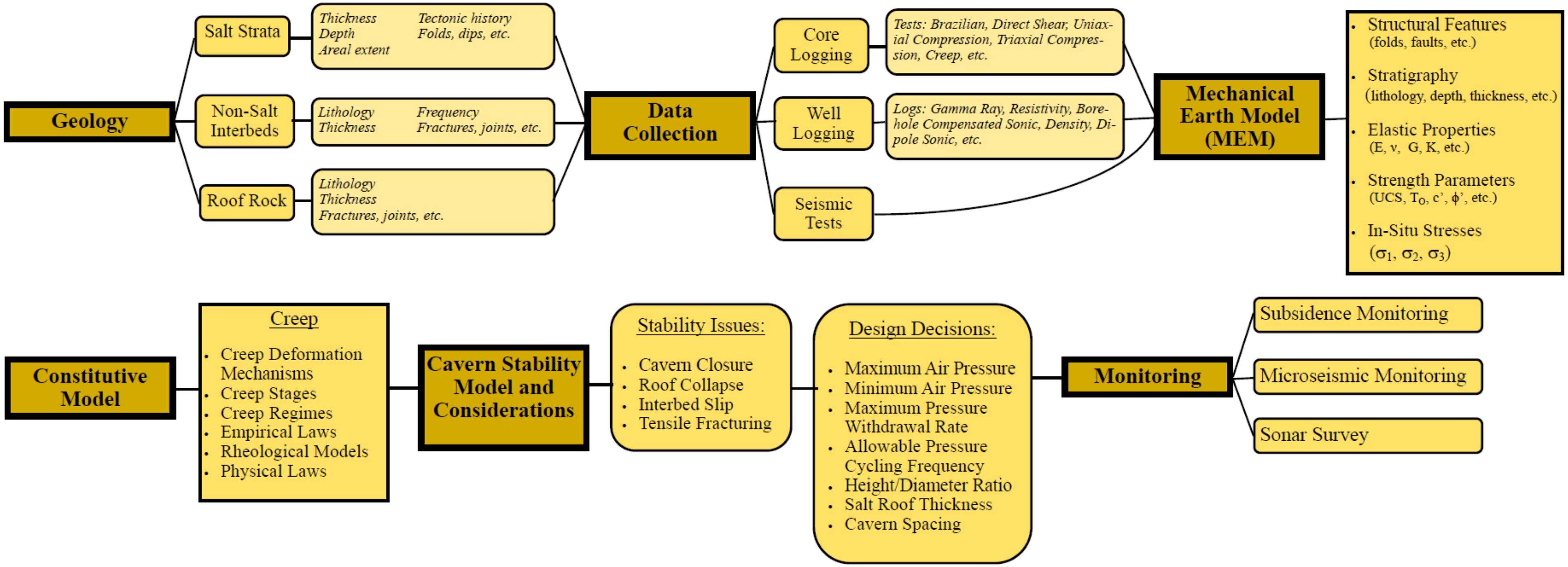

Figure 3: Geomechanical design workflow for CAES.

2.1 Geology

It is essential to interpret and understand the structural geology and stratigraphy of the targeted areas if salt caverns are to be utilized for storing compressed air. The first step before planning for data collection and cavern stability analysis is to confirm the presence and type of salt deposit. Various types of salt deposits exist and have varying impact on cavern stability. In addition, non-salt interbeds are also encountered within salt deposits and influence cavern stability depending on lithology and location.

2.1.1 Types of Salt Deposits

The source of rock salt is seawater, which contains high sodium and chlorine content. Marine transgression and regression results in deposition of salt in an almost enclosed basin; the enclosed basin allows seawater to enter the basin but prevents it from escaping back to the sea. Evaporation and continuous supply of seawater into the basin create an optimal environment for salt deposition (Terralog Technologies Inc., 2001).

Salt deposits can be divided into three types: bedded, domal and tectonic salts. Salts are always primarily deposited as bedded salts, but can be converted into domal and tectonic salts under pressure or tectonism. Salt caverns for storage can be solution mined in any of the salt deposits; however, the deposits have similarities and differences that influence cavern stability and dissolutioning.

Figure 4 displays salt caverns in bedded and domal salt deposits. Bedded salts are the primary rock salt deposit from which domal and tectonic salts emerge. Bedded salts are deposited as laterally continuous layers with non-salt interbeds such as shale, anhydrite and carbonates. Bedded salts can be further divided into thin salts with a thickness of a few meters and thick salts with a thickness of 100s of meters. Examples of bedded salts include the Devonian salt strata in the Western Canadian Sedimentary Basin and the Silurian salt strata in the Michigan Basin.

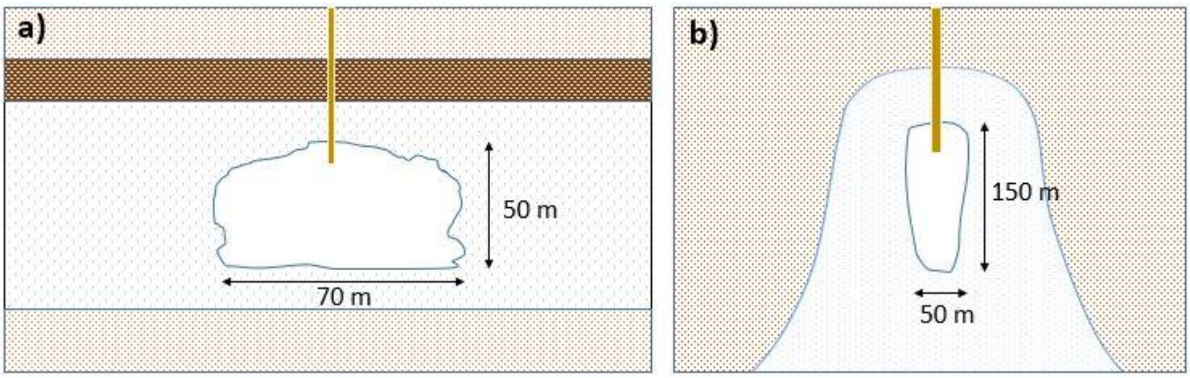

Figure 4: Salt caverns in a) bedded and b) domal salt deposits.

Domal salts are formed when high subsurface temperatures and pressures cause deep-seated salts to rise through buoyancy. As compared to bedded salts, domal salts are limited in lateral extent but are generally much thicker. Domal salts are relatively homogeneous than bedded salts. Examples of domal salts include salt domes of the USA Gulf Coast and the North Sea.

As the name suggests, tectonic salts are modified due to tectonic activity that generates thick and folded salts. Structure of tectonic salts is complex and heterogeneous. It is possible to encounter high frequency and thick non-salt interbeds that are folded within the salt structure. An example of tectonic salt is the salt strata in the Maritimes Basin, which was exposed to continental collision events.

Due to being relatively homogeneous and devoid of non-salt interbeds, it is relatively easy to solution mine in salt domes as compared to bedded and tectonic salts. Tectonic salts could pose the most problems during solution mining due to thick and dipping non-salt interbeds.

If deposited at adequate depth, caverns in salt domes and thick-bedded salts have higher stability as compared to caverns in thin-bedded salts and tectonic salts. It is possible to accommodate a thick salt roof and a height to diameter (H/D) ratio of 1 in salt domes and thick-bedded salts; this significantly reduces roof stability issues as compared to thin-bedded salts that can only accommodate caverns with thin salt roof and H/D ratio of less than 1. Cavern stability issues are the highest in tectonic salts due to complex salt structure that includes folded salt strata with layers of non-salt interbeds.

2.1.2 Non-Salt Interbeds

Bedded salt deposits could contain thin non-salt interbeds within salt beds and thick non-salt interbeds separating salt beds. The thickness and frequency of non-salt interbeds may differ within a basin. Common non-salt interbeds include anhydrite, dolomite and shale. Similar to halite (NaCl), anhydrite ($CaSO_4$) and dolomite ($CaMg(CO_3)_2$) are evaporitic rocks that are formed from precipitation of minerals in sea water. Shale is a clastic rock that is formed through lithification of clay particles that are deposited in a calm water environment.

Obtaining geomechanical properties of interbeds in a basin is not trivial. Terralog Technologies Inc. (2001) has summarized some of the geomechanical properties of non-salt interbeds encountered in the Michigan Basin; Table 1 displays mechanical properties of the non-salt interbeds.

Table 1: General geomechanical properties of salt and non-salt interbeds (Adapted from Terralog Technologies Inc., 2001).

Lithology	E (GPa)	ν	UCS (MPa)	T_0 (MPa)
Salt	30	0.4	25	2.5
Anhydrite	100	0.35	100	10
Dolomite	40-100	0.25	20-80	2-10
Shale	50	0.25	50	2-5

A pure anhydrite is stiff and strong rock with extremely low porosity. In bedded form, anhydrite beds are stiff and strong due to the absence of joints; joints are filled with precipitated minerals as anhydrite undergoes fluid assisted diffusional creep (FADC). High stiffness and absence of jointing make anhydrite an excellent roof rock with strong ability to support the overburden load and minimize deformation in the cavern. Unlike anhydrite and salt, dolomite might contain joints that are salt filled. If jointing is substantial, then lab tests are meaningless as they only represent the intact rock strength; i.e., strength of the rock material between discontinuities (Terralog Technologies Inc., 2001). Similar to anhydrite and halite, dolomite is low in porosity due to pressure solution and precipitation over time. High stiffness of dolomite makes it a good roof rock as long as it is not highly jointed. Shale is hard to characterize as it is laminated, jointed, and displays strong anisotropy; for example, stiffness values in the horizontal direction are greater than the vertical direction. Shale can be problematic as roof rock due to being laminated, which results in higher chances of sloughing. However, the presence of dolomite increases the stiffness and makes shale beds more competent and resistant to sloughing.

2.2 Procedure for Gathering Rock Properties and Developing a Mechanical Earth Model through Core Tests, Well Logging, and Seismic Tests

Table 1 in the previous section displayed the general geomechanical properties of salt and non-salt rocks that can be used for preliminary stability assessment. For a detailed and site-specific geomechanical analysis, an engineer would need to construct a mechanical earth model (MEM) for a specific site. Typically, MEM is developed through core testing, well logging, and seismic tests. Note that “well logging” can also be termed as “borehole logging”.

MEM is a numerical representation of rock mechanical data and earth stresses. Five major components represented in MEM are structural features, stratigraphy, elastic properties, rock strength parameters, and in-situ stresses (Figure 5). Depending on the application, MEM can be developed in 1D, 2D or 3D.

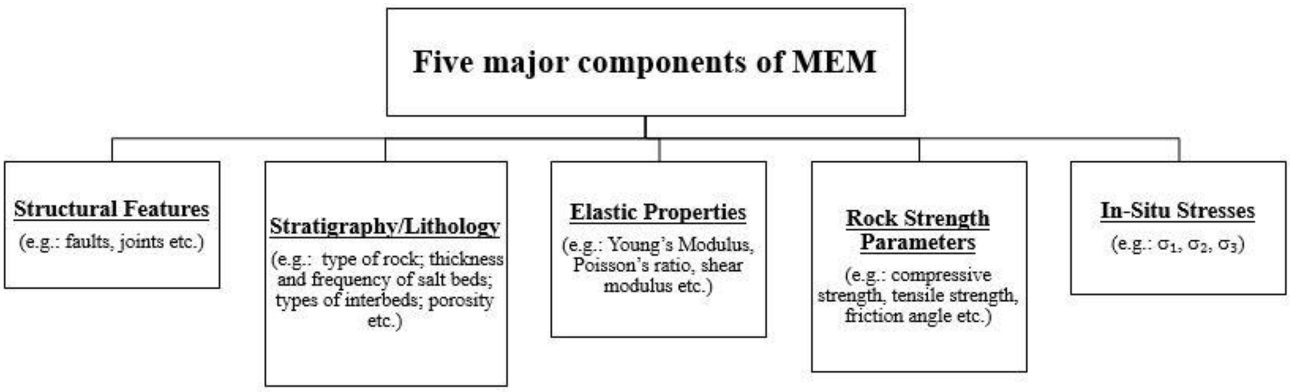

Figure 5: Rock mechanical and earth stress data represented in the mechanical earth model.

Data in MEM is obtained from a combination of core testing, well logging and seismic testing. Core tests can be thought of as the “magnifying glass” of the MEM as it provides rock data about 50 mm from the wellbore.

Well logging can be considered as the “glue” between core tests and seismic data; well logging procedures provide rock data about 1.5 m from the wellbore. Seismic tests cover a large area of the wellbore by providing information of about 60 m of rock data (Looff, 2001).

To get the best picture of the geology and rock parameters, an engineer should perform all the three testing procedures. In reality, the amount of core testing and well logging is restricted due to high costs. Under these circumstances, the MEM relies heavily on seismic tests. However, the seismic tests do not always provide “ground truth” as the seismic test data can be interpreted in many different ways (Looff, 2001). Therefore, seismic data must be integrated and calibrated with core data and well log data to provide better “ground truth” (Figure 6).

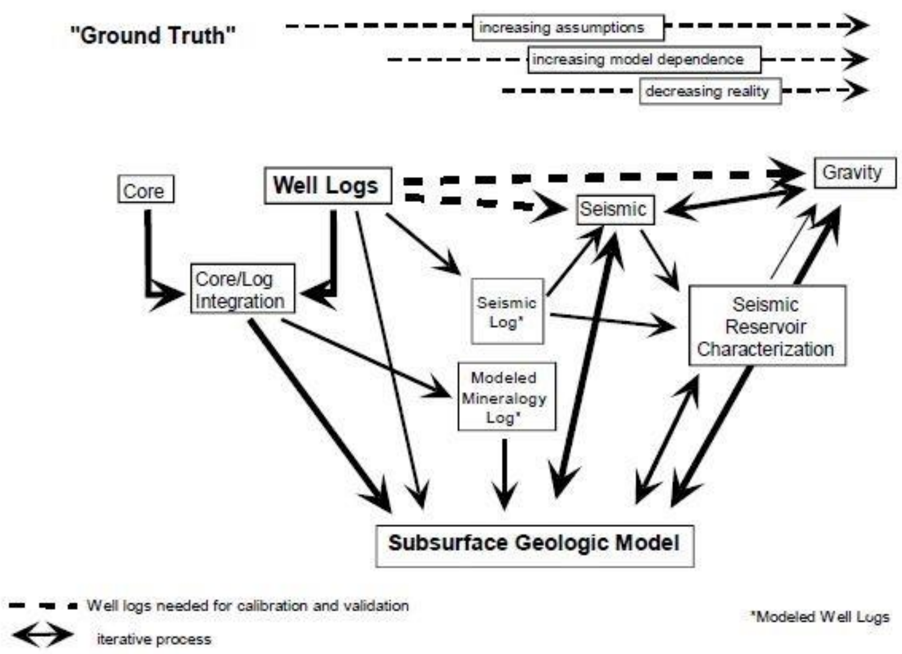

Figure 6: Geophysical data must be integrated with core and well log data to establish better “ground truth” (Looff, 2001).

The following three sections list the standard core tests, well logging tests, and seismic tests that can be performed for developing a reliable mechanical earth model.

2.2.1 Core Tests

Laboratory testing of cores is an essential part of any geomechanics model as it gives an engineer the best chance of understanding the “ground truth”. Also, core test results are a requirement to calibrate the well logging tests. However, when interpreting geology and rock parameters, an engineer should use the core test results with care due to the small size of core compared to the rock formation, anisotropy in the material, the presence of joints/fractures, and wide distribution of material (Hoek, 1977). Some of the standard core tests that can be performed are:

- ***Point load test***: It is an index test that is used to provide an estimate of the uniaxial compressive strength of the core specimen. It does not work in very soft rocks and should be carefully used in anisotropic rocks such as shale. In shales, loading should be applied either parallel or perpendicular to the bedding plane (Hoek, 1977).
- ***Direct shear test***: This test is performed to find shear strength parameters of the rock or discontinuity. The Mohr-Coulomb strength parameters, cohesion (c') and friction angle (ϕ'), are determined from this test.
- ***Uniaxial compression tests***: This test determines the specimen's elastic properties such as Young's modulus, Poisson ratio, and uniaxial compressive strength (UCS).
- ***Triaxial compression test***: In this test, the load is applied axially and a confining pressure is also applied. The test measures Young's modulus, Poisson ratio, and uniaxial compressive strength (UCS).
- ***Creep test***: These tests are only done by a few companies as it requires specialized equipment. This test determines the time-dependent behaviour of salt.

2.2.2 Well Logging

A well logging system would include a logging unit such as a truck with computerized system for data recording and processing, a logging cable for transmitting information from the well bore to the logging unit, a logging tool such as a probe that would contain sensors and processing circuitry for data recording and transmission (Williams, 2013). A logging system can acquire multiple logs at a time; it is easier to interpret the geology and rock parameters by analyzing multiple logs as they are correlated in nature.

Various well logging tests exist, and different logging test plans must be developed depending on the required geological information. A few basic logging tests that could be performed in the salt strata of the Michigan Basin are described below:

- ***Gamma-ray:*** It records the natural gamma radiation emitted by the rocks around the borehole (Williams, 2013). The recorded natural radioactivity data helps in determining the lithology and correlating geologic units from other logs. In the salt strata, it can particularly help identify salt (low gamma radiation) from shales (high gamma radiation). Also, this test can be used to integrate core data with log data by correlating the gamma-ray log test results with natural gamma measured from the core (Looff, 2001).
- ***Resistivity or electric log***: This test records the resistance of a formation to electric current and resistivity is entirely dependent on the amount of water present in the formation. It would help in determining water-bearing zones and permeability of the formation. In the salt strata of southwestern Ontario, the resistivity logs could be used in identifying the top of caprock and

carbonates. There are two types of resistivity tests: induction and laterolog. Laterolog should be utilized in salt strata as induction method does not work in salt.

- ***Borehole compensated sonic (acoustic) log***: This logging procedure involves transmitting acoustic waves and measuring interval transit time. Transit time is dependent on porosity, density and elastic properties of the formation. The transit time and velocity data obtained from this logging procedure are used to calibrate seismic salt proximity surveys (Looff, 2001). In the salt strata of the southwestern Ontario, this procedure will determine the porosity of dolomite caprock beds.
- ***Density*****:** The procedure involves a high-energy gamma-ray source that interacts with natural gamma rays from the formation. The resulting gamma ray counts are dependent on electron density and give bulk formation density. Well log density data are needed to calibrate gravity and seismic data.
- ***Dipole sonic log*****:** This is a more complex version of the sonic log explained above. In this log, interval transit times are measured for compressional, shear, and Stonely acoustic waves. This procedure determines Poisson's ratio, permeability and fractures in the formation (Looff, 2001). Data from this log are critical for calibrating the seismic data.

These were the basic well logs that must be performed. If an engineer needs more geologic information, there are many other logging techniques such as modelled mineralogy log, compensated neutron, combination neutron-density, dipmeter and magnetic resonance.

2.2.3 Seismic Tests

Seismic testing is an essential part of the geologic model as it can test a large area and does not require drilling of wells. In simple terms, seismic testing involve generating sound waves at the surface, which are transmitted through the subsurface and reflected by the subsurface formations. The reflected sound waves are captured by the geophones and analysed for subsurface data. However, seismic data can be interpreted in many different ways and must be calibrated with well log data. Looff (2001) recommends that well log data, especially sonic (acoustic velocity) and density data, are needed at a minimum for calibration. Seismic test data are derived as time, and must be converted to depth using sonic and density data.

2.3 Creep

Creep is time-dependent deformation under constant deviatoric stress. When loads are removed, only parts of strains are recovered and therefore, creep is primarily categorized as plastic deformation. All rocks show creep behaviour due to load change; but in most of the rocks, creep behaviour can be neglected as most rocks experience creep at temperature and stress not encountered at engineering design scale (Dusseault and Fordham, 1993). On the other hand, creep in salt rock can occur at temperature and stress encountered at engineering scale. This section will discuss some of the important aspects of creep behaviour: creep deformation mechanisms, creep stages, rheological models, and physical creep laws.

2.3.1 Creep Deformation Mechanisms

Creep is caused by specific mechanisms: dislocation glide, climb, and cross-slip; diffusive mass-transfer mechanism such as pressure solution; and stable microcrack generation and healing. When laboratory data are extrapolated to analytical equations, it is assumed that certain mechanisms are dominating the creep process (Dusseault and Fordham, 1993). Therefore, understanding of creep mechanisms is essential for extrapolating laboratory results and performing numerical analysis in salt.

- Dislocations are crystallographic defects within a crystal structure, and these defects generate highly localized bond forces. Dislocations would propagate when the bond forces are exceeded. Dislocations can propagate through glide, climb, or cross-slip until the array of atoms reach desired packing, grain-boundary, or another dislocation where healing occurs (Dusseault and Fordham, 1993).
- Diffusive mass-transfer mechanism in salt includes pressure solution or fluid assisted diffusional creep (FADC). In this process, atoms are dissolved in high-stress regions and defect sites. As the solubility increases during high stress periods, concentration gradients are formed and the ions move from regions of high concentration (solubility site) and precipitate in the regions of low concentration (pore space). Ion movement takes place in grain boundary thin water films. It should be noted that solubility rate is inversely proportional to grain size and diffusion rate is sensitive to temperature (Dusseault and Fordham, 1993).
- Stable microcracking occurs after a certain stress limit is reached. It involves crack generation along grain boundaries and therefore, results in dilation. Microcracking is stable because the cracks are healed from FADC. Healing is an important characteristic of salt that results in non-terminating steady-state creep and preventing tertiary creep or rupture to take place in salt caverns (Dusseault and Fordham, 1993).

2.3.2 Creep Stages

Classical creep in rocks has four stages: instantaneous elastic strain, primary (transient) creep, secondary (steady-state) creep, and tertiary creep. However, creep in salt cavern only undergoes the first three stages and does not display tertiary creep (Figure 7). These stages are briefly described below.

- ***Instantaneous elastic strain*:** This strain has magnitude of $\Delta\sigma/E$ and is imposed instantaneously as the stress is applied. The strain is fully recoverable as the load is removed.

- ***Primary (transient creep):*** During primary creep, the strain rate is decelerating ($\partial^2\varepsilon/\partial t^2 < 0$). In Figure 7, it can be noticed that initially the slope is large and then declines with time. Unlike metals, only a part of the primary creep is recoverable when loads are removed. Full primary creep recovery is possible only in metals because they do not have porosity, are insoluble, and have different bond structure. Note that primary creep is recovered gradually with time and this is known as creep recovery.
- ***Secondary (steady-state) creep*:** At this stage, the strain rate is constant and the strains are non-recoverable. In Figure 7, it can be noticed that the slope during steady-state creep is constant ($\partial\varepsilon/\partial t$ = constant, $\partial^2\varepsilon/\partial t^2 = 0$). Steady-state creep can continue for an indefinite period of time until the storage cavern is fully closed and has reached isotropic stress state. The constant strain rate is maintained by balancing of work-hardening processes with recovery processes.
- ***Tertiary creep*:** In this stage, the strain rate is accelerating towards rupture (($\partial^2\varepsilon/\partial t^2 > 0$). This stage occurs in metals and some hard rocks but not in salt caverns. The reason for no tertiary creep stage in salt caverns is FADC, which ensures a balance between recovery and work-hardening (Terralog Technologies Inc., 2001).

  (Note that σ, E, ε and t refer to normal stress, Young's modulus, strain rate and time, respectively)

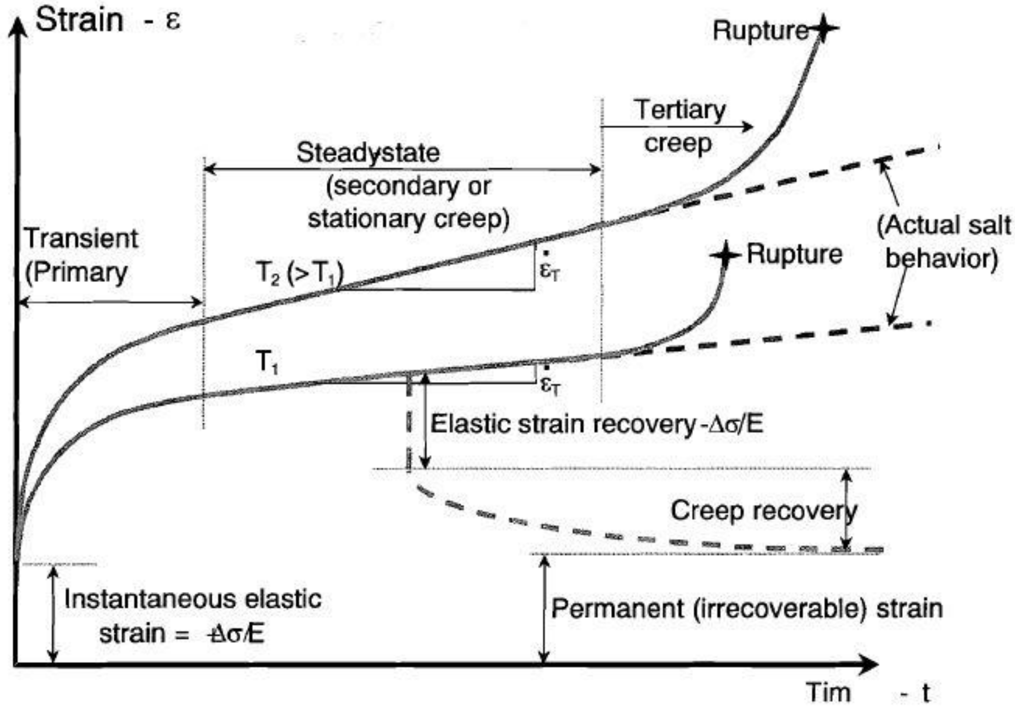

Figure 7: Creep stages in salt and metal. Tertiary stage does not exist in salt creep due to FADC (Terralog Technologies Inc., 2001)

2.3.3 Rheological Models

Rheological models explain macroscopic stress-strain behaviour by using a combination of idealized elements. These elements include spring, dashpot, slider, and rupture element. Elements can be used in series, parallel or various combinations to describe deformation behaviour. Figure 8 displays basic rheological elements with their stress-strain and strain-time plots. The elastic element represents elastic straining of the material when load is applied; strain is completely recovered when load is removed. The dashpot element is a creep strain element that strains over time and strains are not recovered when loads are removed. The slider element represents plastic strains and requires the applied loads to exceed at least the yield stress. Once the yield stress is exceeded, the material strains irrecoverably. The rupture element represents loss of strength in a material due to excessive load or strain (Dusseault and Fordham, 1993).

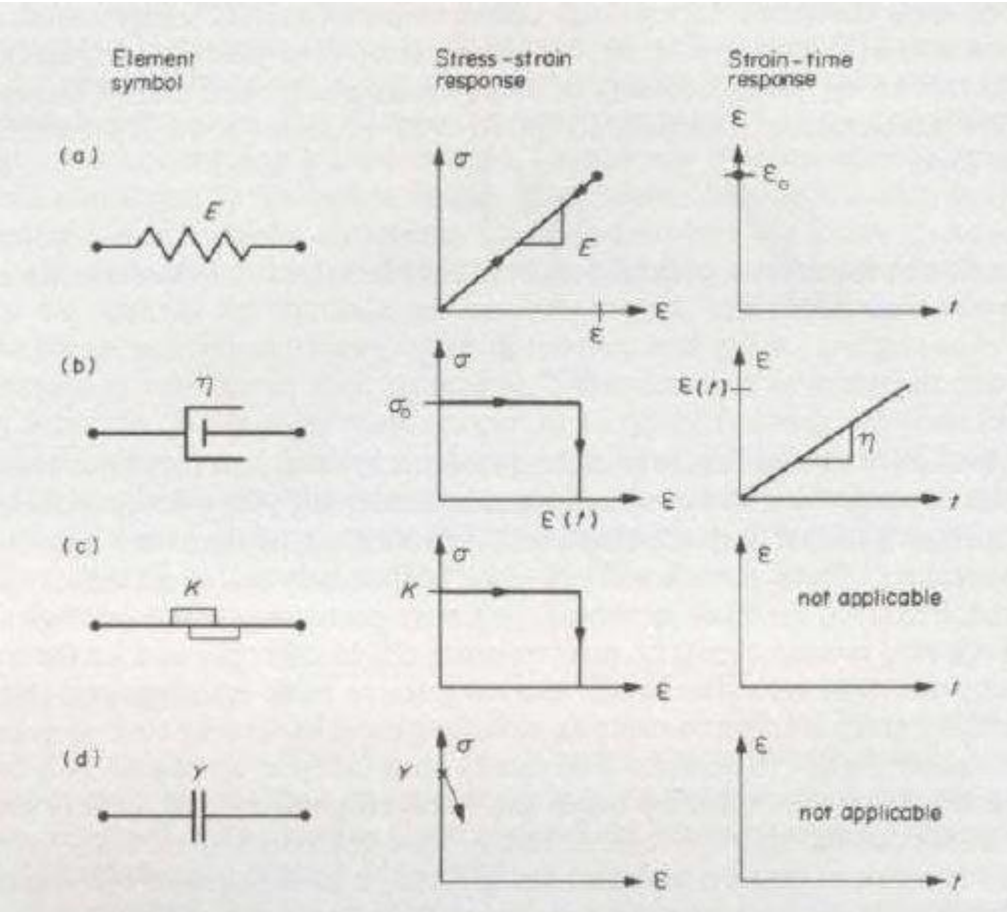

Figure 8: Basic rheological elements with stress-strain and strain-time plots: a) spring, b) dashpot, c) slider, d) rupture (Dusseault and Fordham, 1993).

The components of creep behaviour in salt can be described using Maxwell model, Kelvin-Voight model, and Burgers model (Dusseault and Fordham, 1993). The Maxwell model describes steady-state creep by using linear viscoelastic rheological model; this model puts a spring element and a dashpot element in series (Figure 9). The Kelvin-Voight model describes the transient phase of the creep using a spring element and a dashpot element in a parallel configuration (Figure 10). The Burgers model represents instantaneous, transient, and secondary creep by combining Maxwell model and Kelvin-Voight model. This is the most complete model that puts spring and dashpot elements in series as well as parallel (Figure 11).

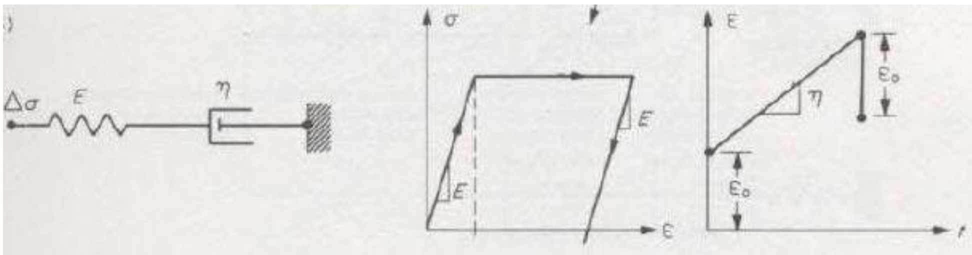

Figure 9: Maxwell model describes steady-state creep using spring element and dashpot element in series (Dusseault and Fordham 1993).

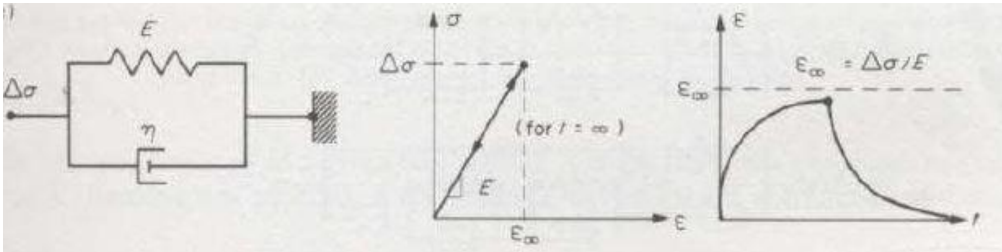

Figure 10: Kelvin-Voight model describes transient creep stage using spring element and dashpot element in parallel (Dusseault and Fordham 1993).

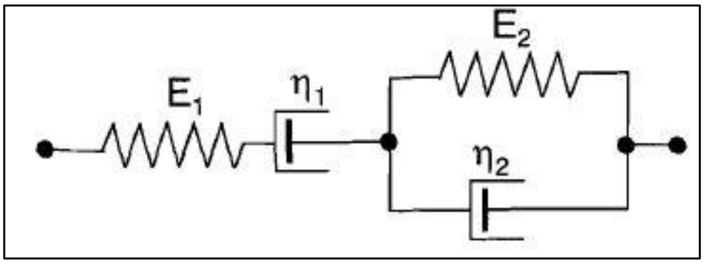

Figure 11: Burgers model describes instantaneous, transient, and secondary creep by combining Maxwell model and Kelvin-Voight model (Terralog Technologies Inc., 2001).

As demonstrated by the three salt creep models mentioned above, rheological models help in understanding creep in salt cavern by decomposing creep behaviour into recoverable viscoelastic and permanent viscoelastic models using spring and viscous elements. However, rheological models must be used with empirical or physical models as they do not provide direct predictions and must be calibrated (Dusseault and Fordham, 1993). Also, they do not consider temperature, intrinsic structure of salt, moisture content, and shear and normal stresses.

2.3.4 Physical Creep Law

Norton Creep Law could be used to predict steady-state strain rate. It is the most commonly used creep law and can incorporate multiple creep mechanisms. Norton Creep Law for a single mechanism is expressed as:

$$\dot{\varepsilon}_{ss} = A\left(\frac{\sigma_1-\sigma_3}{\sigma_o}\right)^n e^{\frac{-Q}{RT}}$$ **[Equation 1]**

Where:

$\dot{\varepsilon}_{ss}$	**=**	**steady-state strain rate**
$\sigma_1 - \sigma_3$	=	deviatoric stress
T	=	temperature
A	=	material-dependent parameter (includes texture, moisture content mineralogy, and impurity content)
n	=	parameter based on different mechanisms or creep regime
σ_o	=	normalizing stress at which a particular mechanism is initiated
R	=	universal gas constant
Q	=	activation energy of a given mechanism

2.4 Geomechanical Design Considerations

Due to its impermeable nature and strength characteristics, salt cavities have been utilized extensively for storage and disposal purpose. However, salt cavities are also exposed to some geomechanical stability issues that must be considered to avoid economic and environmental setbacks. Literature contains a few references where salt cavern projects were either disrupted or abandoned due to cavern stability issues. Major cavern stability issues include cavern closure, roof collapse, interbed slip, and tensile fracturing.

2.4.1 Cavern Closure

Cavern closure is a major issue in salt caverns, and many examples exist where the volume of the salt cavern was significantly reduced after a few years of operation. Rock salt's physical nature to creep is the reason behind cavern closure; the two major creep parameters that affect creep are pressure and temperature.

To generate maximum electricity, cavern operators would wish to extract the maximum amount of air out of the cavern; however, this situation might expose the cavern to extremely low air pressures that can increase the strain rate. As shown in Equation 1, creep increases with higher deviatoric stress; lowering the cavern pressure increases the deviatoric stress and increases creep. Therefore, the minimum cavern pressure must be carefully selected. Generally, the minimum cavern pressure should not be less than 25 % of the lithostatic pressure. For example, in a 650 m deep cavern in a tectonically unaffected basin, the lithostatic pressure would be ~ 15.6 MPa and therefore the minimum operating pressure would be ~ 3.9 MPa. Since lithostatic pressure increases with depth, the required minimum operating pressure would increase with depth too. Figure 12 demonstrates an artistic example of cavern closure in bedded salt deposit.

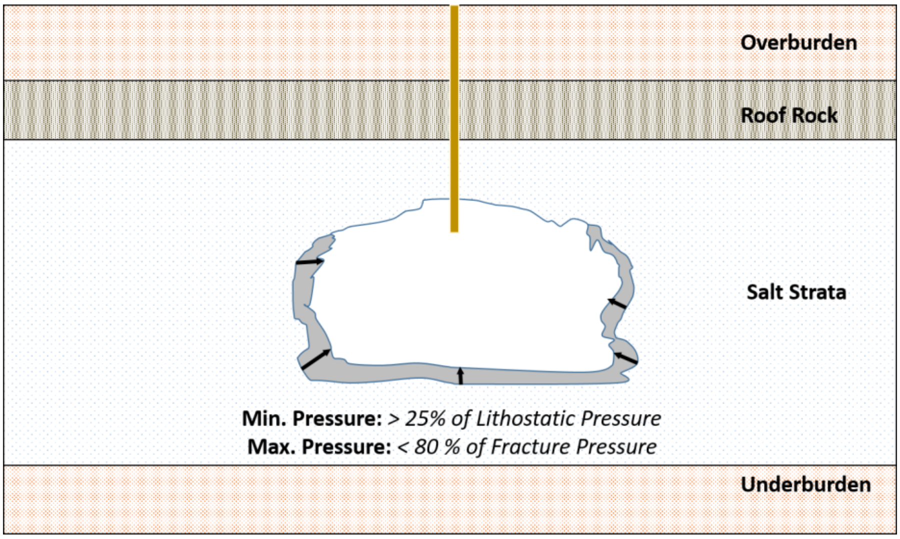

Figure 12: Cavern closure in bedded salt deposit. Minimum pressure and temperature affect closure rate.

In addition to low pressure, high temperatures also result in an increase in creep. Allen et al. (1982) recommended that cavity wall temperature should not exceed 80° C. Temperatures tend to increase with depth, and a geothermal gradient map of a particular area might be used to estimate the temperature of the targeted salt strata.

Many examples exist proving that deeper caverns are susceptible to cavern closure. An example of a well-known salt cavern closure is the Eminence salt dome in Mississippi. The Eminence salt dome was solution mined between 1725 m and 2000 m with the purpose of storing gas. Between October 1970 and April 1972, the pressure in the salt cavern was cycled between 6 MPa and 28 MPa with the geostatic pressure being 40 MPa (Berest et al., 2012). The sonar survey in April 1972 showed that the cavern closed by 40 % and most of the closure was in the lower part of the cavern (Figure 13). The closure is due to low operating pressure and high temperatures encountered at that depth.

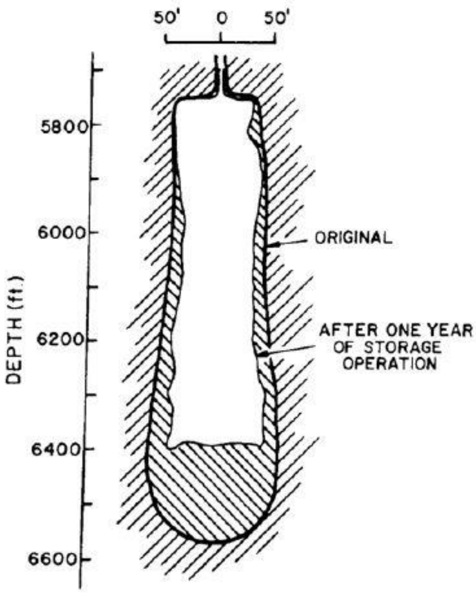

Figure 13: Cavern closure in Eminence salt dome (Serata and Cundey, 1979).

2.4.2 Roof Collapse

Roof collapse is possible due to one or combination of the following reasons: low height/diameter (H/D) ratio, low minimum cavern air pressure, inadequate roof shape, thin salt roof, and thin and incompetent non-salt roof (Figure 14).

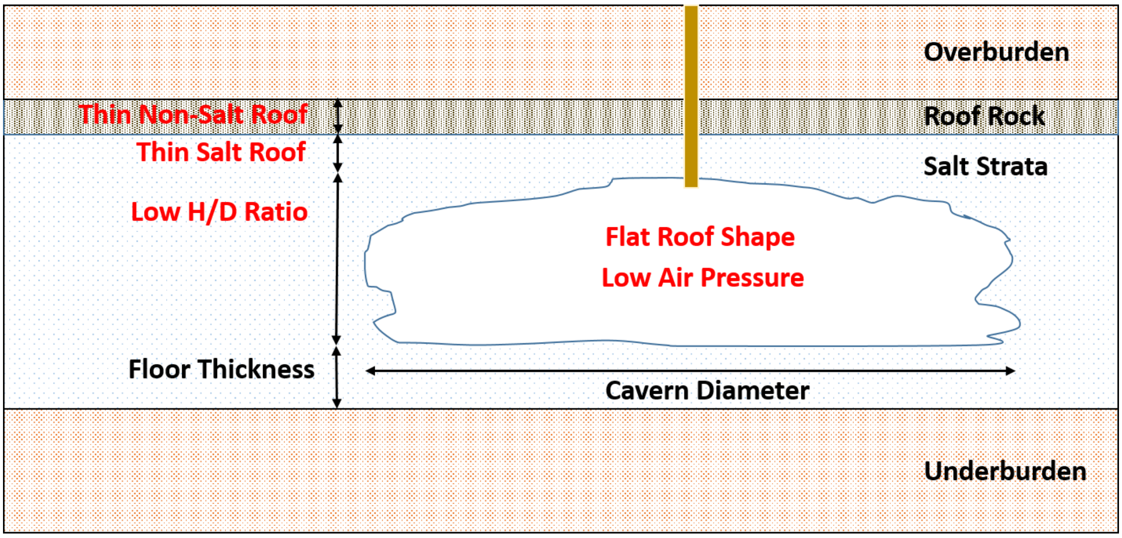

Figure 14: Reasons for roof collapse: low H/D ratio, low cavern air pressure, flat roof shape, thin salt roof, and thin and incompetent non-salt roof.

Low height to diameter ratio: Salt caverns can be solution mined in various sizes depending on the volume requirement and salt bed thickness. Large H/D ratio is desired, but it is only possible in thick salt beds or small storage projects. In many basins, such as the Michigan Basin in Ontario, a low H/D ratio is required to accommodate large salt caverns capable of supporting grid-scale energy storage. Roof stability issues arise when a cavern has low H/D ratio. Due to large roof span, high tensile forces develop in the roof, which can result in roof collapse. Bruno and Dusseault (2002) show that displacement in roof increases when H/D ratio is lowered from 1/1 to 1/4 and 1/2. Zheng et al. (2016) report that a minimum H/D ratio of 1/2 is required for cavern stability. Typically, caverns with a diameter of 60 m or less do not cause many roof stability issues; however, daily pressure cycling in CAES might pose a higher risk to roof stability.

Low minimum cavern air pressure: Low air pressure in the cavern can cause roof failure by reducing the supporting stresses in the roof and hence creating high tensile stress in the roof. An example of the impact of minimum pressure on the roof of the cavern can be demonstrated through a roof collapse event in Kiel, Germany. The gas storage cavern was located at 1305 m depth, and the pressure was reduced from 15.6 MPa to almost zero in a span of five months (Berest et al., 2012). Due to loss of supporting stress, the roof of the cavern broke. This resulted in cavern volume reduction from 36,000 m^3 to 30,200 m^3 (Figure 15).

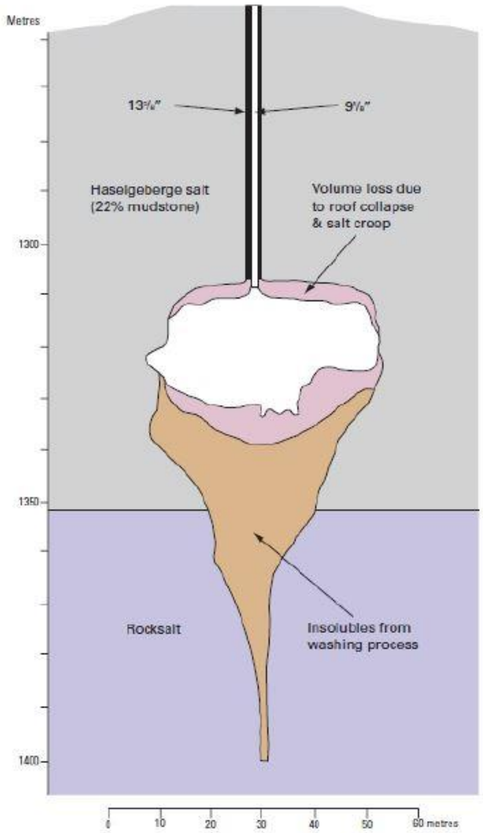

Figure 15: Roof collapse in Kiel, Germany (Evans and West, 2008).

Inadequate Roof shape: Shape of the roof can affect roof stability. Flat shaped roofs must be avoided as they are prone to spalling; whereas, arched roofs provide maximum roof stability and should be carefully generated during solution mining.

Thin salt roof: A certain thickness of salt roof is required between the cavern and non-salt roof rock. Due to creep properties and load-bearing ability, salt roof can offset the deformation impact on non-salt roof layer. A cylindrical cavern with a height of 60 m and diameter of 60 m will be more stable with 30 m of salt roof as compared to 5 m salt roof. Zheng et al. (2016) mention that a salt roof thickness of at least 1/4th of the cavern diameter is required for stability purpose. In salt domes, it is possible to achieve very thick salt roof, so that the cyclic loading in the cavern will not have any impact on the non-salt roof rock.

Incompetent and thin non-salt roof: In most bedded salt deposits, it is not possible to have a very thick salt roof that will eliminate deformation impact on the non-salt roof. In these cases, it is essential to have a competent (high stiffness and minimum jointing) and reasonable thick non-salt roof layer. Non-salt roofs containing anhydrite and carbonates have high stiffness, and are ideal as competent roof rock. For the competent roof layer, a thickness of 1/3rd of the cavern diameter will provide sufficient stability. However, roofs containing mudstones and shales are considered to be weak and might result in higher frequency of roof damage.

2.4.3 Interbed Slip

Salt caverns in bedded salt deposits are subjected to geomechanical issues caused by interbed slip. As discussed in section 2.1.2, commonly occurring interbeds are anhydrite, shale, dolomite, and limestone. The lithology, thickness, and frequency of interbeds will vary with basins. Unlike bedded salt deposits, domal salts are relatively homogenous and do not pose interbed slip risk.

Interbed slip is the result of differential deformation between non-salt interbeds and salt. Since non-salt interbeds do not creep, salt and non-salt interbeds react differently to far-field loading and a stress difference is generated. During low pressure period in the cavern, the stress difference between non-salt interbeds and salt increases, and results in slip. Also, thickness of interbed affects the magnitude of interbed slip; Bruno and Dusseault (2002) showed through numerical simulations that increasing the thickness of interbed increases the probability of slip.

In terms of consequences, the location of interbed determines the type of damage the slip will cause (Figure 16). The worst scenario is if the interbed slip occurs near the roof of the cavern; in this case, roof stability issues can arise and the casing can be damaged as shown in Figure 17. However, interbed slip in cavern center or bottom might not be as harmful as slip near the roof; interbeds will fall to the bottom of the cavern and potentially reduce cavern volume through swelling. In this case, the storage capacity of the cavern will be reduced.

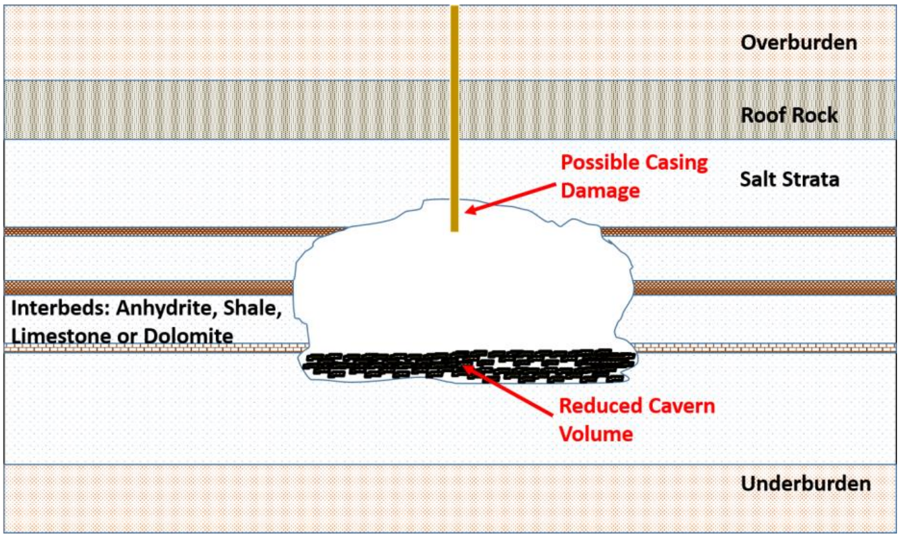

Figure 16: Consequences of interbed slip: casing damage and reduction in volume.

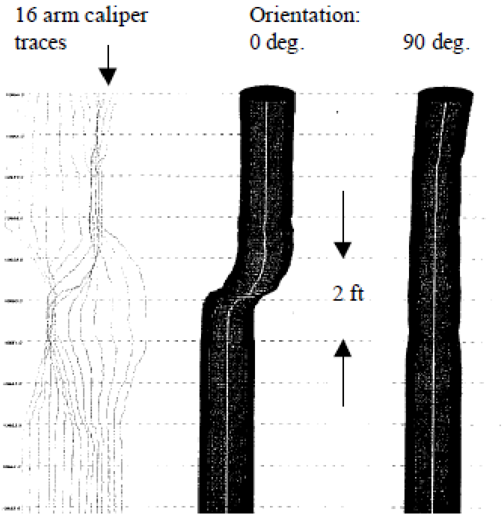

Figure 17: Casing damage due to interbed slip (Bruno and Dusseault, 2002).

2.4.4 Tensile Fracture

Injecting compressed air at high pressure is desired so that more air can be stored at a given time. However, high cavern pressures can lead to cavern stability issues such as tensile fractures in cavern walls and roof. Tensile fractures can even extend up to non-salt roof rock if the salt roof is thin and cavern pressure exceeds the fracture pressure of the non-salt roof. In this scenario, the efficiency of the CAES plant will decrease as compressed air will leak out of the cavern. As a general rule, maximum operating pressure should not exceed 75-80 % of the fracture pressure of the non-salt roof rock and salt strata. For a 650 m deep cavern in a tectonically unaffected basin, the fracture stress would be ~ 15.6 MPa and therefore the maximum operating pressure would be ~ 12.5 MPa.

2.4.5 Multiple Cavern Spacing

Multiple caverns might be required in a large-scale CAES facility due to operational reasons and limited salt strata thickness reasons. First, a cavern might be required to undergo maintenance several times during the lifetime of the facility. During the maintenance period, the cavern will not be able to store compressed air and the CAES facility will be halted. A second cavern can allow the CAES facility to keep providing service to the grid. Also, Crotogino et al. (2001) note that the second cavern can help with the start up process; the start up process for the plant compressor requires a minimum cavern air pressure of 1.3 MPa, which can be provided by the second cavern. In addition to operational reasons, multiple caverns might be desired due to limited salt strata thickness and large storage requirement. For example, two caverns might be required to accommodate a 100 MW CAES facility in 40 m thick salt strata.

It is important to ensure the distance between caverns is enough to avoid cavern stability issues. The salt rock mass between caverns is called pillar, and the distance between caverns is the pillar width. During CAES cyclic loading, induced stresses on the cavern boundaries are transferred to the pillars. Pillar width should be enough to avoid large deformations or failure of the pillar. Typically, pillar width of 4 times the cavern diameter should provide stability. Zheng et al. (2016) recommend pillar width of 2 to 3 times the cavern diameter. Bruno (2005) also demonstrates through numerical simulation that pillar width of 3 times the cavern diameter significantly reduces displacement at the cavern wall as compared to thin pillar width.

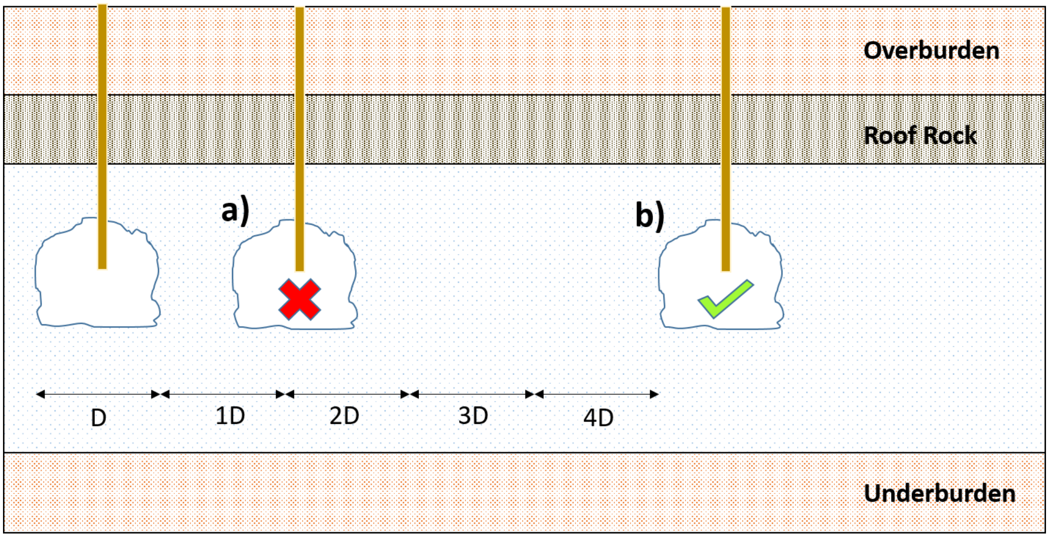

Figure 18: Multiple cavern system displaying a) cavern with unacceptable pillar width and b) cavern with sufficient pillar width.

2.4.6 Other Issues: Pressure Cycling and Temperature Fluctuation

Cyclic loading is experienced in both underground gas storage (UGS) and compressed air storage in salt caverns. It is expected that the effect of cyclic loading on cavern stability is more severe in CAES as the frequency of the loading cycles is high. In UGS, gas is cycled seasonally or at the most a few times in a year. However, compressed air might be cycled on a daily basis in CAES. Therefore, cyclic loading must be accounted for during geomechanical numerical simulation when designing a CAES cavern.

Until now, due to a limited number of CAES plants in the world, the influence of cyclic loading is not fully understood or researched in detail. Nevertheless, a few researchers have tried performing laboratory tests and numerical modelling to get an insight of high-frequency cyclic loading in CAES. The study, “Study of cyclic loading effects on the creep and dilation of natural rock salt” by Roberts et al. (2014) summarize that compared to static loading, cyclic loading does not have a large effect on the creep if the applied stress is under the dilational regime.

An example of cyclic CAES loading is the Huntorf CAES facility in Germany, which is subjected to cyclic loading and has not created any stability issues so far. The profiles of the two caverns in Huntorf were sonar surveyed in 1984 and 2001. The caverns were operated at air pressure between 4.3 MPa to 7 MPa with a maximum pressure drop rate of 1.5 MPa per hour. Figure 19 illustrates the before and after cavern profiles for both the caverns. It was observed that almost no difference existed between the conditions in 1984 and 2001 (Crotogino et al. 2001). However, it can be debated that the deformation was small because the operating pressures were conservative and the difference between the maximum and minimum pressure was small. During regular operation, the difference between the maximum and minimum pressure was only 2.7 MPa. It is still uncertain if cavern stability issues will arise when the difference between the maximum and minimum pressure is large. In a 1000 m deep cavern, it is possible to have a maximum and minimum pressure of 18 MPa and 6 MPa, respectively. Numerical simulations will be needed to confirm if frequently cycling between 18 MPa and 6 MPa is an issue.

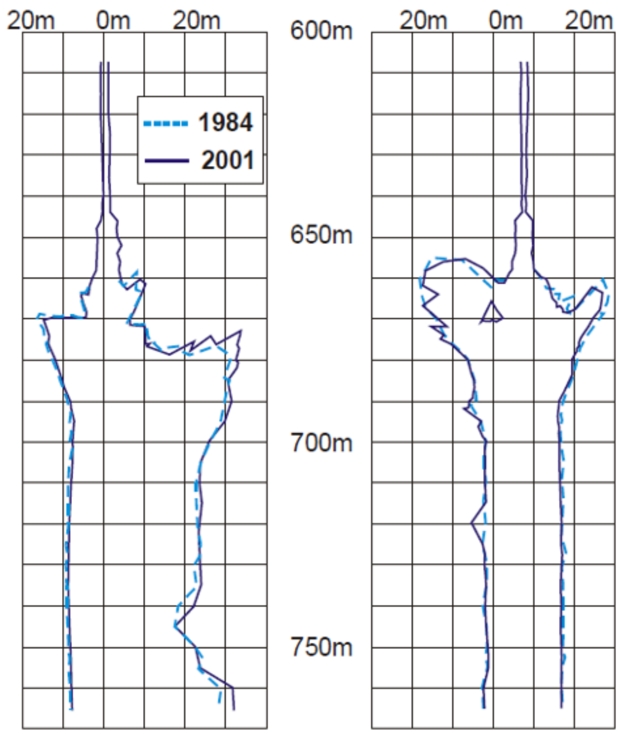

Figure 19: Sonar survey results in the Huntorf Caverns demonstrate that no significant deformation was observed from pressure cycling (Crotogino et al., 2001).

It is understood that air temperature inside the cavern is different from the rock temperature during injection and withdrawal periods. During injection and storage periods, temperature inside the cavern is higher than the surrounding rock mass. During withdrawal period, temperature inside the cavern is lower than the surrounding rock mass. It is also predicted that temperature cycling affects the strength parameters of salt-rock as thermal stresses develop due to temperature difference between compressed air and rock mass. However, at the present stage, the mechanisms of temperature cycling and effects of temperature cycling on the strength parameters are not fully understood and are a topic of research.

The article, “Temperature and pressure variations within compressed air energy storage caverns” by Kushnir et al. (2012), concludes that 1) heat transfer between air and rock plays a significant role in managing temperature fluctuations, 2) wavy cavern walls created during solution mining improves heat transfer, 3) in each temperature cycle, heat is transferred and stored in the cavern wall, 4) temperature fluctuation stops within a short distance from the cavern wall but temperature penetrates deeper into the wall with increase in temperature cycles, 5) injected air temperature affects the peak temperature values reached during injection, and 6) duration of injection and extraction should be maximized to reduce temperature. Another article, “Effect of temperature on compressive and tensile strengths of salt” by Sriapai et al. (2012), mentions that uniaxial compressive strength, triaxial compressive strength, tensile strength, and octahedral shear strength decrease with increase in temperature.

2.4.7 List of Criteria Considered in Geomechanics Design

A list of criteria important to geomechanics design is developed based on salt’s mechanical behaviour and its impact on cavern stability. The criteria are listed in Table 2.

Table 2: List of criteria considered in CAES salt cavern design

	First Order	Second Order
Salt Strata Information	Salt Depth	Temperature
	Salt Thickness	Permeability
	Salt Purity	Porosity
	Stress State	Elastic Parameters: • Young’s Modulus • Poisson’s Ratio
		Strength Parameters: • Unconfined Compressive Strength (UCS) • Tensile Strength • Internal Friction Angle (N/A)
		Creep Parameters
Non-Salt Roof/Load Bearing Rock Information	Non-Salt Roof Rock Lithology	Permeability (mD)
	Structural Features (eg. Faults, fractures, joints)	Porosity (%)
	Strength Parameters: • UCS • Tensile Strength • Cohesion • Internal Friction Angle	Elastic Parameters: • Young’s Modulus • Poisson’s Ratio
Interbed Information	Interbed Lithology	Depth of Interbeds
	Thickness of Interbeds	Number of Interbeds
	Location of Interbeds	Frequency of Interbeds
	Permeability	Porosity
		Elastic Parameters: • Young’s Modulus Poisson’s Ratio

		Strength Parameters: • UCS Tensile Strength • Cohesion • Internal Friction Angle
Operating Pressures in Cavern	Maximum Operating Pressure	
	Minimum Operating Pressure	
	De-Pressurisation Rate	
	Pressure Cycling Period	
Cavern Dimension	Cavern Size Requirement (m^3)	Number of Caverns
	Cavern Shape • Diameter • Height	Cavern Roof Thickness
		Cavern Spacing
		Casing Size

2.5 Monitoring

Monitoring is an essential component of any solution mined cavern project and must be addressed in the geomechanical model. In fact, monitoring is a mandatory requirement by government regulations and is also needed for insurance purposes. From the technical point of view, monitoring can provide important data that can increase productivity, avoid cavern and well failure, calibrate geomechanical laws and models, and increase safety. In the case of salt caverns, the three major monitoring areas/tools are subsidence monitoring, micro-seismic monitoring, and sonar surveying.

2.5.1 Subsidence Monitoring

When an opening is created in the form of salt cavern, stress equilibrium is disturbed and creep mechanisms start acting around the salt cavern. Movement in the cavern due to creep or roof collapse can be transferred to the ground surface and form a wide shallow subsidence bowl. Subsidence magnitude and cone of influence can be studied and modelled mathematically. Typically, creep does not cause high magnitude ground subsidence but roof collapse might result in higher ground subsidence values.

In CAES operations, low cavern pressure during extraction periods can accelerate creep and cause roof collapse. Additionally, caverns with larger roof span are more prone to surface subsidence due to the reasoning that larger roofs have low strength value and unlike the smaller roofs, overburden is not able to bridge across the larger roof opening (Ege, 1979). Therefore, subsidence monitoring is essential in bedded salt caverns. Ground subsidence can be monitored in various ways: levelling monuments (spirit levelling), Global Positioning System (GPS) surveying, Interferometric Synthetic Aperture Radar (InSAR), extensometers, and tiltmeters (U.S. Geological Survey, 2016).

In most cavern leaching projects, levelling monuments are used for displacement monitoring on the surface. Levelling is the oldest method and relatively inexpensive when compared to GPS surveying. It involves placing monuments in the zone of influence (extends beyond the cavern boundaries) and measuring displacement from a known reference point that is not affected by subsidence (U.S. Geological Survey, 2016). Levelling is accurate and highly effective when the zone of influence is small (less than 10 km). It is recommended to set up enough monuments or measurements so that a detailed mathematical analysis can be performed for cavern closure.

GPS surveying is more expensive than levelling, but it can accurately cover a larger area and determine three-dimensional position. The GPS system involves placing flat metal discs (geodetic monuments) in the ground or on the structures in the geodetic monitoring network. Geodetic monuments are connected to the GPS satellites that monitor any movement of the flat metal discs.

InSAR is also an effective technology for measuring ground subsidence as it can cover large areas while providing millions of data points and is cost-effective as compared to levelling and GPS surveying (Galloway and Hoffmann, 2007). InSAR involves a satellite that would record the two-way travel time of radar signals reflected from the earth's surface (Figure 20). Although it can cover large areas, the quality of the InSAR signal is limited by the ground cover, atmospheric effects, and land-use particle. It does not produce high-quality data in densely forested areas as the signals are poorly reflected (Sneed and Brandt, 2007). Therefore, to choose an appropriate monitoring technique, engineers have to account for the extent of the cone of influence, ground cover, and other performance or cost factors.

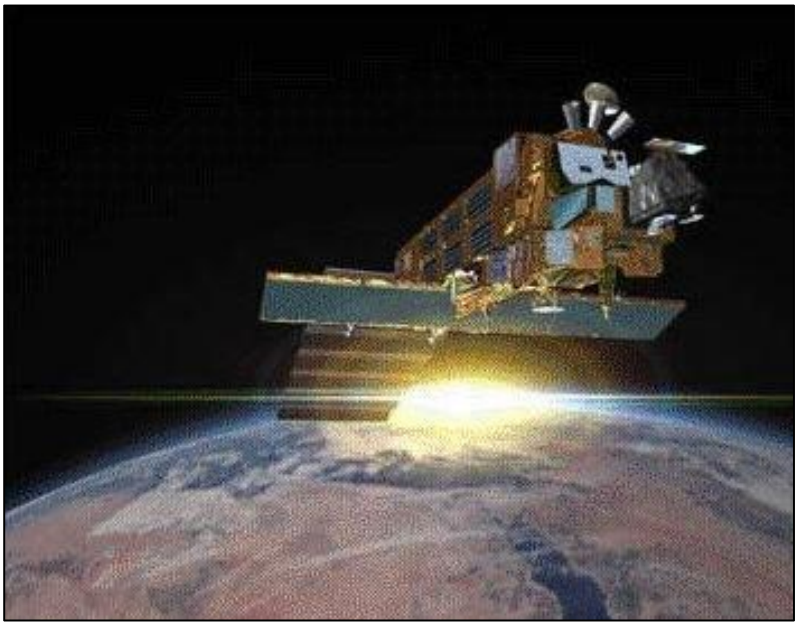

Figure 20: InSAR satellite positioned at 800 Km altitude (U.S. Geological Survey, 2016).

2.5.2 Microseismic Monitoring

During the event of cavern collapse or major damage around the cavern, there might be warning signs months or days before the event occurs. Warning signs include generation of small fractures, slippage in existing fractures, or any abnormal seismic activity. Fortunately, microseismic monitoring can detect sudden bursts of mechanical strain energy and figure out the location and intensity of the seismic events. The microseismic data does not just increase safety but also provide important inputs for the geomechanical earth model (Hosseini et al., 2015). Microseismic monitoring involves inserting microseismic sensors in the wellbore, around the wellbore, and near cavern boundary. Real-time data from the sensors is transmitted to the ground office (Figure 21). Important parameters that are obtained or interpreted from the microseismic data are location, magnitude, event nature, and slip direction.

Microseismic monitoring detects large bursts of mechanical stain energy generated from slip in bedding planes, lithological contrasts, pre-existing joints and fractures, and brittle damages near cavern boundary. Note that microseismic monitoring is not effective for steady-state creep monitoring as it cannot detect extremely small strain rates generated by steady-state creep. In fact, microseismic monitoring is more valuable in bedded salt caverns as compared to domal salt caverns.

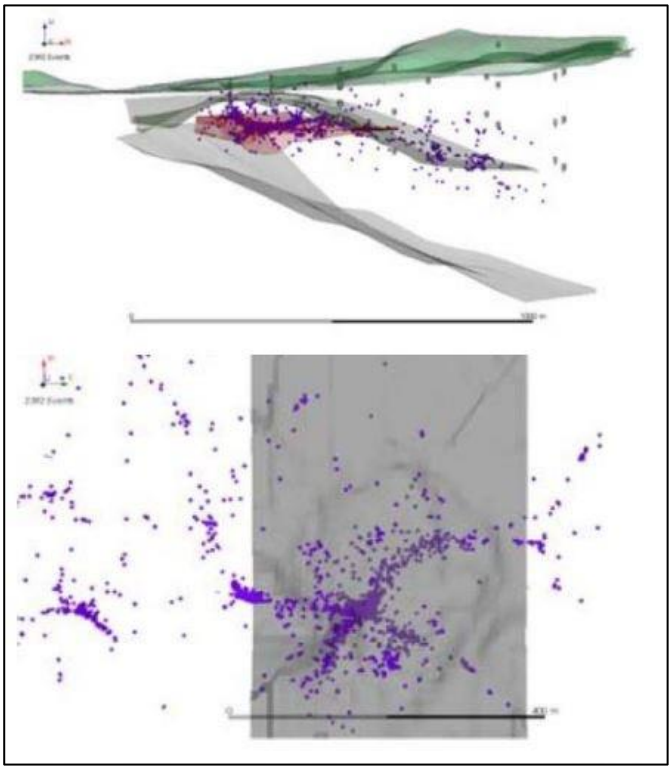

Figure 21: Microseismic monitoring: seismic event location in section (top) and plan views (bottom) (Hosseini et al., 2015).

2.5.3 Sonar Survey

Sonar survey measures the profile of the cavern and displays volumetric results in two-dimensional (2D), isometric, and three-dimensional (3D) plots. Typically, sonar surveys are performed during or immediately after cavern leaching process to get the initial cavern volume. Also, sonar surveys are performed periodically (for example, every 10 years) to estimate change in cavern volume and cavern profile due to creep, roof sloughing, or other damages.

The results of sonar survey are used to predict creep closure rates and calibrate finite element modelling. Cavern profiles generated from sonar survey can predict any abnormalities in the cavern such as ledge hanging or any insoluble material that can cause casing damage in the future (Crossley, 1998). In fact, it can be said that sonar surveying is a good cavern management tool that enhances safety, increases confidence in solution mining models, and provides important inputs to the geomechanical model.

Sonar survey involves point-by-point measuring of the cavern boundaries using sonar downhole survey head that can go up/down and also has tilt functionality (Figure 22). Ultrasonic transducers emit sound waves that hit a certain point in the cavern boundary and then record the time from the reflected sound wave to get the distance to the point (SOCON, 2016). Sonar survey has been effective in surveying profiles of vertical caverns in salt domes or cylindrical caverns in bedded salt where the radius of the cavern does not exceed 300 m (Dawson-Grove, 1969). However, in the case of long horizontal galleries with the length of 1000m, the effectiveness of sonar survey still remains a question. The article, “Sonar Caliper Applications in Western Canada,” noted that the effective radius of sonar is a maximum of 300m (1000ft) (Dawson-Grove, 1969).

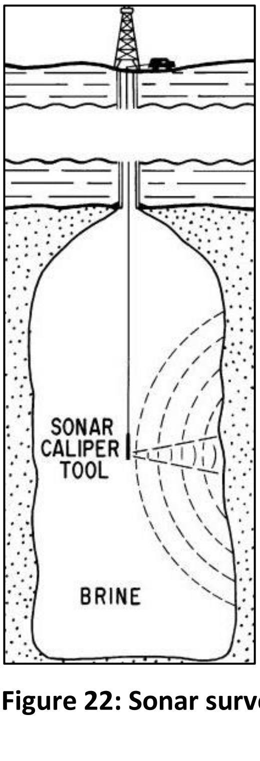

Figure 22: Sonar surveying in salt cavern (Dawson-Grove, 1969).

3) PART II - CAES Siting in Canada: the Geomechanics Perspective

3.1 Introduction

Canada has established plans to develop a low-carbon economy by reducing greenhouse gas (GHG) emissions, which are recognized globally to be the main factor behind climate change. The two major Canadian economies, Ontario and Alberta, have planned to invest significantly in renewable energy sources. Ontario is the first jurisdiction in North America to be coal-free, i.e., free of its dependency on coal-generated electricity. Furthermore, Ontario has planned to extend its renewable generation such as wind, solar and bioenergy to 10,300 MW by 2021. Alberta has also planned to be coal-free by 2030 and replace 2/3rd of its coal generation with renewables. Reduction of GHGs through clean energy will put Canada on par with its commitment in the Paris Agreement.

A major challenge with large integration of renewables is the demand for energy storage. Renewable energy such as wind and solar are intermittent in nature and electricity generation is largely dependent on wind speed and sunlight. Deployment of energy storage will compensate for the intermittent nature by allowing storage of electricity during low demand periods and releasing it back to the grid during high demand periods. As of now, compressed air energy storage (CAES) and pumped hydro storage (PHS) are the only two storage technologies capable of storing large-scale (>100 MW) energy. Due to hydraulic-head constraints, PHS is infeasible in certain locations. CAES also have few advantages over PHS in terms of high energy density, small surface footprint, low-risk construction, and no devastating failure that could affect human life.

To increase the understanding of where CAES can be implemented, CanmetEnergy, a division of Natural Resources Canada (NRCan), funded the University of Waterloo to conduct a first-order siting study for CAES in salt caverns across Canada. As per CanmetEnergy's plan, the study will be useful to the government in developing energy policies, drafting regulations, and utilized by the industry in deciding the location for front-end engineering and design (FEED) studies. The study will form the foundation for future studies related to various topics in CAES such as geomechanics, facility siting, economics, etc.

The objective of the study was to determine suitable sites for CAES based on geology, renewable energy potential, energy demand, and existing infrastructure. Multi-criteria analysis (MCA) was utilized as an evaluation tool, and involved developing scoring and assigning a weight factor to each criterion; scoring and weighting of criteria were assigned by consulting with academic and industrial experts. Data for various criteria used in the study was represented and modified in ArcGIS. Clark Labs'© Terraset software was utilized to integrate MCA methodology and ArcGIS data. The final evaluation framework established allows for a spatially continuous and customisable assessment of CAES potential.

Criteria used in the study are divided into three categories: geology/geomechanics, energy potential, and existing infrastructure. A total of six criteria are used in the evaluation framework: 1) salt strata thickness, 2) depth to salt strata, 3) renewable energy potential, 4) energy demand, 5) proximity to existing natural gas infrastructure, and 6) proximity to existing electrical infrastructure. Although not included in the evaluation framework, additional geomechanical criteria such as interbed thickness and roof rock thickness are also discussed in this chapter. These criteria are considered to be of second-order and therefore not included in the first-order CAES siting study.

A major assumption in the study is that the CAES facility is considered to be a constant volume operation, in which cavern volume stays constant, and cavern air pressure is cycled during injection and extraction. Another option, although not considered in this study, is a constant pressure operation in which a brine pond is required at the surface and the cavern is operated under constant hydrostatic pressure. Since the study is aiming for grid-scale storage, the size of the facility is assumed to be 100 MW with 1200 MWh of storage; this size of the facility requires a cavern with the volume of approximately 165,000 m^3.

This chapter will tend to focus on the geology and geomechanics area of the siting study. Subjects that are discussed in detail include geology of Ontario, Western Canada, and Maritimes; geomechanics criteria such as depth, thickness, interbed thickness, and roof thickness; and evaluation results. Other non-geological criteria and MCA methodology are also described briefly in this chapter. However, for a detailed explanation on non-geological criteria categories, such as energy potential and existing infrastructure, the reader is referred to the report, "First order assessment of the potential of compressed air energy storage in salt caverns across Canada" by Fraser et al. (2017). The sequence of topics in this chapter is as follows: multi-criteria analysis, geological setting of salt in Canada, considerations for CAES site selection, detailed geology/geomechanics decision tree, and results.

3.2 Multi-Criteria Analysis

Investigation of suitable CAES sites requires a methodology that would take into considerations the criteria discussed in section 3.4, and evaluate and compare the chosen sites. Multi-criteria analysis (MCA) methodology offers a robust and flexible evaluation platform that would aid in decision-making. The MCA methodology utilized in this study is similar to the methodology adopted in the “Potential of Brine Disposal in SW Ontario” study, as described in chapter 4.

Many MCA approaches exist in the literature that can be used to compare alternatives. MCA approaches can be divided into non-compensatory and compensatory approaches. In non-compensatory approach, trade-off is not allowed between criteria; whereas, the compensatory approach allows trade-off and most of the real world applications utilize compensatory approach. This study utilizes a compensatory approach: weighted linear combination (WLC). WLC is ideal for this study as it uses scoring and weighting evaluation system, which is a requirement due to a large number of alternatives. In addition, WLC is easier to implement and understand. This will allow other groups to efficiently utilize and modify the inputs if required.

In the WLC model, normalized score (v_i) and weight (w_i) are assigned to each criterion. The scores and weights are developed through discussion with industrial and academic experts and information gathered from the literature. A scoring function with scores between 0 to 100 is assigned to each criterion, which will allow comparison of data within a criterion. A weighting factor between 0 to 1 is assigned to each criterion; the total sum of weight for all the criteria is 1. Weighting factor would allow comparison between multiple criteria used in the MCA. The total score for a site is obtained by multiplying the normalized criterion score (v_i) by the assigned criterion weighting (w_i) for each criterion and then summing the product over all criteria (Equation 2).

$$\boldsymbol{S(a) = \sum_i w_i * v_i(a)} \qquad \textbf{[Equation 2]}$$

where S(a) is the total score for site a, w_i is the weighting factor for the i^{th} criterion, and $v_i(a)$ is the criterion score for the i^{th} criterion for site a.

3.3 Geological Setting of Salt in Canada

Canada has prominent salt formations in three major sedimentary basins: the Western Canadian Sedimentary Basin which underlies much of the prairies, the Michigan Basin which underlies part of southwestern Ontario, and the Maritimes Basin which underlies the Maritime provinces of Nova Scotia, Prince Edward Island and New Brunswick and parts of eastern Quebec. The locations and approximate extent of these major salt basins are shown in Figure 23.

Figure 23: Locations of major salt basins in Canada (Adapted from http://www.saltinstitute.org/salt-101/production-industry/ accessed 29/05/2017).

3.3.1 Michigan Basin

Salt beds in Ontario are part of the eastern flank of the Michigan basin. The basin has a bowl-shaped geometry with its depositional centre near Saginaw Bay in Michigan. The salt beds are thickest in the centre of the basin and thin out in all directions away from the centre (Johnson & Gonzales, 1978). Since Ontario is situated on the eastern flank of the Michigan Basin, the salt beds there are relatively thin and shallow because the dip of the salt beds is towards the centre of the basin. Salt strata in Ontario belong to Salina Group of the Silurian Period. Figure 24 shows a generalised stratigraphic section of southwestern Ontario. Because of the dip of salt beds in the southwestern direction, the salt beds are found at various depths throughout southwestern Ontario, and the thickness varies from place to place. Salt beds are the thickest on the western front of southwestern Ontario and thin out eastwards until they fade out near London (Hewitt, 1962).

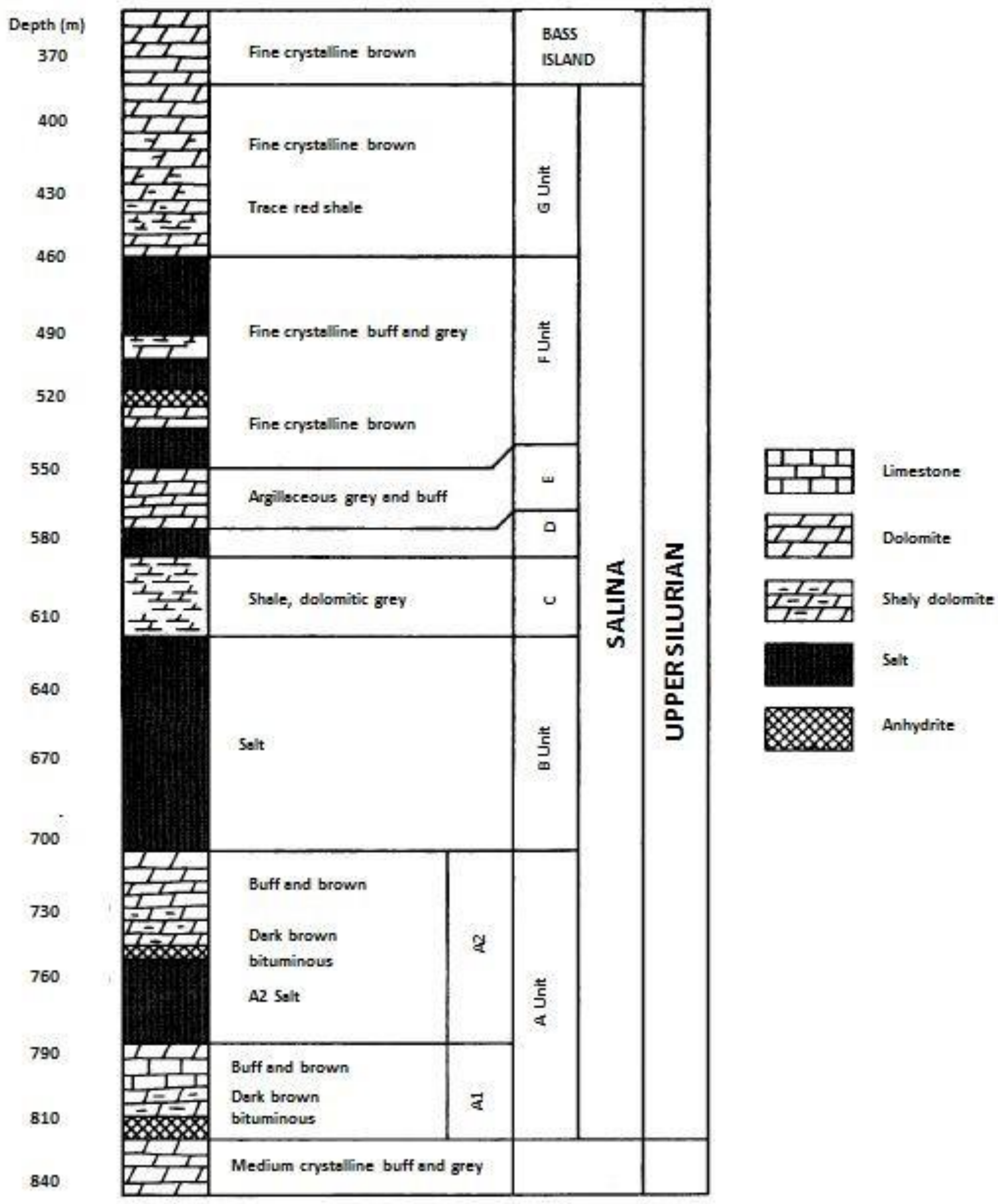

Figure 24: General salt stratigraphy section of southwestern Ontario (Hewitt, 1962).

Salt is contained in units F, D, B, and A2; Figure 25 displays the lithological description of these units in the Salina Group. Unit F is the shallowest unit with starting depths ranging from 275 m to 450 m. It contains sequences of salt beds separated by beds of shale, anhydrite and limestone. It has been used for underground mining in the Windsor area. Unit D is the thinnest salt unit with a maximum thickness of 12 m. No mining has been done in this unit. Unit B is the thickest salt unit with thin dolomite layers. The thickness can exceed 90 m at some places in Ontario. It has been used for solution mining around Goderich and Windsor, and cavern storage in Sarnia and Windsor. Unit A2 is the deepest salt unit with starting depths ranging from 500 to 700 m and has a maximum thickness of 43 m. It is present within the Sarnia-Goderich salt region but is absent in the Windsor region. It has been used for underground mining at Goderich and cavern storage at Sarnia (Carter, 2009). For CAES purposes, only units B and A2 are considered as they meet the minimum thickness criteria and are also located at an ideal depth for cavern development. Isopach and depth maps of the salt units are given in Appendix A.

Formation	Unit		Description
Upper Salina			Top of Salina Formation.
		G	Fine crystalline brown dolomite, shaly dolomite, some anhydrite, red shale.
	Upper Salt Beds	F	SALT, in thick beds separated by beds of shale, shaly dolomite, grey and buff and brown crystalline dolomite; anhydrite nearly always present.
		E	Thin shaly unit, argillaceous grey and buff dolomite.
		D	SALT, nearly pure; thin partings of buff dolomite.
		C	Dolomitic grey shale.
		B	SALT, thick salt beds with thin dolomite layers. (Main upper salt unit.)
Lower Salina		A2	Fine to medium brown to brownish grey dolomite; Fine grey to dark-grey dolomite, some dark bituminous shale; SALT (Lower salt) up to 140 feet thick; where salt is absent the base of A2 marked by anhydrite.
		A1	Fine- to medium-grained, buff to brown dolomite; Fine to dense, brown-grey and dark-grey dolomite with dark-grey bituminous shale; Anhydrite at base.

Figure 25: Lithological description of the Salina Group units (Hewitt, 1962).

Units B and A2 can accommodate large storage caverns in the Sarnia and Goderich region. In Sarnia region, Unit B is approximately 90 m thick and 610 m deep; while unit A2 is 40 m thick and 750 m deep.

The geological data for Ontario was obtained from the Ontario Oil, Gas and Salt Resources (OGSR) Library. The data included GIS files for thickness and depth data of salt units B and A2.

3.3.2 Western Canadian Sedimentary Basin

Salt strata in Alberta are thicker and located at deeper depths as compared to salt strata in Ontario. Accordingly, Alberta is favourably endowed with thick salt strata that can accommodate grid-scale storage in a single salt cavern. Thick salt deposits are regionally distributed within the Devonian Elk Point Group in the Western Canada Sedimentary Basin. The four salt-bearing groups within the Devonian Elk Point Group are (from oldest to the youngest): the Lower Lotsberg salts, the Upper Lotsberg salts, the Cold Lake Formation, and the Prairie Evaporite Formation. Figure 26 illustrates the location of these salt units. Isopach and depth maps of the salt units are shown in Appendix A.

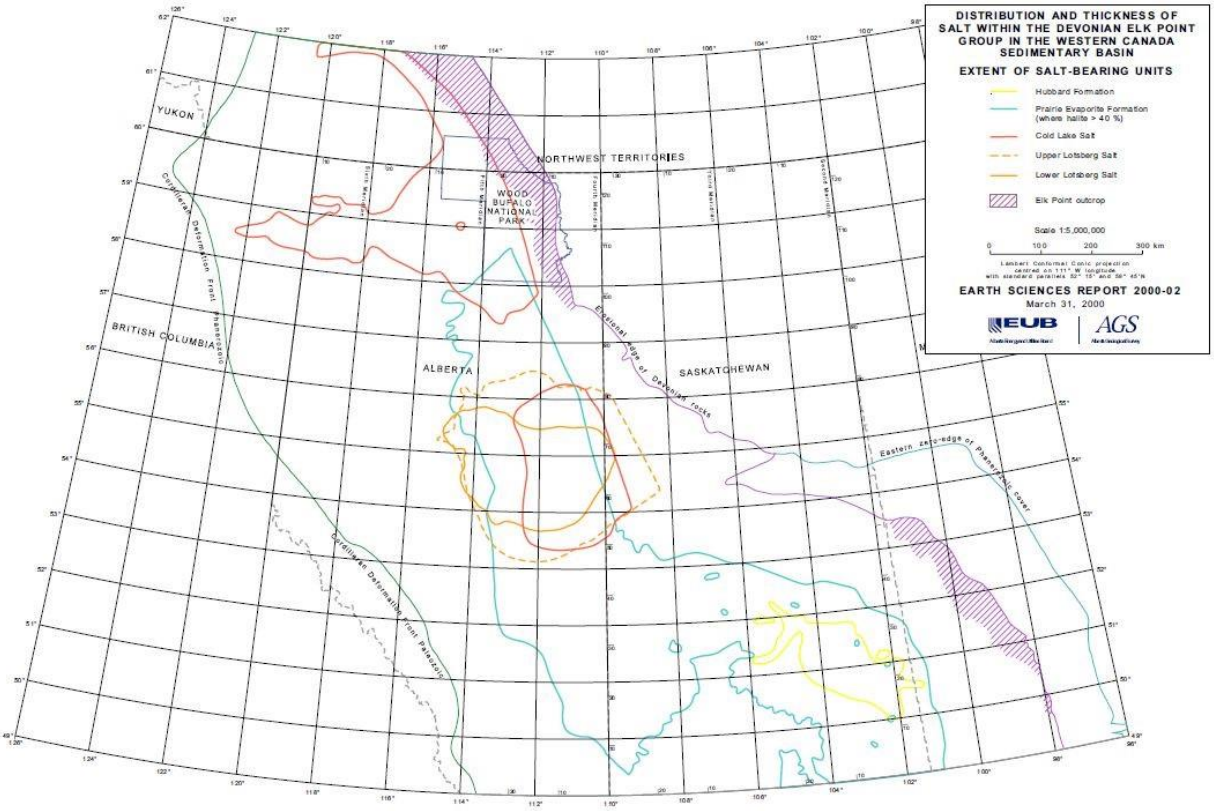

Figure 26: Extent of salt beds in western Canada (Grobe, 2000).

The Lower and Upper Lotsberg salts are present in east-central Alberta and extend into Saskatchewan. Major landmarks that overlie the Lotsberg salts are Edmonton, Lloydminster, Cold Lake, and Athabasca River flowing south of Fort McMurray. Because of multiple phases of solution and redeposition, the Lower and Upper Lotsberg salt have very high purity. The depth to the Lower Lotsberg salts ranges from greater than 2100 m in the west to 1050 m in the east. The maximum thickness of the Lower Lotsberg salt is 60 m at its depocenter. The depth to the Upper Lotsberg salts ranges from greater than 2100 m in the west to 750 m in the east. The maximum thickness of the Upper Lotsberg salt is 150 m at its depocenter. The Lower and Upper Lotsberg salts are separated by a 28 to 67 m thick red shale interval (Grobe, 2000).

The Cold Lake Formation is present in two locations: (1) east-central Alberta and west-central Saskatchewan, and (2) northern Alberta and northeastern British Columbia. In east-central Alberta and west-central Saskatchewan, the maximum thickness of the Cold Lake Formation is 60 m, and the depth to the salt ranges from 1600 m in the southwest to 550 m in the east. In northern Alberta and northeastern British Columbia, the maximum thickness of the Cold Lake Formation reaches 80 m, and the depth to the salt ranges from 2400 m in the west in northeastern British Columbia to 700 m in the east at the Wood Buffalo National Park boundary.

The Prairie Evaporite Formation varies in purity as it has been subjected to fresh meteoric water that dissolved and carried away the salt. Areas where the salt content in the Prairie Evaporite Formation is greater than 40% extend from eastern Alberta to southern Saskatchewan and southeastern Manitoba. In the areas with greater than 40% salt content, the depth to the Prairie Evaporite Formation ranges from 200 m in northeastern Alberta to 2300 m in central Alberta. The thickness of the Prairie Evaporite Formation ranges from 300 m in northeastern Alberta to 25 m in southern Alberta (Grobe, 2000).

The geological data for western Canada was obtained from the Alberta Geological Survey (AGS). The data obtained included the GIS files for thickness and depth data regarding the four salt units.

3.3.3 Maritimes Basin

Salt strata in Nova Scotia (NS) and New Brunswick (NB) belong to the two Upper Paleozoic groups: 1) the Horton Group and 2) the Windsor Group. The Horton Group evaporites belong to the late Tournasian to early Visean age and were deposited as local playa lake deposits. The Horton Group is deposited in at least two locations in NB and one location in NS (Howie, 1988). The Windsor Group evaporites belong to the early to middle Visean age and are conformably to unconformably underlain by the Horton Group rocks. The Windsor Group is widely distributed in the Maritimes Basin and comprises of more than 50 % evaporites including halite (rock salt), anhydrite, gypsum and a small quantity of potash (Boehner, 1986). Webb (2009) reports that the Windsor Group contains thick clean salt deposits that offer potential sites for storage of liquid hydrocarbon products.

The strata in the Maritimes Basin have been tectonically modified due to continental collision events that terminated with the formation of the Appalachian Mountains. Originally, salt was deposited as thick bedded salt layers that precipitated from seawater. However, the continental collision events turned the bedded salt layers into isolated domes, anticlines, and pillows (Boehner, 1986). Accurate interpretation of salt deposits is complicated in the Maritimes Basin because of the complexity of the salt structures that developed from the tectonic activity and the lack of subsurface data. The present interpretation of salt deposits was made with the aid of exploratory drilling, gravity surveys, and the location of salt springs. As a result of the complex geology, the maps of geologic criteria for the Maritimes Basin were scored manually, and no geologic metric maps of depth or thickness were included in Appendix A for the east coast. The dominance of salt domes on the eastern seaboard means that the geologic criteria maps are spotty and irregular instead of forming continuous colour contour maps.

In the Horton group, the salt deposits can be found in two locations in NB and one location in NS, shown in Figure 27. A hole drilled in the Cornhill area encountered a 108 m thick salt deposit at a depth of 786 m. In the Weldon-Gautreau area of NB, lens-shaped deposits containing salt, glauberite, anhydrite, and shale occur with a thickness of 488 m at a depth of 368 m. In NS, the Horton Group salt occurs in the Wallace Station area in the Cumberland sub-basin. The Horton Group salt deposits in this area were encountered at 4538 m depth below sea level and are bedded salt deposits since they are relatively flat lying. The thickness and areal extent of these deposits are unknown (Howie, 1988).

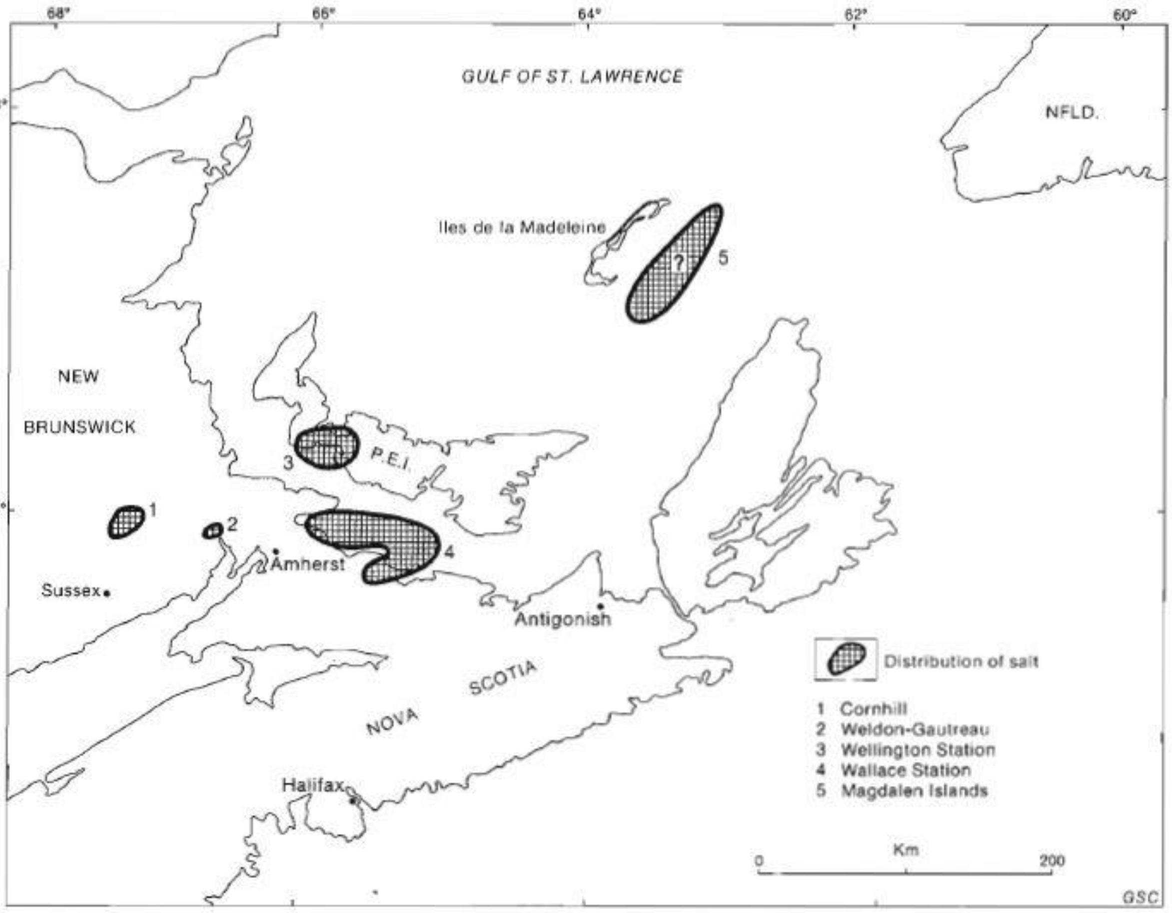

Figure 27: Distribution of the Horton Group salt in the Atlantic Canada (Howie, 1988).

New Brunswick is a major Canadian producer of potash, and the mines there are operated by the Potash Corporation of Saskatchewan: New Brunswick Division. Along with potash, these mines also produce salt from the Windsor Group. Currently, the NB government is evaluating the potash/salt resources available to develop a strategic plan for using them, potentially for salt cavern storage. Nova Scotia has mined a large quantity of salt from three mines: the Malagash, Pugwash, and Nappan mines. All of these mines are located in the Cumberland area which contains thick salt domes. These salt domes are considered potentially suitable for salt cavern storage.

The Windsor Group contains large salt deposits at a suitable depth and thickness for cavern development. The Windsor Group evaporites were deposited over a wide area when the Windsor Sea flooded the Magdalen Basin and adjacent areas in the early to middle Visean age. Figure 28 illustrates and numbers areas underlain by the Windsor Group salt deposits. Table 3 summarises depth, thickness, and salt complexity information available for the deposits numbered 1 through 18 in Figure 28. Note that the depth and thickness values provided are approximate and were obtained from gravity or drilling data reported in the sources. Due to the complexity of salt structures in NB and NS, depth and thickness will vary within the reported area.

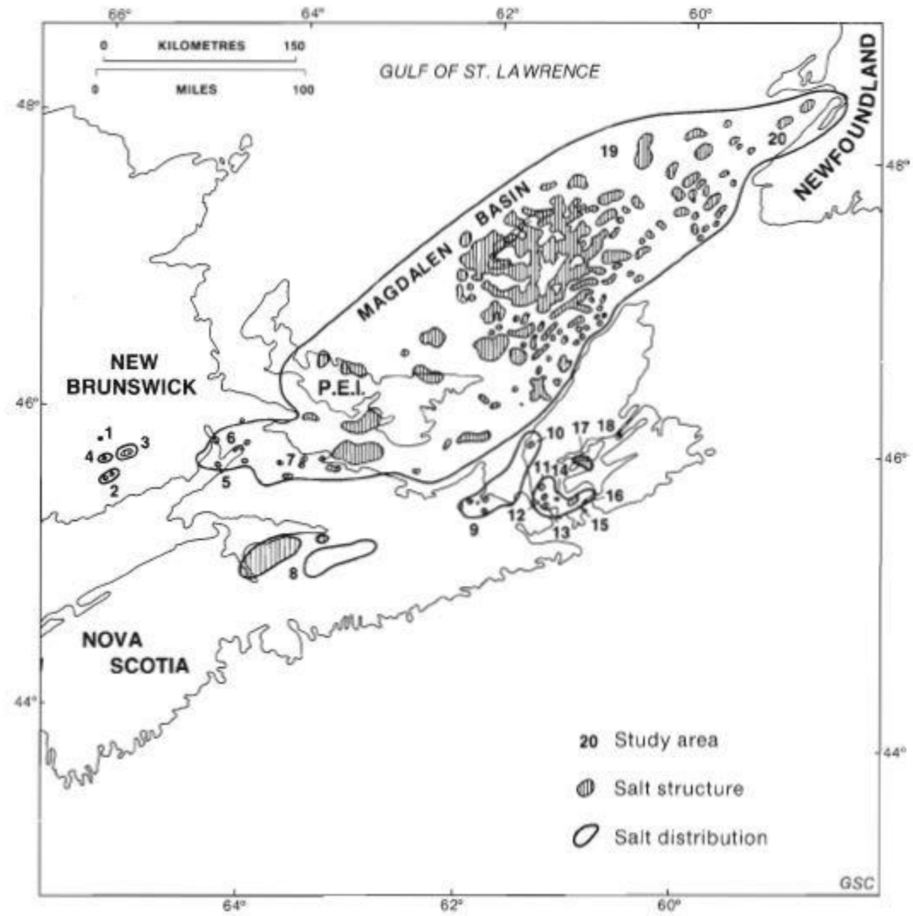

Figure 28: Distribution of the Windsor Group salt in the Atlantic Canada (Howie, 1988).

Table 3: Summary of the Windsor Group salt deposits (After Howie, 1988 and Webb, 2009).

Label	Area	Approximate Depth (m)	Approximate Thickness (m)	Comments
1	Cody area, NB	N/A	N/A	Bouguer gravity map shows gravity lows that might be related to salt deposits.
2	Salt Springs area, NB	606	60, 75, 150	The salt is divided into three members: Upper Halite, Middle Halite and Basal Halite.
3	Plumweseep-Penobsquis area, NB	184	890	Potash Corporation of Saskatchewan (New Brunswick Division) owns the Penobsquis mine, which has produced more than 13 000 000 t of salt from the Penobsquis-Plumweseep deposit.
4	Lower Millstream-Apohaqui area, NB	950	68	Boreholes, surface seismic, and other geophysical surveys confirmed the presence of halite.
5	Riverside-Shepody Bay area, NB	640	N/A	Gravity surveys predict a thick domal salt deposit in this area.

				The structure has not been confirmed by drilling.
6	Dorchester area, NB	350	1116	Salt is pure and accumulated as a diapir structure.
7	Cumberland sub-basin, NS	415 (Nappan deposit)	1400 (Nappan deposit)	Camberland sub-basin contains three mines in NS: Malagash mine (abandoned), Pugwash mine, and Nappan mine.
8	Minas sub-basin, NS	450 (Stewiacke area)	300 (Stewiacke area)	Minas sub-basin is divided into two categories: 1) Windsor-Kennetcook (deformed salt) and 2) Shubenacadie-Stewiacke area (thick bedded salt).
9	Antigonish sub-basin, NS	408 (James River)	210 (James River)	Geophysical surveys and drilling confirm the presence of salt in the following areas: Ohio, James River, Antigonish, Southside Antigonish Harbour, and Pomquet Forks.
10	Mabou sub-basin, Cape Breton Island, NS	425	1275	Salt is interbedded with shale, gypsum, and limestone.
11	Kingsville area, Cape Breton Island, NS	500	NA	Salt is interbedded with anhydrite, limestone, and siltstone. The salt structure is a diapiric anticline.
12	McIntyre Lake area, Cape Breton Island, NS	257	381	Salt mass varies in purity and dips steeply between 20 to 70°.
13	Inhabitants Harbour area, Cape Breton Island, NS	508	245	Salt interclasted with anhydrite and siltstone.
14	Cleveland area, Cape Breton Island, NS	732	146	Salt interbedded with mudstone and shale breccia.
15	Seaview area, Cape Breton Island, NS	N/A	N/A	Gravity surveys indicate zones of low gravity in the Seaview area. However, the presence of salt is not confirmed yet.
16	St. Peters area, Cape Breton Island, NS	376	550	Salt with various amounts of shale and anhydrite.
17	Malagawatch-Ashfield-Orangedale, Cape Breton Island, NS	550	400	Salt contains deposits of potash and is interbedded with anhydrite
18	Kempt Head area, Cape Breton Island, NS	N/A	400	Salt interbedded with anhydrite, sandstone, carbonates, and two zones of potash.

3.4 Considerations for CAES Site Selection

Criteria considered for CAES site selection were obtained through professional judgement and discussion with academic and industrial experts. This section discusses the importance of the selected criteria and the thought process behind the scoring system. Criteria considered for CAES site selection are divided into three major categories:

A) Geology/Geomechanics

1) Depth to salt strata
2) Salt strata thickness

B) Energy Potential

3) Renewable energy potential
    a. Wind energy potential
    b. Solar energy potential
4) Electrical energy demand

C) Existing Infrastructure

5) Proximity to existing natural gas infrastructure
6) Proximity to existing electrical infrastructure.

Although not included in the evaluation framework, additional geomechanical criteria such as interbed thickness and roof rock thickness are also discussed in this section.

3.4.1 Depth

Criterion scoring for salt cavern depth is primarily dependent on geomechanical stability issues and functional integration with turbo-machinery requirements. Salt caverns' stability at a particular depth is dependent on the minimum and maximum air pressure imposed on the cavern. In this study, an operating pressure range of 4 to 8 MPa is assumed. This pressure range is similar to those used in the current CAES caverns at Huntorf and McIntosh which operate at pressures between approximately 4.6 and 7.5 MPa (Budt et al., 2016). These facilities have demonstrated the stability of this relatively conservative operating range for caverns within the optimal depth range. Furthermore, an operating range of 4-8 MPa satisfies the pressure needs of commercially available CAES expander equipment.

At shallower depths, high cavern pressures can fracture the caprock or the walls of the cavern. This, in turn, will cause air to escape from the cavern. As a rule of thumb, the maximum cavern pressure should be limited to 80% of the fracture pressure or geostatic stress. Note that this is just an approximate reference point and a detailed geomechanics analysis should be performed to check this limit prior to salt cavern operation (Bruno, 2005). If a cavern is shallow enough that the maximum allowable operating pressure is below approximately 8 MPa, then the range of operating pressures begins to shrink, and therefore less energy storage is achieved per unit volume. This mechanical limitation governs the scoring system for the depth criterion for values shallower than optimal depth.

The deeper range of the depth criterion is controlled by the minimum air pressure in the cavern. Low air pressure can increase the creep by increasing the deviatoric stress ($\sigma_1 - \sigma_3$). Steady-state creep is defined as time-dependent deformation under constant deviatoric stress. Salt can experience significant creep deformation on the engineering time scale, and it must, therefore, be carefully considered in the design of the underground storage cavity. A commonly used steady-state creep law is Norton's Creep Law as mentioned in section 2.3.4; the equation is restated below:

$$\dot{\varepsilon}_{ss} = A\left(\frac{\sigma_1-\sigma_3}{\sigma_o}\right)^n exp^{\left(\frac{-Q}{RT}\right)}$$ **[Equation 1]**

where:

$\dot{\varepsilon}_{ss}$	=	**steady-state strain rate**
$\sigma_1 - \sigma_3$	=	deviatoric stress
T	=	temperature
A	=	material-dependent parameter (includes texture, moisture content mineralogy, and impurity content)
n	=	parameter based on different mechanisms or creep regime
σ_o	=	normalizing stress at which a particular mechanism is initiated
R	=	universal gas constant
Q	=	activation energy of a given mechanism

From the above equation, it can be observed that creep increases exponentially with higher deviatoric stress; at a similar cavern pressure, the deviatoric stress is greater in deeper caverns as compared to shallower caverns. The equation also demonstrates that creep increases with temperature. In the subsurface, the temperature of rocks increases with depth with an average geothermal gradient of 25 °C/km. Therefore, creep is a major concern in deeper caverns because of high rock temperature and large deviatoric stress. For example, a cavern in the Eminence Salt Dome in Mississippi, built between depths of 1725 m and 2000 m, experienced a 40% loss of volume between October 1970 and April 1972. The bottom of the dome was raised by 36 m; whereas, the top of the dome had remained intact. Bérest & Brouard (2003) suggested that the loss in volume from the cavern's bottom is caused by high ambient rock temperature and large overburden stress. To avoid excessive volume loss to creep, the minimum pressure should be at least 25% of the lithostatic pressure (Bruno, 2005). Volume loss to creep is undesirable because it decreases the available storage for compressed air.

To summarise, the cavern depth and operating pressures are a complex balance between storage longevity, associated cavern risks, mechanical equipment needs, and cost. These considerations are reflected in the following salt depth scoring system. A cavern built within a depth range of 450 to 800 m is given a score of 100 as it meets the equipment needs of a pressure range from 4 to 8 MPa. Caverns built at depths shallower than 350 m are given low scores because they may not be able to contain pressures up to 8 MPa without fracturing and therefore would restrict the operating pressure range. Conversely, caverns deeper than 800 m are given a lower score as the minimum pressure of 4 MPa may induce significant strain rates, which result in excessive cavern closure during its operating life. Deeper caverns can use higher minimum and maximum pressures so that just as much if not more air can be stored in the same volume, but higher pressures also mean more energy must be consumed to compress the air. This increased energy investment will not result in an equal increase in energy output because the mechanical equipment is restricted in how high of inlet pressure it can take in. Therefore, generally speaking, the higher the cavern operating pressures, the greater the energy loss associated with air pressure throttling. Given this ideal range of operating pressures and the lithostatic conditions for which these pressures work in, a global scoring system was developed for salt cavern depth which is shown in Figure 29. Using this scoring system, depth scoring maps were generated for salt units and are listed in Appendix B.

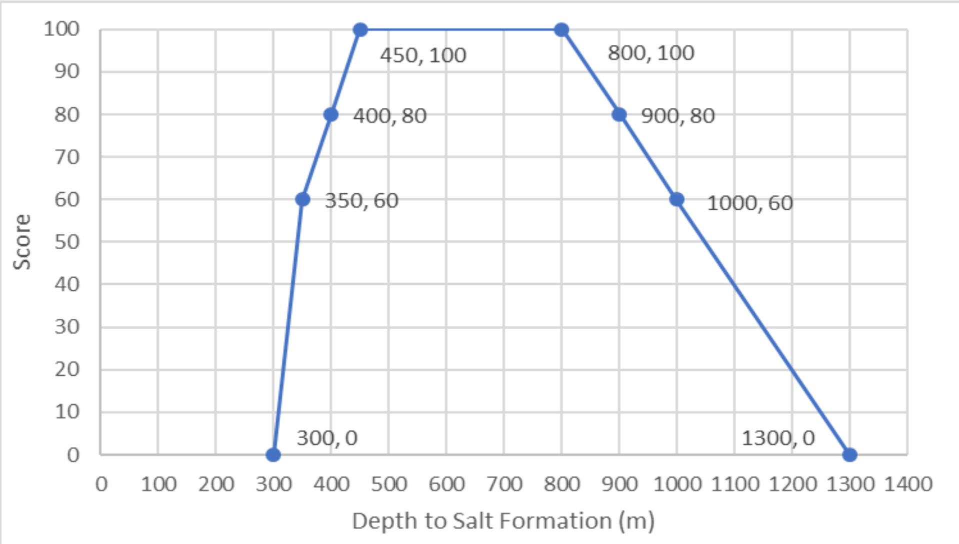

Figure 29: Criterion scoring for depth to the salt strata.

It is important to note that this scoring system was developed for a constant volume operated cavern. Constant pressure salt cavern operation is considered more challenging to implement because it usually requires a surface brine pond which adds to construction costs and makes environmental permitting and public acceptance challenging. An alternative depth criterion for a pressure compensated cavern is expected to favour deeper salt formations because cavern pressure is directly proportional to depth. This is because the cavern pressure must be in balance with the weight of the column of liquid used to maintain a steady cavern pressure. This liquid is usually brine, so the cavern pressure is limited to the density of saturated brine, approximately 12 MPa/km, multiplied by the depth of the cavern.

3.4.2 Thickness of Salt

The thickness of salt strata is an important criterion while selecting a suitable site for CAES. Salt strata should be thick enough to accommodate grid-scale storage caverns with individual volumes of at least 150,000 m^3. In addition to supporting large volumes, a thicker salt strata will aid in increasing cavern stability and integrity by providing a larger buffer of rock salt between the cavern ceiling and overlying non-salt caprocks. The thickness of salt formations is a major consideration in bedded salt deposits but not as much in salt domes because the domes are typically extensive in the vertical direction. In fact, salt domes tend to be hundreds of meters thick as a minimum; whereas, bedded salt strata are relatively thin, from centimetres to a few hundred meters, and may or may not be thick enough to house large storage caverns within.

The thickness of salt strata and the volume requirement will determine the shape of salt caverns. Achieving the large cavern volumes necessary for CAES operations can be done in three ways related to cavern shape and the number of caverns. Solution-mined salt cavities in salt domes use the most common approach of a single vertical cylindrical cavern. Alternatively, multiple cylindrical caverns can also be used (Huntorf is connected to two). Finally, long horizontal galleries are ideal for thinner bedded salt formations, but the techniques needed to mine them are not well developed. The proposed salt cavern shapes and configurations are illustrated in Figure 30. In cylindrical caverns, the diameter of the cavern is limited by roof stability issues. Caverns with larger diameters than height are susceptible to roof failure if the pressure inside the cavern is not able to support the roof. As a reference, for deep caverns, it is advised to keep the height/diameter ratio equal to or greater than one. For shallower caverns, the height/diameter ratio may be reduced; however, the geomechanical analysis is advised to assess the long-term stability of the roof. Single cylindrical caverns can be built if salt strata are thick enough to accommodate the required volume; these are economically advantageous as only one well has to be drilled. Note that drilling wells for CAES is a significant cost because large diameter wells have to be drilled to meet the air mass flow rates required for the expanders. If the salt strata are not thick enough for a single cylindrical cavern, then multiple cylindrical caverns can be built to accommodate the required volume; however, this is an expensive option as multiple wells will be needed to connect underground storage to surface facilities. A potential alternative for storage in marginally thin bedded salt is to create long horizontal galleries. These are tunnel-shaped caverns with a horizontal length of hundreds of meters and a diameter of a few meters. Either a single long horizontal cavern or multiple long horizontal caverns can be built depending on the required volume. As previously discussed, for the purpose of scoring, this study assumes a CAES plant with a size of 100 MW is considered and that a storage volume of 165,000 m^3 is required. In other words, to receive a score, the salt beds should be thick enough to provide space for a total cavity volume of at least 165,000 m^3 within a reasonable number of caverns.

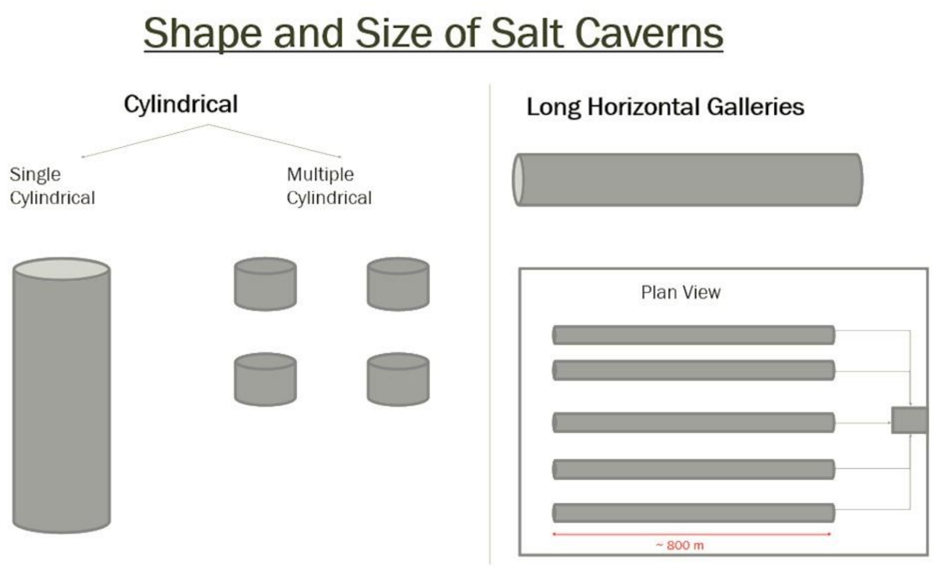

Figure 30: Salt cavern configuration alternatives for achieving large volumes.

Salt beds with a thickness of fewer than 20 m are not suitable for cavern development because of stability and potential air loss issues. Between 20 to 90 m, an intermediate score is assigned as these salt strata might require multiple caverns to satisfy the required air volume. Salt strata with a thickness of more than 90 m are given high scores as they are more likely to be able to use a single large cavern. Figure 31 shows the global scoring system used to evaluate the salt formation thickness criterion. Using this scoring system, thickness scoring maps were generated for salt units and are listed in Appendix B.

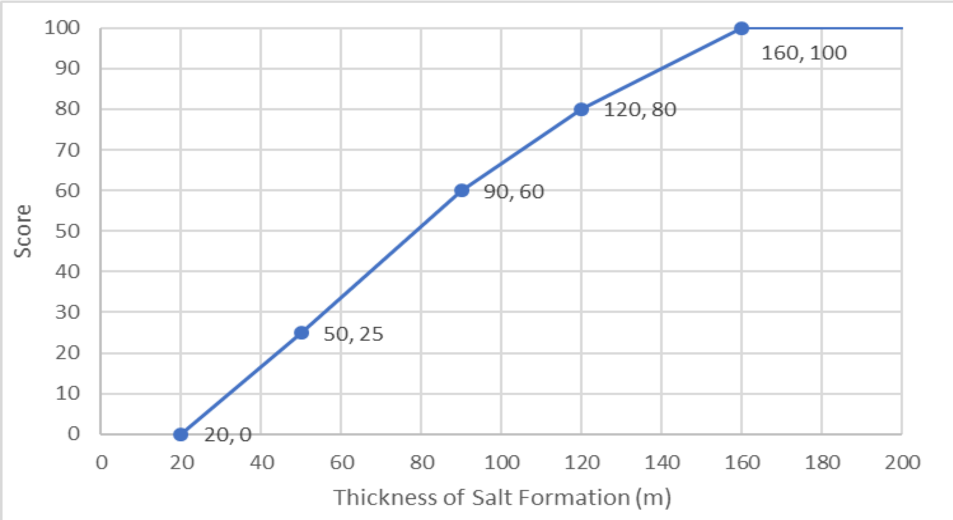

Figure 31: Criterion scoring for salt strata thickness.

3.4.3 Interbed Thickness

Even though not included in the first-order assessment study, interbed thickness must be accounted for when siting an underground salt cavern for CAES. It is not practically possible to include interbed thickness for a countrywide study. However, once the sites are narrowed down, a detailed geomechanics investigation must contain interbed thickness as one of the parameters.

Non-salt interbeds such as anhydrite, dolomite and shale are commonly found in bedded salt deposits. Investigating interbed thickness is important for solution mining and cavern stability purpose. Thickness of interbeds determines the total brinable salt volume. Thin non-salt interbeds typically fall off under their own weight during solution mining. However, thick interbeds tend to reduce the “brinable salt volume” as they do not fall and hence divide the cavern into multiple parts. Hamilton (1971) suggests a maximum acceptable non-salt interbed thickness of 3 m (10 ft) for solution mining purpose. Due to reduction in supporting stresses, interbeds in caverns with large radius are more likely to collapse as compared to interbeds in caverns with a small radius. In addition, lithology of interbeds plays an important role in determining the maximum allowable thickness; low stiffness interbeds such as mudstone are more likely to collapse as compared to high stiffness interbeds such as anhydrite.

Apart from solution mining issue, interbed thickness impacts cavern stability. Salt and non-salt interbeds have different deformation mechanisms, such as salt creeps and non-salt rocks do not creep over the engineering time scale. During extraction period, differential deformation between salt and non-salt interbed could lead to interface slip, which can cause casing damage. Bruno and Dusseault (2002) show that increasing thickness of non-salt interbed increases the probability of interface slip in the cavern.

3.4.4 Salt and Non-Salt Roof Rock

Consideration of salt and non-salt roof thickness is a vital part in detailed salt cavern siting study. As is the case with interbed thickness, roof thickness could not be included in the first-order study due to countrywide study area. However, an insight on it is given below, which can be utilized during detailed CAES siting investigation for specific sites.

Roof rock plays an important role in cavern stability as it acts as a load-bearing structure. A competent roof rock bears the weight of the overburden and distributes it away from the salt cavern. In addition to stabilizing the cavern, an impermeable roof rock would also trap the injected air and prevent upward migration.

Roof rock consists of two types: salt roof and non-salt roof. Salt roof can be defined as the salt strata situated between the top of the cavern and the non-salt overburden. The non-salt roof is the first non-salt layer above the salt strata. In general, caverns in salt domes and thick-bedded deposits tend to have a thick salt roof, sometimes more than hundreds of meters thick; in these cases, the salt roof is enough to bear the load and minimize deformation in the cavern. However, caverns in bedded salt deposits typically do not have a thick salt roof. In these circumstances, thin salt roof and non-salt roof have to act together to bear the overburden load and minimize deformation in the cavern.

In the cases where the non-salt roof is required to bear the overburden load, such as in bedded salt deposits, the non-salt layer should contain the adequate roof rock characteristics: high elastic modulus, large thickness, no major faults/joints, and very low permeability. Good examples of competent non-salt roofs are anhydrite and carbonates, which have high stiffness. For the competent roof layer, a thickness of 1/3rd of the cavern diameter will provide sufficient stability.

3.4.5 Renewable Energy Potential

One of the goals of CAES is to integrate renewable energy, such as wind and solar, into the electrical grid. Although research on integration and connection of renewable energy is not in the scope of this study, an attempt is made to consider the energy potential of wind and solar sources. Siting a CAES facility near renewable energy power plant is economically feasible to reduce the costs associated with transmitting energy. This study utilizes available energy potential maps to generate scoring for wind and solar potential. Appendix A lists the wind and solar energy potential maps for Western Canada, Ontario, and Maritimes.

The renewable energy potential criterion is dependent on both the wind and solar potentials, available in terms of energy density and measured in W/m^2 of the turbine blade swept area and in terms of annual mean daily global insolation and measured in MJ/m^2/day of panel area, respectively. The renewable energy potential score for a given site is a combination of 1) 50% average available resource and 2) 50% best available resource (Equation 3). A potential site is evaluated for this criterion based on the average potential of renewables within a 10 km radius. The scoring systems for wind and solar energy potential are displayed in Figure 32 and Figure 33, respectively. Using this scoring system, wind and solar energy potential scoring maps were generated and are listed in Appendix B.

$$\boldsymbol{Renewable\ energy\ potential\ score = 0.5 * average(ws, ss) + 0.5 * max(ws, ss)}$$

[Equation 3]

Where: ws = wind energy potential score
ss = solar energy potential score

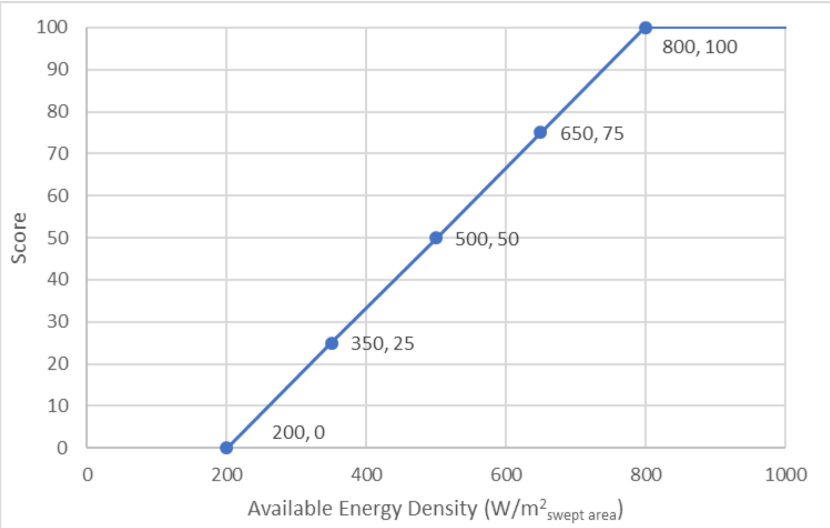

Figure 32: Criterion scoring for wind energy potential.

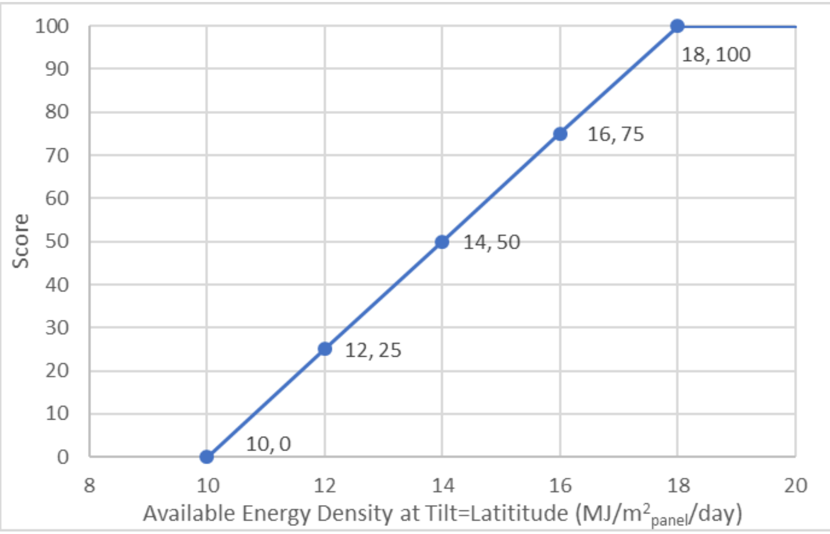

Figure 33: Criterion scoring for solar energy potential.

3.4.6 Electrical Energy Demand

It is economically desirable to build a CAES facility near energy consumption centers, which will allow reducing costs associated with transmitting stored energy. In this study, electrical energy demand is calculated through multiplying population of the district with average energy consumption per capita for the respective province; the electricity demand score for a site is determined by summing the energy demand within a 10 km radius (Equation 4). Note that energy demand within electoral districts is assumed to be equally distributed across the area. Appendix A lists the electrical energy demand maps for Western Canada, Ontario, and Maritimes.

$$\boldsymbol{Electrical\ energy\ demand} = \sum_{i=1}^{n} \frac{A_i}{A_{t,i}} P_i * ED_{capita} \qquad \textbf{[Equation 4]}$$

where: n = number of districts partially or completely within a 10 km radius of the site
A_i = area of district ‘i’ within a 10 km radius of the site
$A_{t,i}$ = total area of district ‘i’
P_i = population of district ‘i’
ED_{capita} = energy demand per capita for the province in question

Figure 34 displays scoring for electrical energy demand; the scoring is a linear function resulting in high or low scores for a site depending on energy demand in the 10 km radius. Using this scoring system, electrical energy demand scoring maps were generated and are listed in Appendix B. Note that the average energy use per capita includes all energy consumed in the province, including residential, industrial, and commercial sectors.

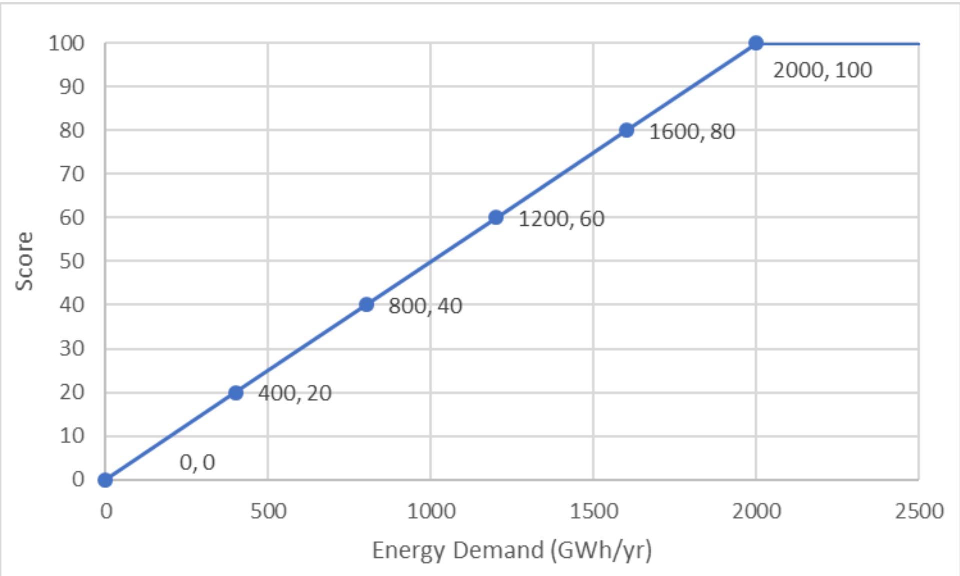

Figure 34: Criterion scoring for electrical energy demand.

3.4.7 Existing Infrastructure

Due to high cost of building new electrical and natural gas transmission lines, it is economically desirable to build a CAES facility closer to existing transmission network. Appendix A lists the electrical and natural gas transmission line maps for Western Canada, Ontario, and Maritimes.

The scoring functions for the transmission infrastructure are influenced by other similar studies in the US and Iran (McGrail et al., 2013; Satkin et al., 2014). Figure 35 displays scoring for proximity to electrical and natural gas transmission infrastructure. The scoring function is linear and is measured on a scale of distance (km). Using this scoring system, electrical and natural gas transmission line scoring maps were generated and are listed in Appendix B.

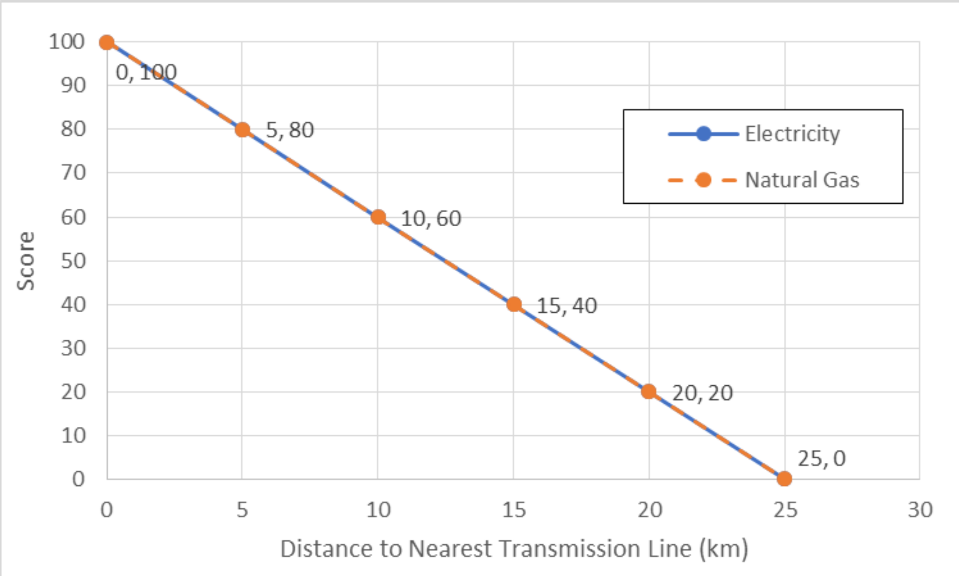

Figure 35: Criteria scoring for electrical and natural gas transmission infrastructure.

3.5 Decision Tree: Geology and Geomechanics

The decision tree presented in Figure 36 represents geology and geomechanics parameters that should be considered during detailed CAES siting study. This is not a part of the first-order study as it is impractical to obtain some of the data for Canada wide study. However, the decision tree provides an insight on what parameters should be considered in a detailed study.

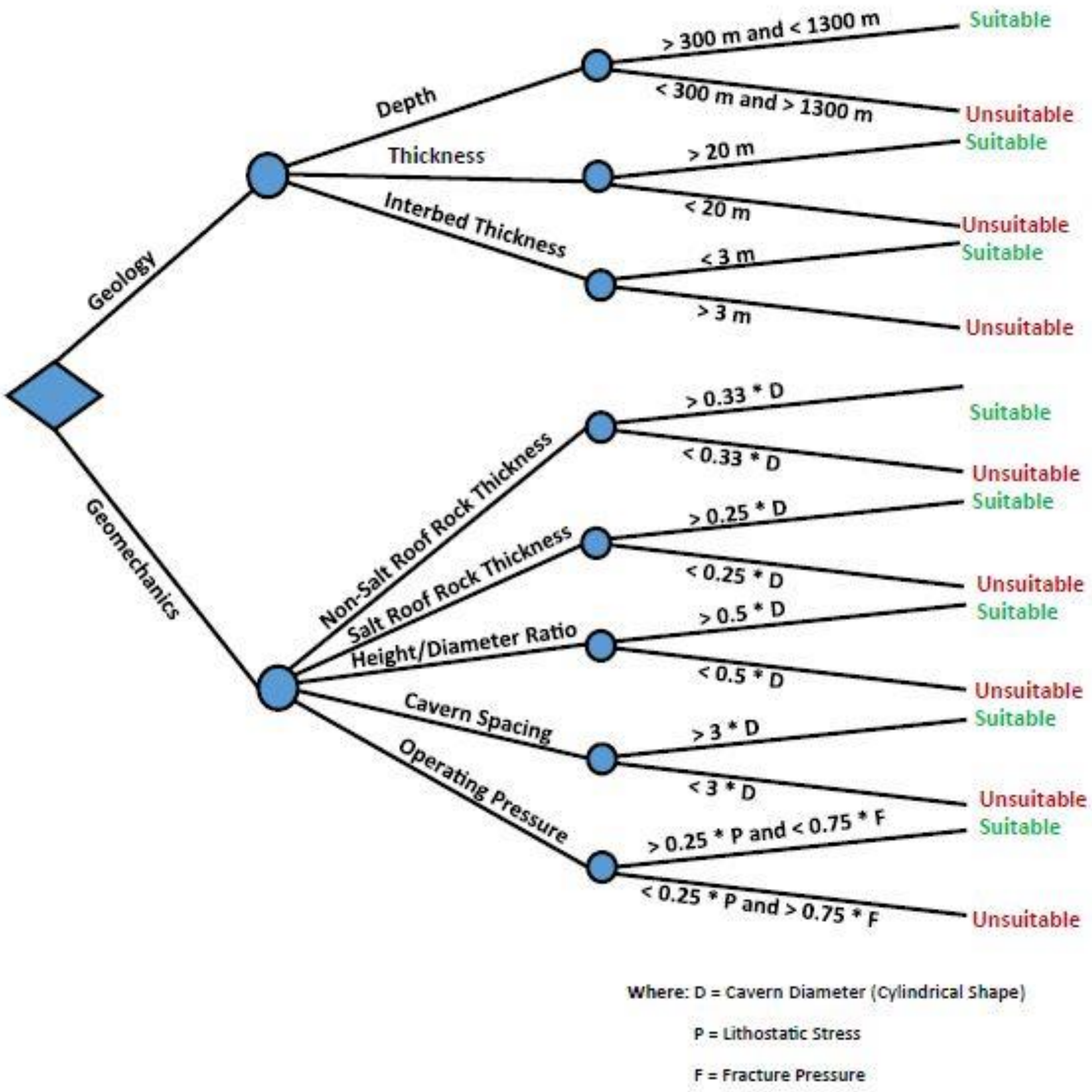

Figure 36: Decision tree - geology and geomechanics.

3.6 Results and Discussion

The MCA results for CAES site suitability are displayed and divided into three categories based on the geologic basins: Ontario (Michigan Basin), Western Canada (Western Canada Sedimentary Basin), and Maritime Provinces (Maritimes Basin). The results displayed contain criteria with the following weights: 0.2 for salt depth, 0.2 for salt thickness, 0.15 for renewable energy potential, 0.15 for proximity to electrical transmission lines, 0.15 for proximity to natural gas transmission lines, and 0.15 for electricity demand. It can be observed that geology has high weighting and might strongly influence the total score. Criteria scoring maps for each geologic basin are shown in Appendix B.

3.6.1 Ontario

MCA results for CAES potential in Ontario are displayed in Figure 37. A few cities in Ontario offer good potential for building a CAES facility. These areas have reasonably thick salt deposits at optimal depth. On the other hand, due to unavailability of salt strata, a major part of Ontario is not suitable for CAES. Since salt strata are limited to southwestern Ontario, the final CAES potential result map of Ontario only displays southwestern Ontario.

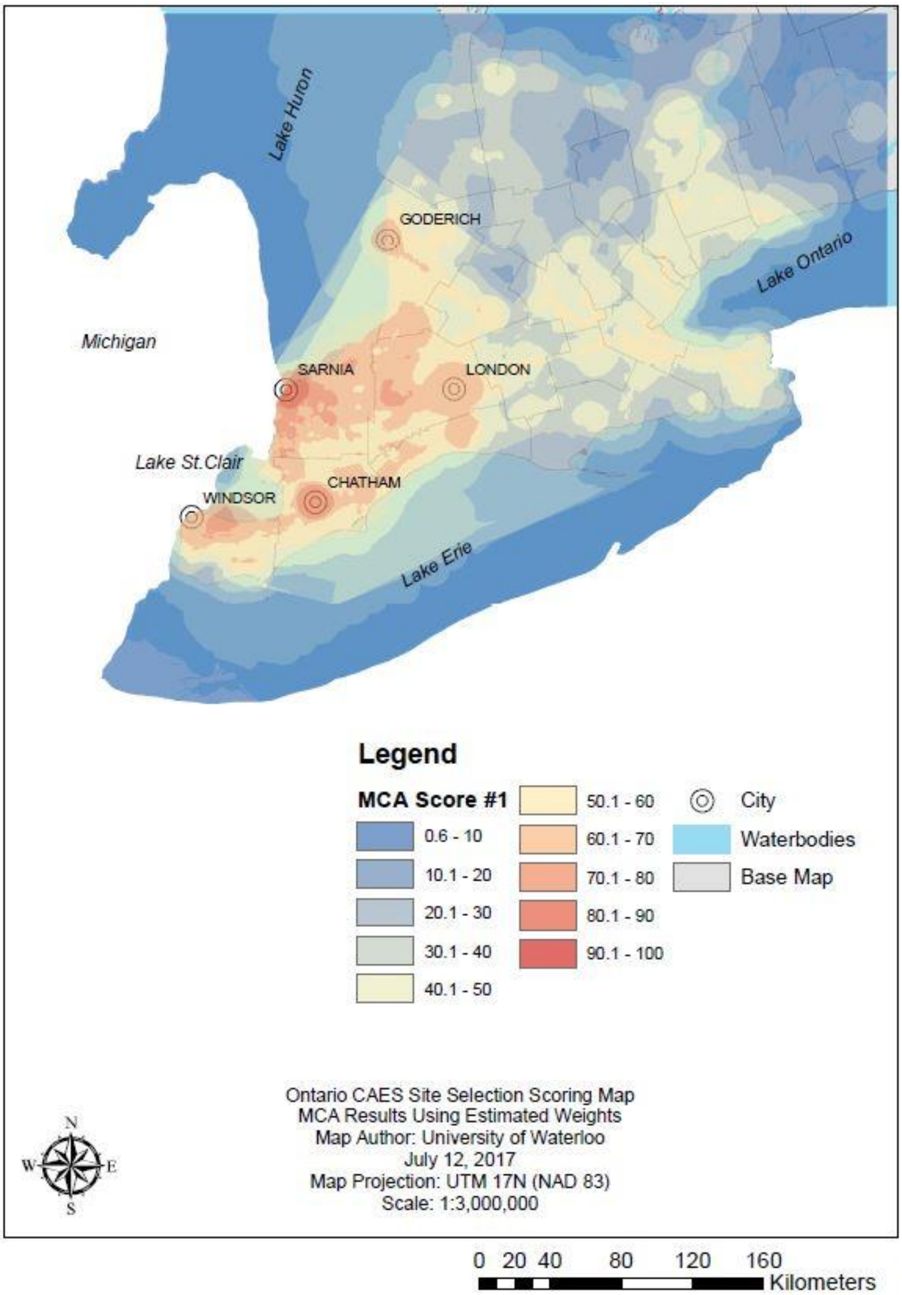

Figure 37: MCA results for CAES potential in Ontario.

Salt strata in SW Ontario are thin as compared to strata in Western Canada and Maritime Provinces; however, depth to salt is not an issue in SW Ontario. The only two salt units that can accommodate salt caverns are unit B and unit A2 of the Silurian Period. Due to larger thickness, Unit B is preferred over unit A2 throughout

Ontario. For example, in Sarnia, Unit B is 90 m thick and 610 m deep; whereas, unit A2 is 40 m thick and 750 m deep.

The city that shows the highest CAES potential is Sarnia. It has the thickest salt in Ontario, with 90 m thick Unit B salt strata deposited at a depth of 610 m. Sarnia also scores high in energy demand criterion. The renewable potential, electrical transmission line, and natural gas transmission line scores for Sarnia are similar to other major cities in SW Ontario. It can be safely said that optimal geology differentiates Sarnia from other sites in SW Ontario and make it the best location to implement CAES in Ontario. Other cities that show decent potential are Goderich, Windsor and Chatham; as compared to Sarnia, these cities score less in salt thickness criterion.

3.6.2 Western Canada

MCA results for Western Canada are displayed in Figure 38. The map displays a long northwest-southeast band that has good potential for CAES in Alberta and Saskatchewan. The position of the band is highly influenced by the presence of optimal salt strata in that area. Even though multiple salt strata exist in the Western Canada Sedimentary Basin, the Prairie Evaporite Formation has the highest influence on the position of the band due to its presence in Saskatchewan and lack of presence of other salt formation in Saskatchewan. Apart from the Prairie Evaporite Formation, Cold Lake Formation and Lotsberg Formations also show great geologic potential in Alberta.

Middle to northeastern Alberta has the highest CAES potential, and this is attributed to the thick salt units present in these areas. Examples of the cities that show high potential are Cold Lake, Bonnyville, and Lac la Biche. Eastern Alberta also scores high in electrical and natural gas transmission infrastructure. The CAES potential band goes through the middle of Saskatchewan and the Prairie Evaporite Formation is the only salt strata deposited in middle Saskatchewan regions. Areas that show high CAES potential include Yorkton, Saskatoon, and North Battleford. These areas have optimal geology, high energy demand, good transmission infrastructure, and high renewable potential. Lloydminster also shows good CAES potential with high scores in geology, transmission infrastructure and renewable potential.

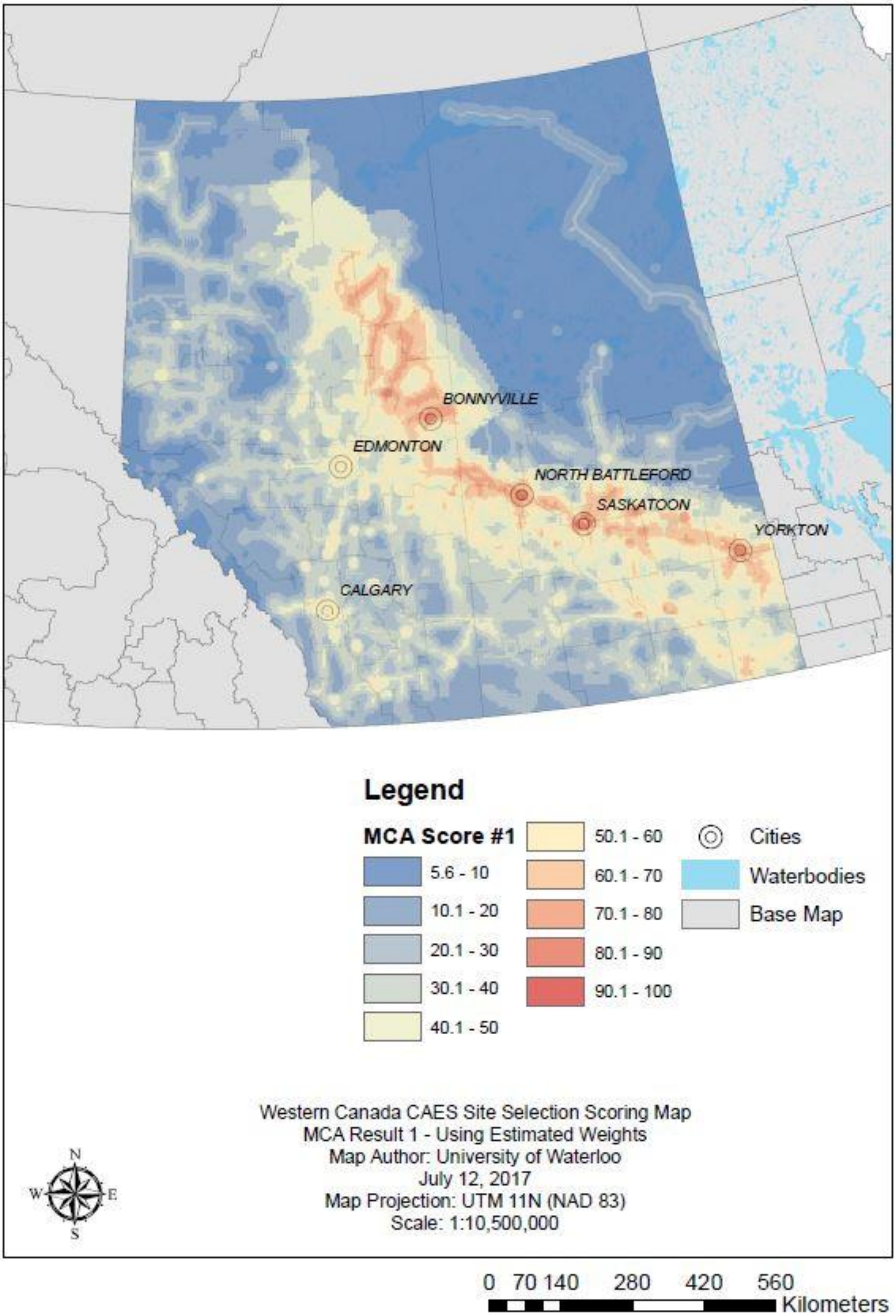

Figure 38: MCA results for CAES potential in Western Canada.

3.6.3 Maritime Provinces

MCA results for New Brunswick and Nova Scotia are displayed in Figure 39. Salt geology in the Maritimes Basin is complex due to tectonic activity that turned bedded salts into domes, anticlines, and pillows. This means that salt is represented in patches as compared to continuous representation in Western Canada and Ontario. As displayed in Figure 39, significant CAES potential exists in Nova Scotia and New Brunswick in locations that contain salt strata. Fortunately, salt is present near major urban centers.

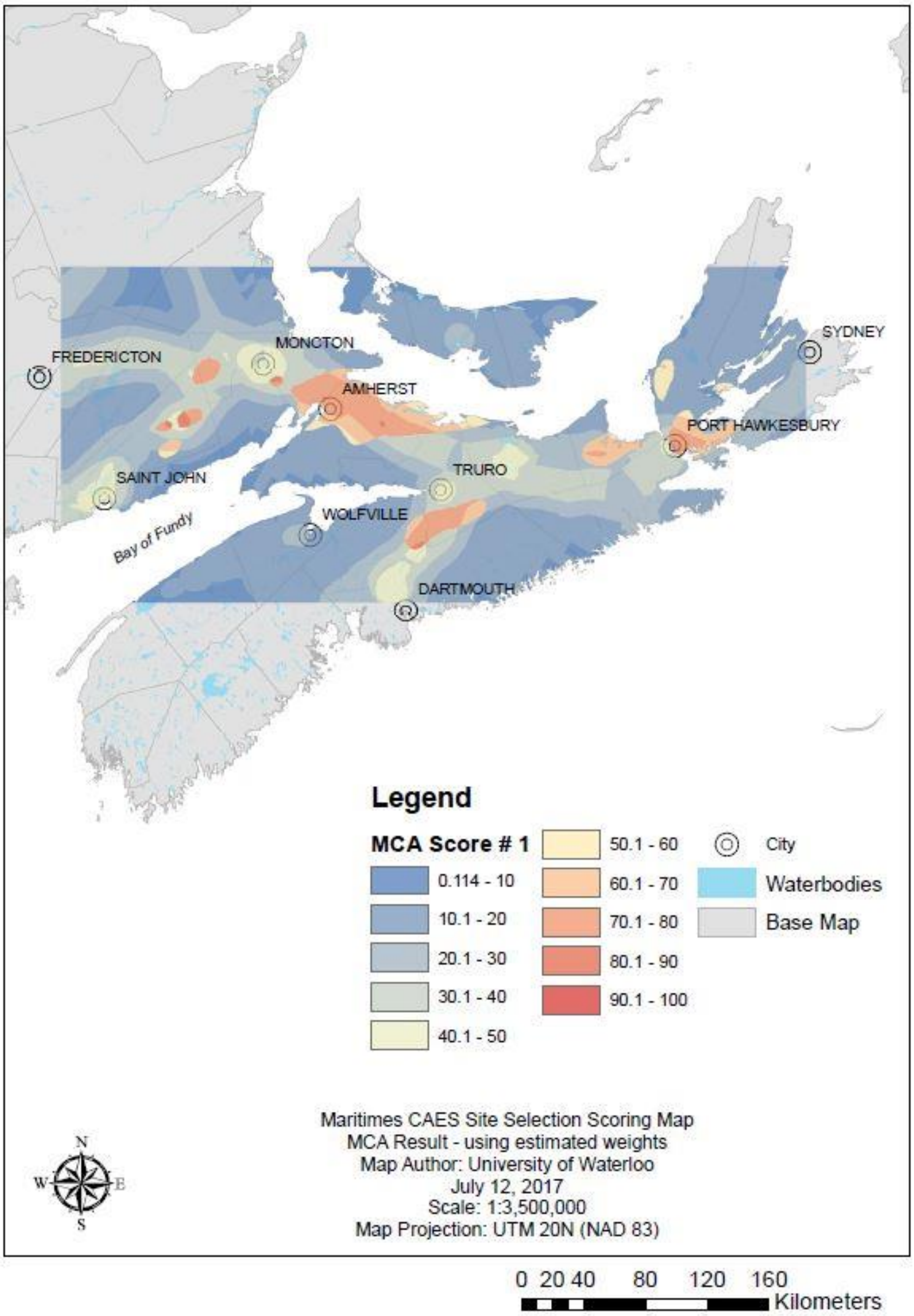

Figure 39: MCA results for CAES potential in Maritimes.

In New Brunswick, significant CAES potential exists in southeast New Brunswick and areas west of Moncton. These areas have thick salt beds located at optimal depth and decent renewable energy potential. The areas are close to major urban centers such as Moncton and Amherst, which have high energy demand and good transmission infrastructure. Regions that show high CAES potential in Nova Scotia are Amherst, Port Hawkesbury, Antigonish, and the area between Truro and Dartmouth. All of these regions have strong wind potential and score 100 in depth and thickness criteria. Areas with high energy demand include Truro and Dartmouth; even though these cities are not underlain by thick salt strata, the cities are well connected with the thick salt strata areas through transmission infrastructure.

4) PART III - Potential of Deep Brine Disposal in Southwestern Ontario

4.1 Introduction

In the past, salt caverns in southwestern Ontario and elsewhere in North America have been used for disposing oil field wastes, storing liquid and gaseous hydrocarbon products, and producing salt for commercial use. Now, with the demand for energy storage growing rapidly, salt caverns are proposed to be used as a storage medium in compressed air energy storage (CAES). Apart from pumped hydro, CAES is the only technology that can provide grid-scale energy storage. For this to occur, implementation of CAES in southwestern Ontario would require solution mining large salt caverns to be used as storage vessels. This, in turn, would generate large volumes of brine that must be disposed of safely.

Historically, the three most common ways to dispose brine were discharge to surface waters, disposal into surface ponds, and deep well disposal. However, because of environmental issues such as soil and groundwater contamination, discharge to surface waters and disposal into surface ponds are discouraged or prohibited by regulations. Deep well disposal has fewer environmental issues as compared to other options, but requires a suitable aquifer that can be shown to provide containment and is also subject to the regulatory process, supervised by the Petroleum Operations Section of the Ontario Ministry of Natural Resources and Forestry.

Though deep brine disposal has been used by industries in Ontario, there is a lack of a comprehensive investigation of site suitability for deep brine disposal. This study aims to investigate suitable sites for brine disposal in southwestern Ontario based on geological, geomechanical, and petrophysical parameters. A multi-criteria analysis evaluation system is developed based on relevant disposal parameters and applied to sites throughout southwestern Ontario.

The chapter starts with discussing the geological, geomechanical, and petrophysical parameters that influence disposal in the subsurface. Then, in section 4.4, the study goes on to briefly discuss southwestern Ontario's general Paleozoic geology and the relevant subsurface formations that hold the most potential for disposal. Sections 4.5, 4.6, and 4.7 present the multi-criteria analysis framework, the decision tree, and criteria scoring and weighting, respectively. The last section discusses the disposal potential results in southwestern Ontario.

The assessment technique developed is intended to yield a "first-order" estimate of preferred brine disposal sites in southwestern Ontario based on a broad set of geological, geomechanical and petrophysical parameters. The final results of this study, which show suitable brine disposal sites, will help in locating suitable areas to implement CAES. It is economically and environmentally preferred to solution mine salt caverns, as required for CAES, near the disposal site. Transporting brine a large distance through pipelines, trucks, or any other method will be expensive and can also result in spills.

Since this is a "first-order" study, a detailed investigation must follow once the list of suitable disposal sites is narrowed down to a few sites. The detailed investigation must consider at least the following subjects: permeability, porosity, thickness, depth, areal extent, and formation pressure of the disposal formation; impermeability, strength, thickness, and continuity of the confining rock mass; proximity to faults and tectonic history of the area; proximity to valuable resources such as potable water, oil and gas, and mineral deposits; and presence of unplugged or inadequately plugged wells in the vicinity of the disposal site.

4.2 Feasibility Considerations

This section will discuss the geological, geomechanical and petrophysical parameters that affect brine disposal into the subsurface. Before discussing the parameters, it is essential to briefly review the hydrogeologic principles that govern injection and movement of injected fluids in the disposal formation. For representation purpose, Figure 40 displays an ideal brine disposal set-up. An ideal disposal set-up represents brine movement in the form of an expanding cylinder in the formation that is isotropic, homogeneous, has uniform thickness, and contains no leakage pathways to other formations. However, in reality, disposal formations typically display anisotropy and heterogeneity, such as different horizontal and vertical permeability; also, brine disposed in real disposal formations has a high chance of encountering leakage pathways such as joints, faults, and unplugged wells.

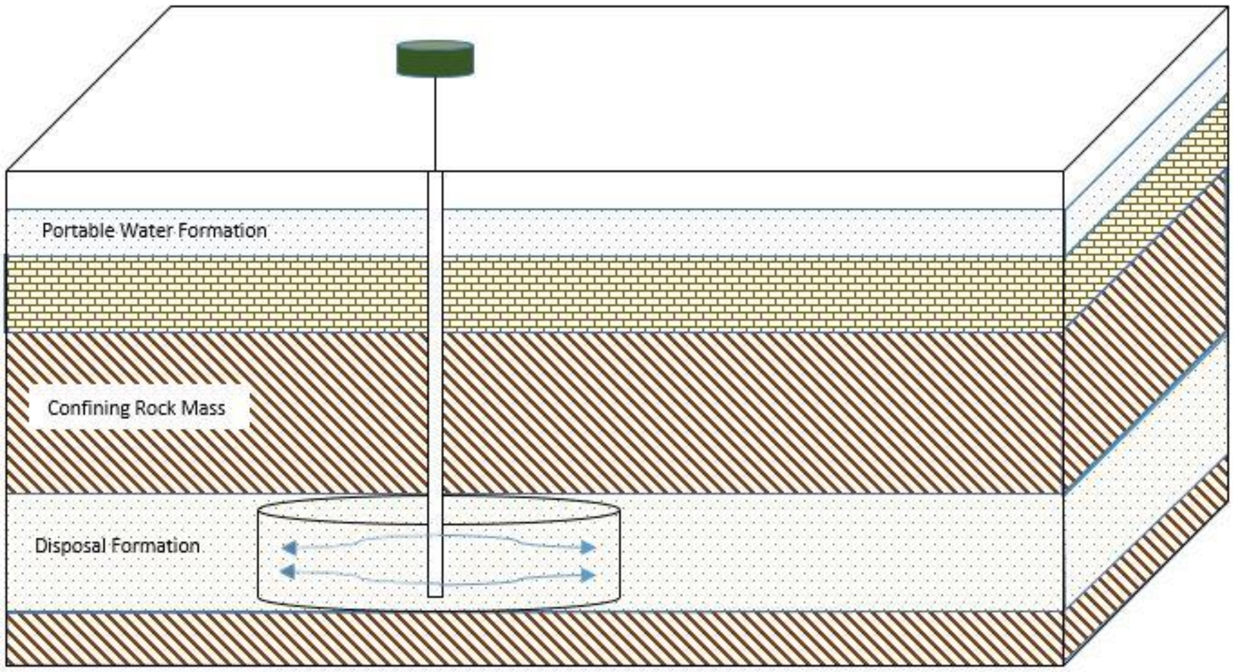

Figure 40: Ideal brine disposal set-up.

Injection pressure is of utmost importance in any brine disposal project. Low injection pressures are preferred to avoid high-power surface equipment that would increase the cost of the project. In addition to cost, high injection pressures are discouraged as they can lead to potential caprock stability issues. The required injection pressure can be explained by the fundamental Law of Darcy, which explains the factors that control fluid movement through porous media. Equation 5 is a form of Darcy's Law, and it gives the formula for the pressure differential (ΔP) that is required to cause radial flow in the disposal formation. This equation assumes that the formation is isotropic, homogeneous and has uniform thickness. Equation 6 gives the formula to calculate injection pressure (P_i) given formation fluid pressure (P_f), pressure of fluid column (P_s), friction loss in tubing (P_y), and pressure required to maintain radial flow (ΔP). From the two equations, it should be noted that permeability and thickness are the most influential parameters for injection pressure (McLean, 1968).

$$\Delta P = \frac{Q\,\mu\,Ln\frac{Re}{Rw}}{7.07\,kh}$$ **[Equation 5]**

where Q is flow rate, μ is fluid viscosity, Re is effective radius of formation at static pressure, Rw is radius of well, k is permeability, h is formation thickness, and ΔP is pressure differential to cause radial flow.

$$P_i = P_f - P_s + P_y + \Delta P$$ **[Equation 6]**

4.2.1 Permeability

Permeability is defined as the ability of rock formation to transmit fluid. It is the most important parameter in deep brine disposal as the main goal of disposal project is to store and transmit the fluid through the formation. Injection pressure is also largely dependent on permeability; low permeability would require high injection pressure that can make the project expensive and even impractical. The unit for permeability is the darcy; one darcy is equal to the value of permeability that permits one cubic centimeter of fluid of a unit viscosity to flow through a length of one centimeter and a cross-sectional area of one square centimeter in one second under a pressure differential of one atmosphere. Formations with permeability greater than 100 mD are preferred for large volumes of brine disposal, i.e., they are considered as aquifers.

It is relatively convenient to obtain a rock’s porosity as compared to permeability. In many circumstances, large porosity means large permeability; however, this is not always the case. Permeability depends on interconnected pore space, pore throat radius, and fracture network density. Two examples in which the formation might have high porosity but less permeability are (1) when the pores are cemented and fluid is not able to flow through the pores, and (2) when the formation consists of fine-grained rock that has small pore sizes through which the flow is limited. It should be noted that hydraulic fracturing is a proven technique to enhance permeability. It is possible to have high permeability in a low porosity formation if the formation consists of a network of natural or induced fractures; an example is fractured limestone (Nadeem and Dusseault, 2007).

4.2.2 Porosity

Porosity is defined as the ratio of the void space volume to the rock’s bulk volume. In simple terms, it measures the rock’s ability to store fluid. Two types of porosities exist: primary porosity and secondary porosity. Primary porosity refers to void space formed during deposition of the sediments. Secondary porosity refers to void space formed after deposition through geochemical or tectonic process. In fact, porosity is categorized further into two categories: total porosity and effective porosity. Total porosity refers to the ratio of total pore volume to the rock’s bulk volume; whereas effective porosity refers to the ratio of interconnected pore volume to the rock’s bulk volume. In brine disposal, only effective porosity is of importance since only the interconnected void space will transmit and store the brine.

High effective porosity is desired for an economical disposal operation. As a reference, porosity values greater than 15 % are desired for large brine disposal operations.

4.2.3 Depth

The minimum and maximum constraints for the depth depend on environmental issues and drilling costs, respectively. The disposal formation should maintain a certain distance from the formations containing freshwater; in Ontario, freshwater typically occurs at shallow depths. Also, at shallower depths, the confining rock mass is at a low stress condition and would fracture under high injection pressure. This can result in major environmental issues such as polluting the shallow potable water formations (McLean, 1968). Therefore, in southwestern Ontario, a minimum depth constraint of 120 m is advised. At this depth, caprock is strong enough to withstand the injection pressures that will be needed, and the disposal formation is far away from the groundwater formations. That being said, depth to the groundwater can vary and the minimum depth constraint needs to be double-checked before finalizing a potential site.

The maximum depth constraint is controlled by the cost of drilling and operational machinery. Drilling is expensive and deeper disposal formations can significantly increase the capital cost of the project. Also, deeper formations have higher formation pressures and therefore require higher injection pressure to maintain the flow. Higher injection pressure would require high-powered surface equipment and this would increase the operation cost of the project. In fact, in deeper formations, it is possible to have formation pressures so high that the disposal operation in not feasible.

4.2.4 Thickness

The thickness of the disposal formation is an important parameter due to its impact on transmissivity and injection pressure, as well as storage volumes available.

Transmissivity is defined as the rate at which water is transmitted through a unit width of an aquifer under a hydraulic gradient of unity. Equation 7 displays the formula for transmissivity; it is equal to the hydraulic conductivity of an aquifer times the thickness of an aquifer. The units for transmissivity are m^2/day or L/day/ft (gal/day/ft). For disposal purpose, higher transmissivity is desired so that large amounts of brine can be disposed. Equation 7 shows that formations with large thickness will have larger transmissive potential.

$$T = Kb \qquad \text{[Equation 7]}$$

where T is transmissivity, K is hydraulic conductivity, and b is thickness.

The formation thickness is one of the crucial parameters that controls injection pressure. Given that other disposal formation conditions are the same, thinner formations require higher injection pressure and vice-versa to achieve the same injection rates. Higher injection pressure would be uneconomical, as it would require high-power surface equipment.

The thickness of the disposal formation also controls the spread of the injected fluid. In a comparison of two homogeneous formations with similar effective permeability, brine would spread farther in a thin formation as compared to a thick formation (McLean, 1968). It is desirable to contain brine near the well so that it does not pollute valuable resources or pose other environmental issues. Confinement of the brine will also assist in developing an effective monitoring system that can be placed in the vicinity of the well. Another challenge in injecting brine into a thin aquifer is the acceptance of fluid. Typically, only a few meters of area from the well accepts large amount of fluids. All the above-noted points make it obvious that thicker disposal formations are preferred.

4.2.5 Areal Extent

A disposal formation with a large areal extent is preferred to accommodate large volumes of brine and avoid pressure build-up during long-term injection. First, given adequate permeability and thickness, the amount of brine stored is directly related to the areal extent of the formation. The amount of brine storage increases with increasing areal extent or reservoir volume.

In addition, formations with large areal extent are necessary to avoid pressure build-up during long-term injection. Injected brine pushes and compresses the formation fluids while moving radially away from the well. Since the formation fluids are only slightly compressible, pressure builds up quickly in an aquifer with small areal extent (McLean, 1968).

In a confined aquifer, it is possible that formation pressures are so high that the disposal operation is not feasible. Also, over the time, with more injection, formation pressure can reach critical pressure values at which reservoir stability issues can arise. Two possible stability issues are caprock breach and well damage due to high pressure. Therefore, McLean (1968) suggests that a formation with large areal extent is needed to distribute the pressure.

4.2.6 Confining Rock Mass

All disposal formations require a caprock that confines the injected fluid into the disposal formation; confinement is necessary to avoid polluting formations containing groundwater, oil and gas, and other minerals. The main requirements of an adequate caprock are impermeability to reservoir fluid, strength, thickness, and continuity. Caprock should be impermeable and unfaulted, so that the brine does not escape the disposal formation. A confining rock mass should be sufficiently strong so that the high formation pressures due to long-term injection do not fracture the caprock. In fact, if the caprock has high stiffness, then the fractures will be limited to the disposal formation. Also, the caprock should be thick and continuous; a thick caprock provides additional protection in shallow disposal projects where the distance between the groundwater formation and the disposal formation is only a few meters.

Preferred and proven caprock include shale and dense carbonates (Rudd, 1972). Having said that, even other rocks that are dense can act as a barrier to the injected fluid; for example, sandstones that are heavily cemented can become impermeable to brine and act as an adequate seal.

Shales are commonly found as confining rocks for hydrocarbon reservoirs. They are fine-grained sedimentary rocks formed by consolidation of clay minerals into thin impermeable layers bonded together by cementation, friction, and adhesion to thin layers of water. The impermeable nature of unfractured shale is due to very small pore throat sizes and ductile behaviour.

Apart from shales, dense carbonates can form an effective seal. The effectiveness is due to fine grains and small pore throat sizes that can impede flow. Rudd (1972) explains that non-ductile rocks, such as carbonates, are similar to a glass jar that can prevent flow, but is brittle and can fracture under high pressure.

4.2.7 Formation Pressure

For successful long-term disposal, it is required that the formation pressure be below certain limits which depend on other factors such as permeability and volume of the reservoir. High formation pressure would increase the operational cost by requiring higher injection pressure. In addition, high injection pressures needed to achieve design rates could cause environmental problems by damaging the caprock and possibly polluting other formations.

Over time, fluid injection may result in increased formation pressure. Therefore, to avoid reaching a high formation pressure, initial formation pressure should be low. Low formation pressure also suggests that the formation has adequate porosity and permeability. However, very low formation pressure could also mean that the disposal formation is not confined and a leakage pathway exists through the caprock.

4.2.8 Proximity to Formations with Valuable Resources

According to government regulations, injection of brine should not affect any formation containing valuable resources; valuable resources can include potable water, oil and gas, and other mineral deposits (McLean, 1968). A safe distance must be maintained from these resources, and multiple confining layers should exist between the disposal formation and the valuable resource formation.

Since ground water typically exists at shallower depth, particular attention needs to be paid when disposing brine at depths of less than 180 m. Disposal at greater depth does not normally pose a threat to potable water sources. However, oil and gas deposits and mineral deposits can exist at greater depth.

4.2.9 Proximity to Faults

If a fault is present through the caprock and the reservoir, it can cause major environmental issues. The brine can escape through the fault under the influence of pressure and pollute other formations. Similarly, areas containing caprock with high fracture density should be avoided as fractures in the caprock can allow brine to escape the disposal reservoir (Figure 41).

It is also desired that the disposal site be located in a tectonically stable area. Large earthquake activity can pose a threat to reservoir stability through generation of fractures or faults. Seismic activity can also open existing faults or fractures. Fortunately, southwestern Ontario is seismically stable.

4.2.10 Unplugged Wells

During the last decades of the 19th century, many exploratory and production wells were drilled for oil and gas. Unfortunately, many of these wells were left unplugged or inadequately plugged. The records of the location of these wells have been lost and this creates an environmental concern during subsurface disposal. McLean (1968) estimates that more than 10,000 wells were left unplugged or inadequately plugged. Most of these wells are located in the Devonian and the Silurian strata.

During injection, brine can escape under the influence of pressure through the unplugged wells and pollute other formations (Figure 41). In the past, environmental incidents occurred in Ontario where industrial waste escaped the disposal formation through unplugged wells (Raven et al., 1990). Therefore, the location of unplugged wells must be determined before brine injection. McLean (1968) suggests that, at least, an area covering the radius of 2.5 km around the well should be surveyed for unplugged wells.

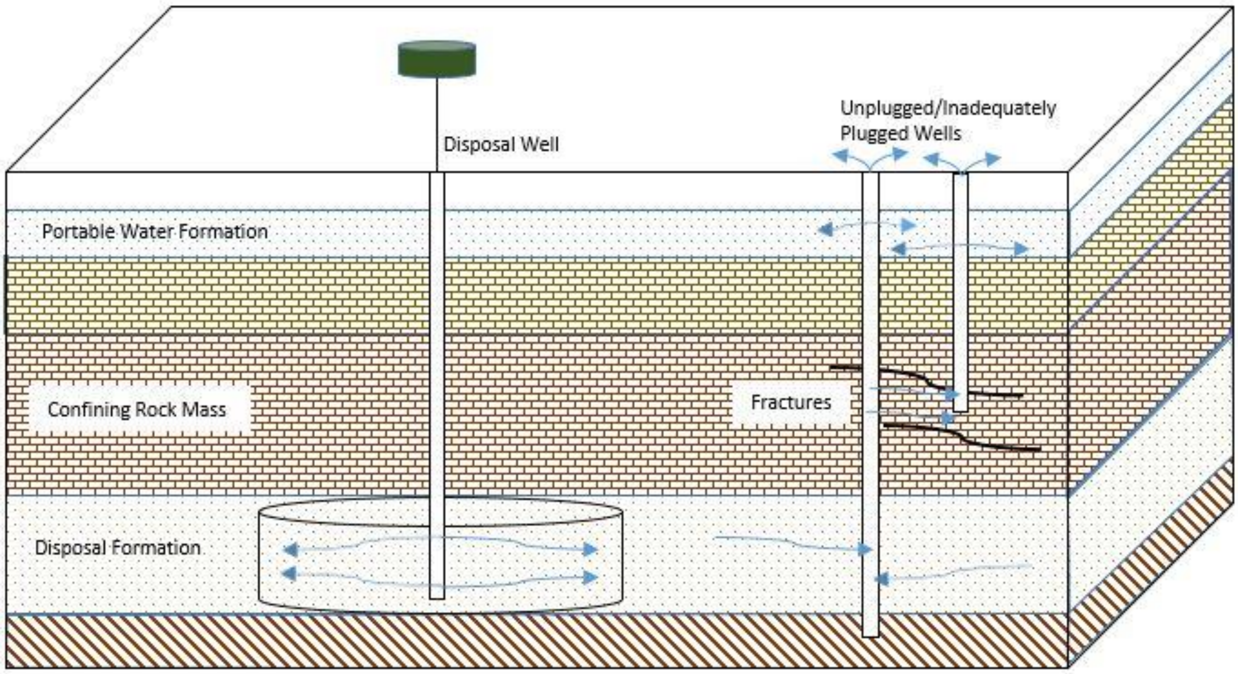

Figure 41: Unplugged/Inadequately plugged wells can cause environmental issues.

It should also be noted that some wells were inadequately plugged and will need to be plugged properly. Even the wells that were plugged properly were plugged to withstand normal reservoir pressure. High formation pressure from surface disposal can damage the plugging and pose environmental issues. Therefore, all the plugging within the vicinity of the well must be checked for stability against high imposed formation pressures.

4.3 Disposal Regulations

Deep well disposal operation is regulated under the Oil, Gas and Salt Resources Act, R.S.O. 1990. The regulations are enforced by the Ministry of Natural Resources and Forestry. This section describes the disposal regulations and recommendations relevant to the brine deposal study.

One of the potential strata for brine disposal is the Lucas Formation in the Detroit River Group. It contains 'lost circulation' zones that enhance permeability and makes the formation ideal for brine disposal. However, the Detroit River Group is located at shallow depths in most parts of southwestern Ontario and this may pose a potential environmental risk to freshwater sources. The regulation, under *R.R.O. 1990, Reg. 341, s. 7(2)*, states that no disposal should take place in the Detroit River Group within 8 km of the St. Clair River. Also, under *R.R.O. 1990, Reg. 341, s. 7(1)*, it states that no liquid industrial waste should be discharged into the Detroit River Group. These disposal regulations for the Detroit River Group were in response to several leakage incidents that occurred in the Sarnia region. In the late 1960's, industrial waste flowed to the ground surface, and brine was found at greater distances from the injection well (Raven et al., 1990). The leakage occurred due to flow through abandoned and improperly plugged wells that were drilled earlier in the 20th century in the search for oil and gas.

In addition to the regulations mentioned above, the Oil, Gas and Salt Resources Act also makes recommendations on proper practices for deep disposal. Some of the recommendations relevant to this study are:

- If possible, fluid should be injected by gravity feed with no applied pressure. However, if gravity feed is not feasible, lowest practical injection pressure should be applied. The applied injection pressure must not exceed 75% of the fracture gradient.
- The operator should isolate and protect formations containing potable water, oil and gas, and mineral deposits.
- The operator should ensure that fluid migration does not take place between permeable formations, and the fluid is contained within the disposal formation.
- Formation pressure at the midpoint of the disposal zone should not exceed 75% of the formation fracture pressure.

For more information on the regulations and recommendations, the reader is encouraged to visit the website of the Ontario Government and search for "Oil, Gas and Salt Resources of Ontario, Provincial Operating Standards."

4.4 Geological Setting

Sedimentary rocks in southwestern Ontario belong to the Paleozoic era, and overlie the Precambrian rocks of the southern margin of the Canadian Shield. Figure 42 shows a generalized bedrock geological map of southwestern Ontario; it is noticed that younger rocks outcrop in the southwesterly direction from the Canadian Shield margin to the southwestern Ontario margin.

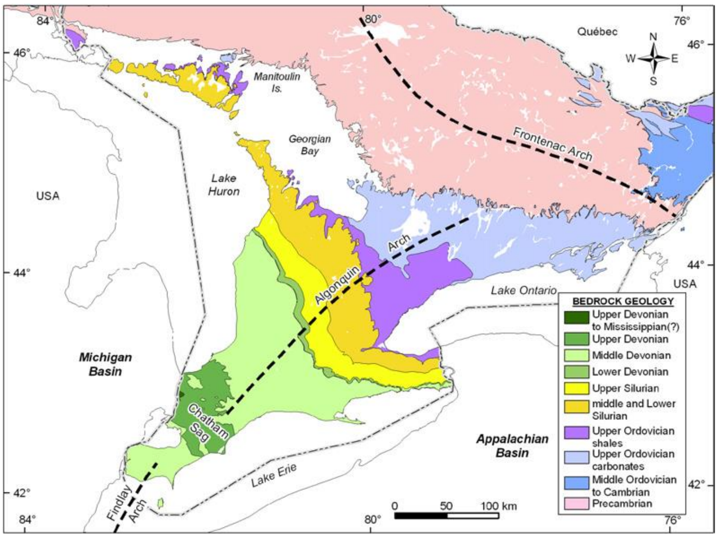

Figure 42: Generalized Paleozoic bedrock geology of southern Ontario (Armstrong and Carter, 2010).

Sedimentary strata in southwestern Ontario consist of two major sedimentary basins: the Michigan Basin and the Appalachian Basin (Figure 43). A northeast-southwest direction trending structurally high feature, the Algonquin Arch, separates these two basins throughout southwestern Ontario. The Findlay Arch, the tectonic equivalent of the Algonquin Arch in the United States, runs in the northward direction from Ohio. The Algonquin and Findlay Arch are separated through a structural low feature known as the Chatham Sag (Armstrong and Carter, 2010).

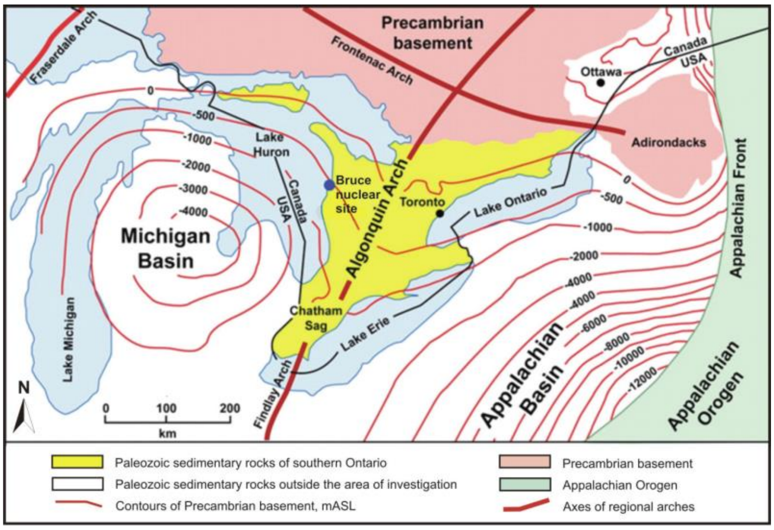

Figure 43: Michigan Basin and Appalachian Basin in southwestern Ontario (AECOM Canada Ltd. and Itasca Consulting Canada, Inc., 2011).

The Michigan Basin has a bowl-shaped geometry with its depositional center near Saginaw Bay in Michigan. At the center of the basin, sediment thickness approaches 4,800 m. The sedimentary strata in southwestern Ontario consist of the eastern flank of the Michigan Basin. Therefore, sediment thickness is far less in southwestern Ontario, with maximum sediment thickness reaching 1400 m. The Appalachian Basin is a foreland basin that was formed due to collisional tectonic events at the eastern edge of North America. Sedimentary strata in southwestern Ontario consist of the northern edge of the Appalachian Basin. The maximum thickness in the center of the Appalachian basin, not in Ontario, is 7,000 m; whereas, the maximum thickness of the Appalachian Basin in Ontario is approximately 1400 m. Since the Algonquin Arch separates these two basins, the beds dip away from the arch towards the center of these basins. A dip of 3 to 6 m/km is recorded in the southwest direction along the Algonquin Arch, and 5.5 to 8.5 m/km in the west direction and southward direction towards the center of the Michigan Basin and the Appalachian Basin, respectively (AECOM Canada Ltd. and Itasca Consulting Canada Inc., 2011).

Disposal formations in southwestern Ontario are located in strata of the Paleozoic era during which the Michigan Basin and the Appalachian Basin were formed. Paleozoic rocks are mainly made from marine sediments as southwestern Ontario was intermittently covered by basin-centered inland seas during the Paleozoic era. Due to the isolation of the Michigan Basin, rocks in the basin tend to be carbonate rich and also contain evaporite beds. However, due to the supply of clastic sediments from the highlands, rocks in the Appalachian Basin tend to be siliciclastic in nature (Armstrong and Carter, 2010).

The general stratigraphy of southwestern Ontario is shown in Figure 44. The figure is divided into three columns based on stratigraphy from northwest to southeast: Ontario’s portion of the Michigan Basin (eastern Michigan Basin), around the Algonquin Arch, and Ontario’s portion of the Appalachian Basin (western Appalachian Basin).

The disposal potential in southwestern Ontario is limited as compared to the areas in the United States that share the Michigan and the Appalachian Basins. This is indeed due to southwestern Ontario’s location on the flanks of the Michigan and Appalachian Basins; the sedimentary strata in southwestern Ontario are thin and limited in areal extent as compared to the thick and extensive strata in the neighbouring areas. Nevertheless, the sedimentary strata in southwestern Ontario contain a few formations that possess adequate brine disposal potential. The two rock strata that can take large quantities of brine are the Lucas Formation and the Cambrian age strata. Locally, other formations such as the Guelph, Bois Blanc, and Bass Islands Formations have limited potential as well (McLean, 1968). The Lucas Formation contains karstic networks, and has been extensively utilized for brine disposal. The Cambrian strata are mostly comprised of sandstone, and contains adequate porosity and permeability for large quantity of brine disposal. The Guelph Formation holds vast deposits of hydrocarbons and is also utilized for natural gas storage; it is recommended that brine should not be disposed in areas containing hydrocarbons and potential natural gas storage reservoirs.

However, if allowed by the regulations, the Guelph Formation can be utilized for brine disposal in depleted oil and gas reservoirs. The Bois Blanc and Bass Islands Formations have also showed water recoveries in limited areas, and these areas might offer limited brine disposal capacity. A thorough discussion of the disposal potential in the above noted formations is presented in section 4.9.3.

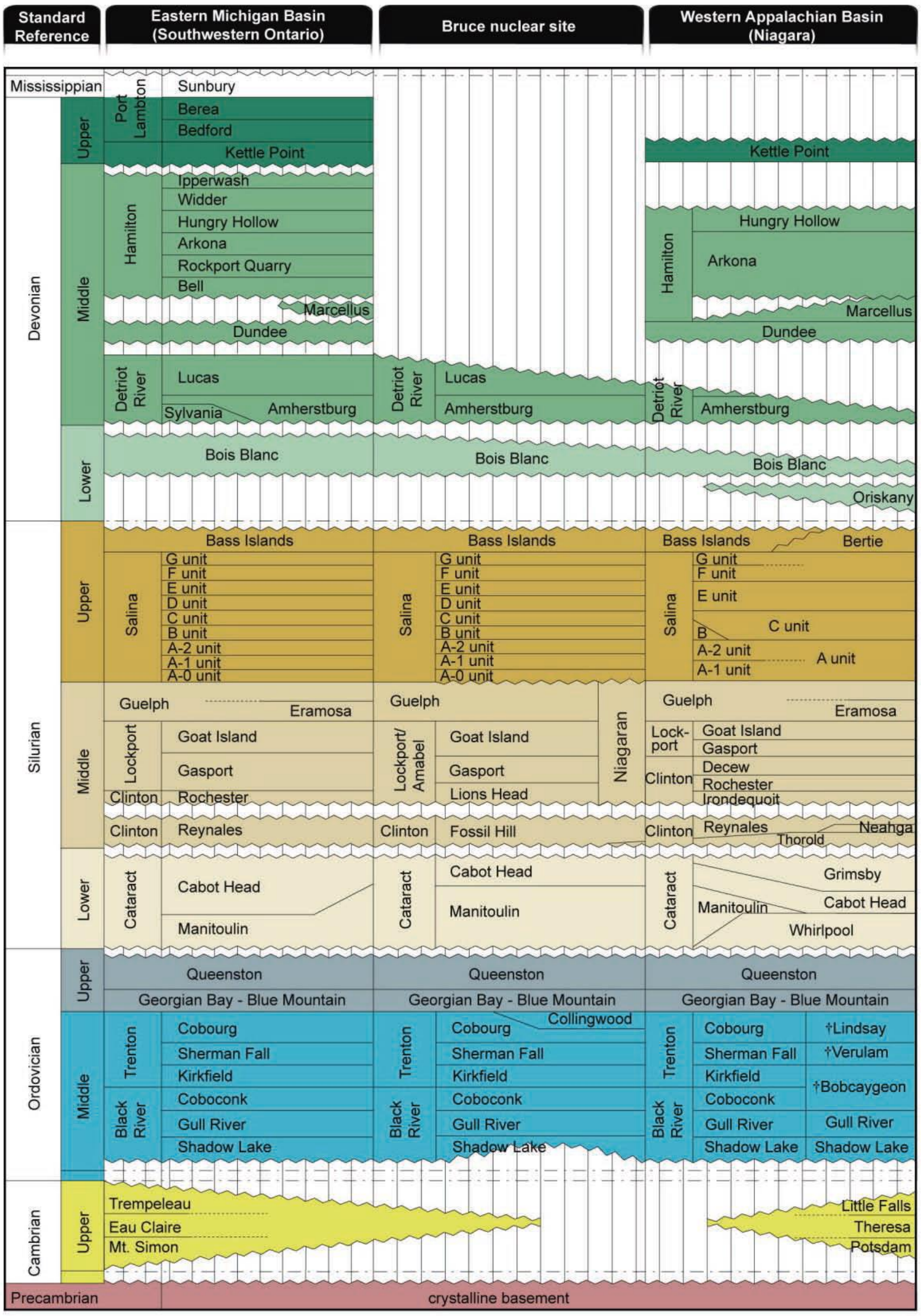

Figure 44: Paleozoic stratigraphy of southwestern Ontario (AECOM Canada Ltd. and Itasca Consulting Canada Inc., 2011).

4.4.1 Cambrian Age Strata

The Cambrian strata unconformably rest on the crystalline rocks of the Precambrian basement. The Cambrian strata cover limited areas in southwestern Ontario because of the presence of the Algonquin Arch. Figure 45 shows the isopach map of the Cambrian strata, along with the black dotted line that displays the depositional edge of the Cambrian rocks. It is thought that the Cambrian strata once covered the whole of southwestern Ontario. In the Cambrian period, sediments were deposited during the marine transgression over the southwestern Ontario's Precambrian basement that included the Algonquin Arch. However, post-depositional uplift of the Algonquin Arch led to erosion of the Cambrian sediments to present day configuration. Relative to the Algonquin Arch, the Cambrian Strata thickens and dips westwards towards the Michigan Basin and southwards towards the Appalachian basin. The Cambrian strata are unconformably overlain by Ordovician rocks; the unconformity is known as the "Knox unconformity" (Armstrong and Carter, 2010).

Rocks in the Cambrian strata are dominated by sandstone, and the three major rock types include, in ascending lithologic order, quartzose sandstones, interbedded sandstone and dolostones, and dolostones (Armstrong and Carter, 2010). The nomenclature of Cambrian strata is different in the Michigan Basin and the Appalachian Basin. The longitude of 81° W separates the nomenclature in southwestern Ontario, with west of 81° W belonging to the Michigan Basin and east of 81° W belonging to Appalachian Basin. Cambrian strata west of 81° W are known as, in ascending order, the Mount Simon, Eau Claire, and Trempealeau Formations. The Cambrian strata east of 81° W are known as the Postdam, Theresa, and Little Falls Formations (Figure 44). In this study, it is considered that these formations are correlative and the nomenclature of the Cambrian strata from the Michigan Basin is used to describe the physical characteristics of the formations. In fact, in the next few paragraphs it will be clear that the formations in the Cambrian strata show similar characteristics, and the Cambrian strata will be treated as a single unit.

The Mount Simon Formation is the oldest Cambrian strata encountered in southwestern Ontario. It is deposited only in certain counties: Essex, Lambton, Elgin, Norfolk, Huron, and Bruce Counties. In Essex County, it can be as much as 30 m thick, and in Elgin County, it can reach thickness of over 15 m. The Formation consists of white to light grey quartzose sandstone; typically, the basal sandstone is well-sorted and coarse-grained. Among all the Cambrian strata, the Mount Simon Formation contains the highest porosity and is the most permeable (McLean, 1968).

The Eau Claire Formation overlies the Mount Simon Formation. It has the largest areal extent in southwestern Ontario and covers parts of the following counties: Norfolk, Essex, Brant, Elgin, Kent, and Lambton Counties. It reaches thickness of more than 60 m in Lambton and Essex Counties. The formation consists of fine to medium-grained quartzose sandstone with interbeds of fine-crystalline dolostone and shaly dolostone. Due to the presence of carbonates and shale, the porosity and permeability values in the Eau Claire Formation are lower than values in the Mount Simon Formation (McLean, 1968).

The Trempealeau Formation overlies the Eau Clair Formation. It has a very limited areal extent in southwestern Ontario and covers parts of the following counties: Elgin, Kent, Lambton, and Essex Counties.

It can attain thickness of up to 45 m in the Michigan Basin counties and up to 30 m in the Appalachian Basin counties. The formation consists of buff, fine to medium crystalline dolostone. Compared to the other Cambrian formations, this Formation contains the lowest porosity and is the least permeable.

Due to relatively similar characteristics of the three Cambrian formations mentioned above, it is difficult to differentiate between them. Therefore, geologists tend to treat the Cambrian strata as a single unit. The petroleum industry has been treating the Cambrian strata as a single unit, and so do most of the well log interpretations for correlation analysis. The isopach and depth maps of the Cambrian age strata are displayed in Figure 45 and Figure 46, respectively. Section 4.8 on "Data collection and interpretation" explains the method used to create the isopach and depth maps. .

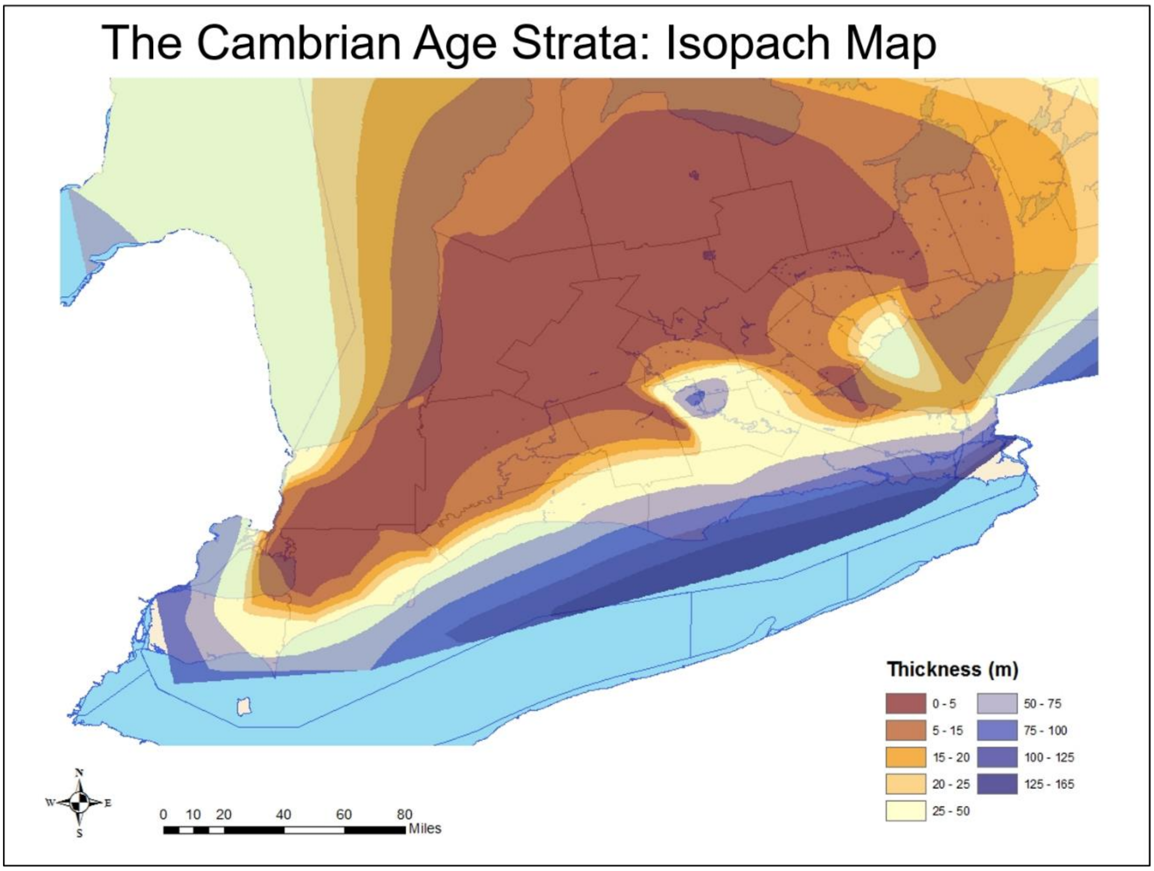

Figure 45: Isopach map of the Cambrian age strata (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

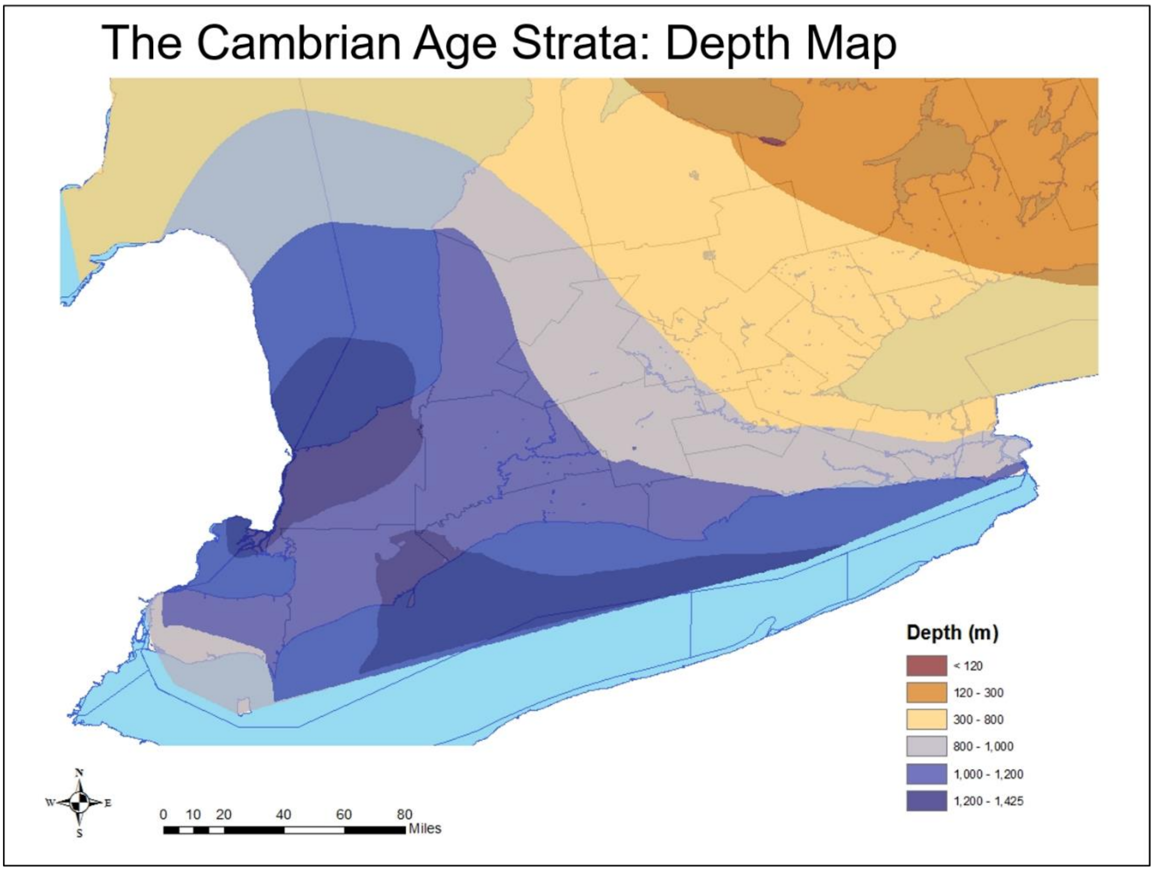

Figure 46: Depth map of the Cambrian age strata (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

Average porosity values in the Cambrian strata can range from 5 to 15%; however, values as high as 20% have been recorded in sandy facies. Permeability values in the strata average around 50 mD, although streaks of 250 mD are also recorded (McLean, 1968).

The limit for potable water is around 5,000 p.p.m. of total dissolved solids, and no disposal should take place near potable water sources. It is shown that the range of total dissolved solids in the waters of the Cambrian strata is 200,000 to more than 400,000 parts per million (p.p.m.). However, the Cambrian strata closer to the surface might have significantly lower total dissolved solid values, and exceptionally (locally and when shallow) might be suitable as a potable water resource.

4.4.2 Lucas Formation (Detroit River Group)

The Detroit River Group is from the Middle Devonian Period and is comprised of three formations: the Sylvania, Amherstburg, and Lucas Formations. Of these three formations, only the Lucas Formation is suitable for large volumes of brine disposal. In fact, in the past, the Lucas Formation was extensively utilized for deep disposal of petrochemical wastewaters. But due to environmental accidents in the late 1960s, new regulations prohibited disposal of industrial waste in the Lucas Formation within 8 km of the St. Clair River. The regulations still permit disposal of brine in the Lucas Formation, as long as the disposal site is 8 km away from the St. Clair River and the disposal operation does not pose contamination threat to formations containing freshwater, oil and gas, and mineral deposits.

The Lucas Formation conformably overlies the Amherstburg Formation and it is unconformably overlain by the Dundee Formation. It is comprised mainly of limestones and dolostones; however, anhydrite beds and local sandy limestones are also encountered (Armstrong and Carter, 2010). Typically, anhydrite beds thicken towards the center of the basin. In some areas of southwestern Ontario, especially towards the basin center, anhydrite beds have been dissolved and have created karstic features. These locations have very high permeability and have been termed as "lost circulation" zones.

Similar to other formations of the Michigan Basin, the Lucas Formation is thickest in the center of the basin. It attains a maximum thickness of 96 m in Sarnia and thins out southeastwardly towards Lake Erie (Armstrong and Carter, 2010). The isopach and depth maps of the Lucas Formation are displayed in Figure 47 and Figure 48, respectively.

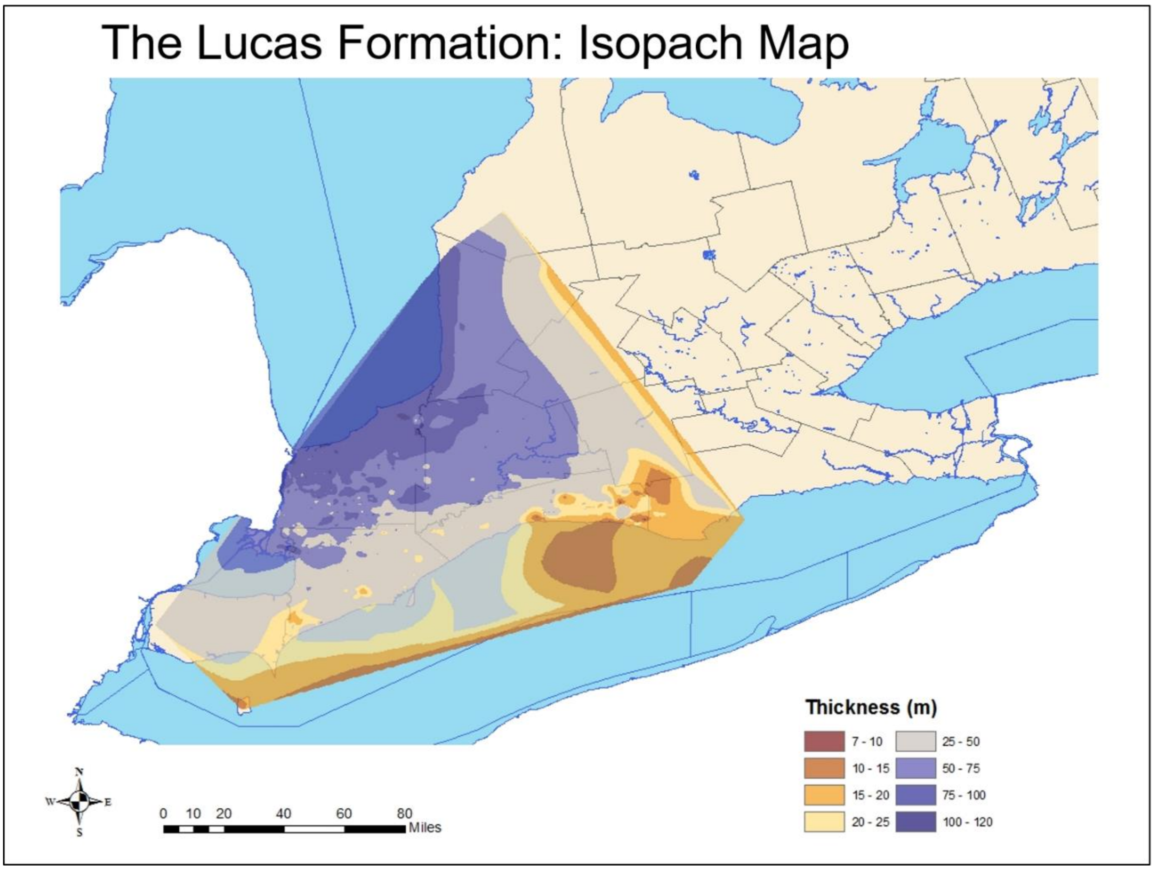

Figure 47: Isopach map of the Lucas Formation (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

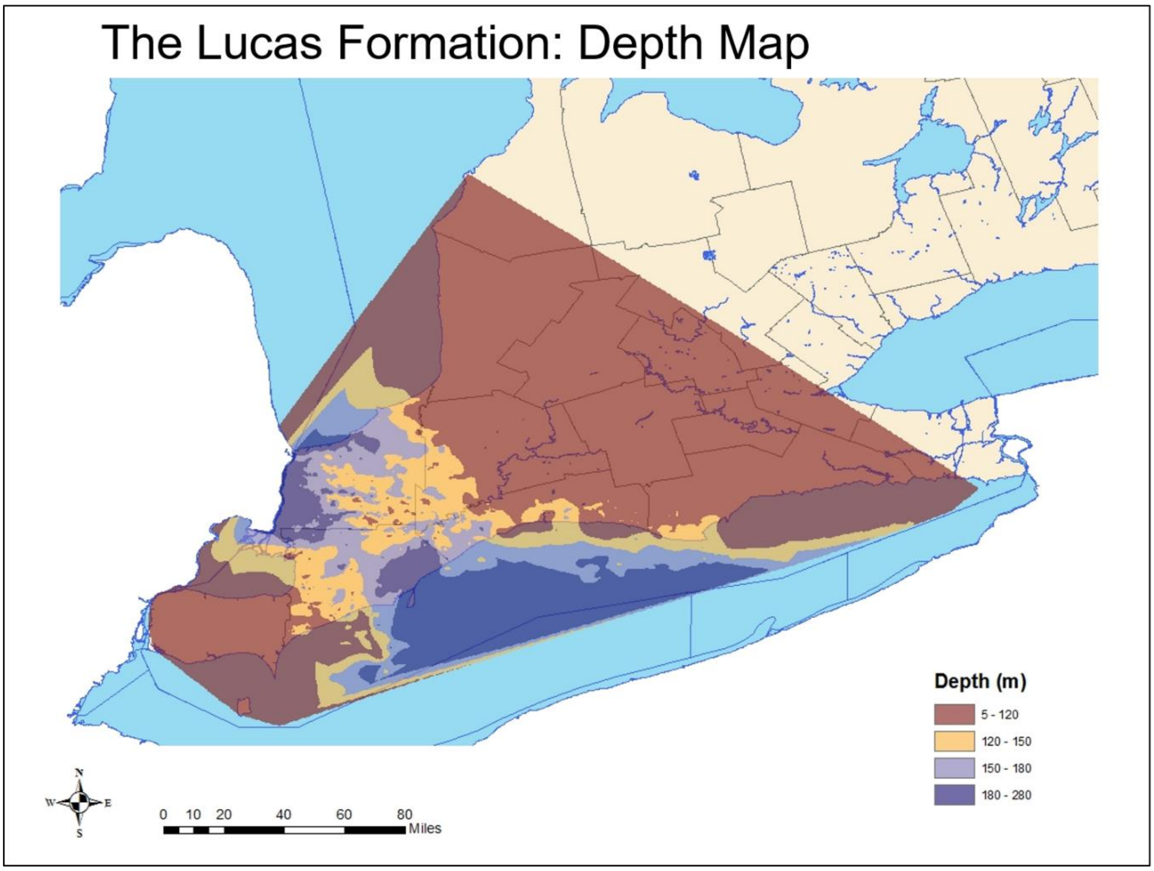

Figure 48: Depth map of the Lucas Formation (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

Permeability and porosity values are relatively high in Lambton and Kent Counties. Thick salt beds are present in the Salina Formation under these counties, and the differential dissolution of the salt beds created fractures in the Lucas Formation; hence, an improvement is seen in porosity and permeability values.

In Lambton County, the Lucas Formation has porosities ranging from 8 to 20% and permeability values ranging from 10 mD to 50 mD; streaks of over 200 mD are also present locally due to karstic features (McLean, 1968). Note that core data are limited for the Lucas Formation and very rare in counties other than Lambton.

4.4.2.1 Karstic Aquifers – Lucas Formation

Karstification refers to the dissolution of soluble rocks, such as carbonates and evaporites, from exposure to undersaturated water. Dissolution enhances the permeability of the soluble reservoir through enlargement of joints and fractures, and subsequently, formation of conduits and/or caves. Karstification normally occurs in shallow formations due to the presence of freshwater; karstic features found in deeper formations are known as paleokarst, and were formed during or soon after deposition. Permeability in paleokarst formations is largely reduced due to compaction from the overburden and infilling by mineral deposition of sulphates and carbonates as at the Bruce Deep Geological Repository (Intera Engineering Ltd., 2011).

Flow in karstic aquifers occurs due to three processes: matrix flow, fracture flow, and conduits/cave flow (Hurley et al., 2008). Matrix flow occurs through small pore spaces that are part of the primary porosity of the rock. Flow through the matrix is very slow, with flow rates of less than 1 m per day. Carbonate rock mass contains fractures as part of the secondary porosity, and these fractures are enhanced due to dissolution. Flow rate is high in fractures, with rates that can reach more than tens of meters per day. Dissolution in carbonates and evaporites can also create conduits and caves, where the flow rates are potentially quite rapid. Flow rates of more than 100 m per day are possible in conduits (Worthington, 2011).

In southwestern Ontario, karstic features/systems are present in the near-surface formations containing carbonates. The karstic formations in southern Ontario belong to the carbonate and evaporitic rocks from the Ordovician, Silurian, and Devonian ages. For brine disposal purposes, only the carbonate formation of the Devonian age is considered. The Lucas Formation, containing limestone and dolomite beds interbedded with anhydritic beds, is reported to be karstic. Hurley et al. (2008) reports that drill cores from boreholes in the Lucas Formation have consistently indicated the presence of karst. After deposition of the Lucas Formation, continental uplift drained the sea that had covered Ontario for millions of years, and this resulted in an unconformity between the Lucas Formation and the Dundee Formation. Hurley et al. (2008) suggested that the uplift and subaerial exposure could have created faults, fractures, and solution channels in the Lucas Formation. Figure 49 displays the areas underlain by known and inferred karst. A substantial area of southwestern Ontario is categorized under the ‘unknown’ category. Even though the ‘unknown’ area could not be mapped due to thick overburden, the drill cores and geologic history show that the Lucas Formation is potentially karstic in most of southwestern Ontario, especially in Lambton and Kent Counties.

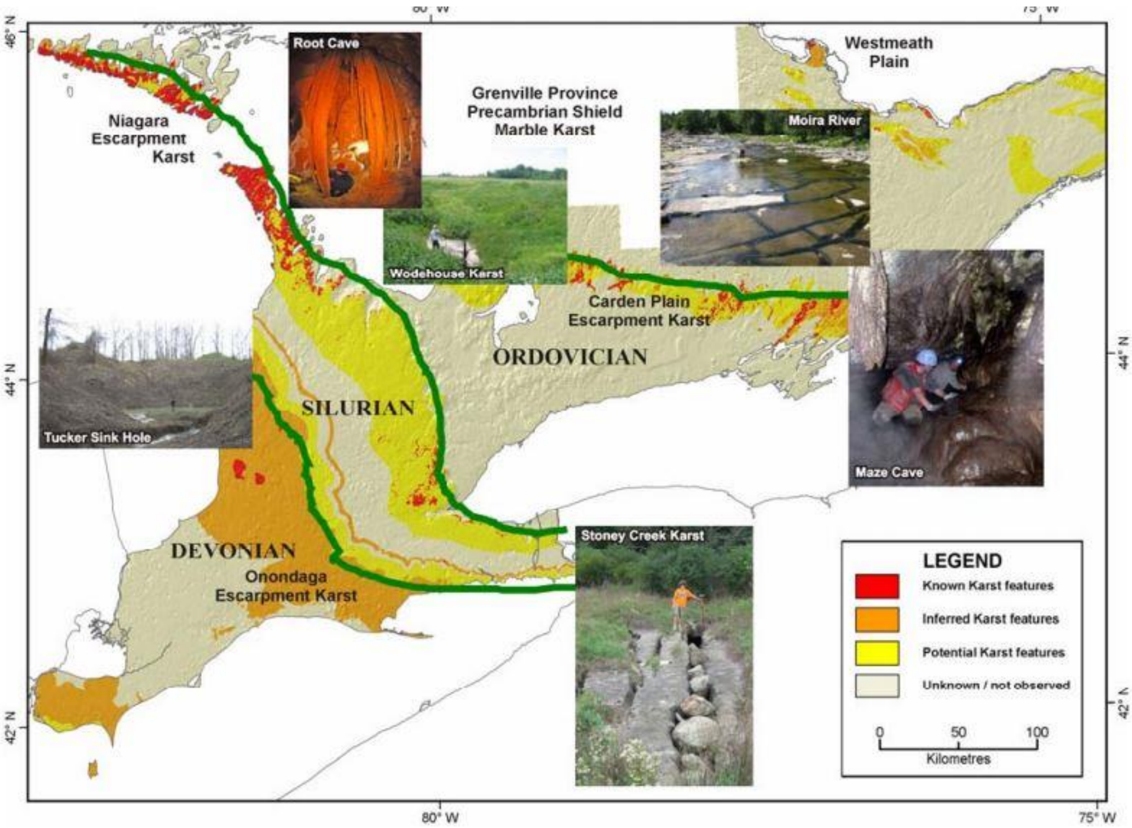

Figure 49: Areas underlain by karst in Ontario (Brunton and Dodge, 2008).

4.5 Multi-Criteria Analysis

Due to a large number of parameters involved in the rating of the brine disposal sites, a formal evaluation system must be developed to aid in decision-making. Multi-criteria analysis (MCA) is a decision-making tool that evaluates alternatives based on multiple criteria based on decision rules. There are three major components of the MCA: value scaling (criteria scoring), criteria weighting, and decision rule (Malczewski and Rinner, 2015). A major benefit of MCA is that it can include both quantitative and qualitative criteria, as long as the qualitative criteria can be scored on a continuous scale.

MCA involves two major methods: multiple-attribute decision analysis (MADA) and multiple-objective decision analysis (MODA) (Figure 50). The difference between MADA and MODA is the number of objectives; MADA is used when only one objective is defined, such as in site selection studies; MODA is utilized when multiple objectives are defined, such as in allocating land for housing, agriculture or industrial development. In this study, MADA is used as there is only one objective: evaluate and rank areas in southwestern Ontario for the potential of deep brine disposal.

MADA is further divided into non-compensatory and compensatory approaches based on if trade-off is allowed between criteria or not (Greene et al., 2011). The non-compensatory approach is used when trade-offs between criteria are not allowed; it is easier to implement and contains binary decisions such as 1 if passed or 0 if failed. However, most of the real-world scenarios require some extent of trade-off and compensatory approaches fit these situations the best. Even though there are many compensatory approaches, only one will be discussed and used in this study: the weighted linear combination (WLC).

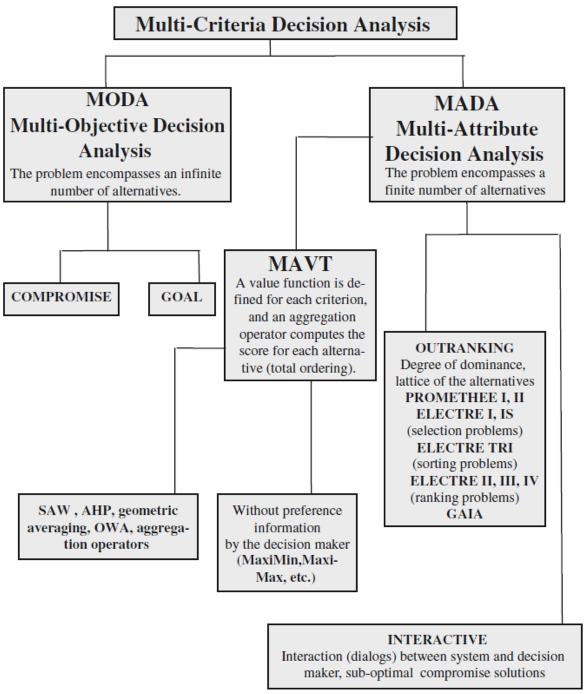

Figure 50: MCA can be classified into two major methods depending on the number of objectives: MODA and MADA (Giove et al., 2009).

WLC is a simple but effective technique to rate potential disposal sites. It works by multiplying the normalized criterion score (v_i) by the assigned criterion weighting (w_i) for each criterion and then summing the product over all criteria; the result is a total score for each site (Equation 8).

$$S(a) = \sum_i w_i * v_i(a)$$ **[Equation 8]**

where S(a) is the total score for each site a, w_i is the weighting factor for the i^{th} criterion, and $v_i(a)$ is the criterion score for the i^{th} criterion for each site a.

Normalized criteria scores will be assigned to each criterion. Criteria scoring is a mathematical representation of experts' judgement on the criteria. An example of criteria scoring is shown in Figure 51. The shape of the function in the criteria scoring graph is determined by the opinions of experts. In this study, scores between 0 to 100 will be assigned; 0 will mean the least suitable and 100 being the most suitable.

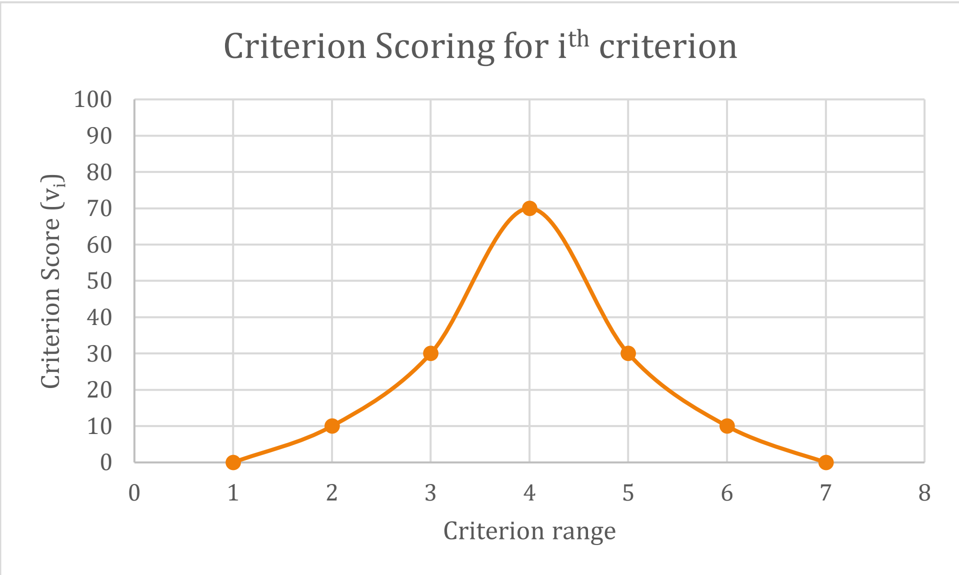

Figure 51: Example of criterion scoring; horizontal axis is criterion range and vertical axis is criterion score.

Each criterion will be assigned a weighting factor. This will allow a comparison between multiple criteria used in the disposal study. The weighting factors will be assigned based on opinion of experts. In this study, a weight factor between 0 and 1 is given to each criterion; the sum of the weights for all criteria will equal to 1. Higher weights will represent more importance and vice versa. In a case of n criteria, a set of weighting factor and the sum of weighting factors are defined as:

$w = (w_1, w_2, w_3, \ldots, w_k, \ldots, w_n)$ and $\sum w_k = 1$ **[Equation 9]**

4.6 Decision Tree

The aim of the decision tree used in this study is to provide an assessment of whether the site should be considered for further investigation. Figure 52 displays the decision tree for brine disposal in southwestern Ontario. It incorporates the parameters listed in section 4.2 and returns the following two decisions: 1) suitable and 2) unsuitable. Since the decision tree has a 'go' or 'no-go' approach, it does not describe the level of suitability of a particular parameter. For sites that pass the decision tree by falling into the "suitable" category, a detailed evaluation is carried out using the MCA developed in the previous section. The next sections will show the application of the MCA on sites in southwestern Ontario. It should be noted that due to limited data availability, only the following parameters are considered for pass/fail decision: permeability, porosity, depth, and thickness of the disposal formation. These parameters provide a "first-order" assessment as to whether the site should be considered for detailed evaluation. In future studies, if data are available, other parameters demonstrated in the decision tree should be also be considered.

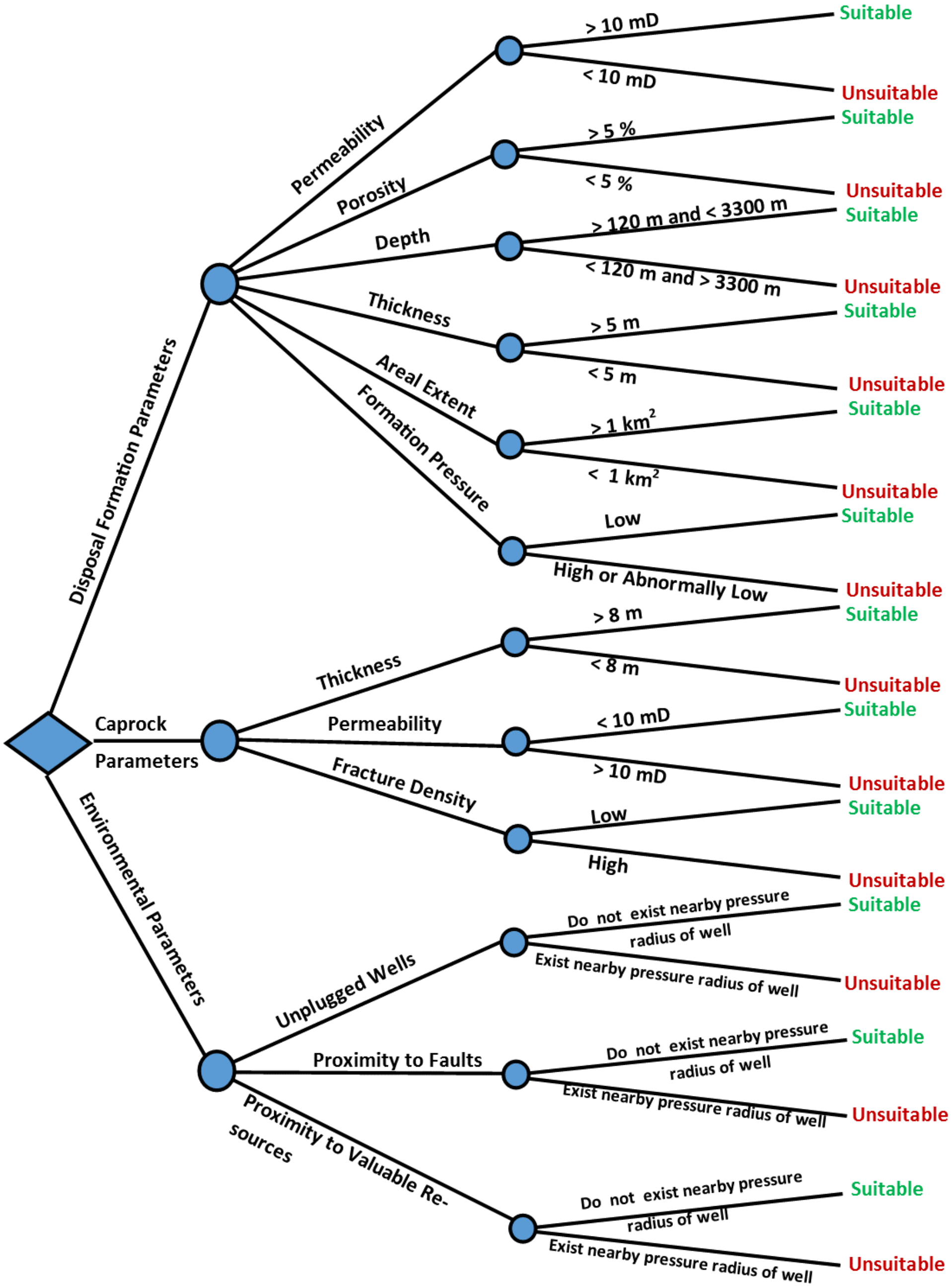

Figure 52: Decision tree for brine disposal in southwestern Ontario.

4.7 Criteria Scoring and Weighting

A major step for evaluating and comparing the potential disposal sites is generating standardized scores for important criteria and providing a weighting factor for each criterion. The scores and weights are developed through discussion with experts, information gathered from the literature, and performance of previous disposal wells. Due to the time involved, a formal expert elicitation and analysis are not part of this study.

It should be noted that the MCA methodology created in this study can be applied to other areas in the world. The parameters used in the MCA to assess brine disposal potential are of primary importance and will need to be considered in all disposal potential studies. However, the weight and scoring for criteria can be adjusted.

The criteria used in the MCA are selected from the various feasibility parameters that were discussed previously in section 4.2. Because of limited data availability and the large extent of the study area, only the most relevant parameters were chosen for scoring and weighting process: permeability, porosity, depth, thickness, disposal formation lithology, and caprock lithology. The criteria included in the evaluation system should provide a first order estimate of the brine disposal potential in southwestern Ontario.

In future studies, if detailed investigation is warranted for a limited number of sites, it is recommended to incorporate other criteria in the MCA as well: areal extent and formation pressure of the disposal formation; strength, thickness, and continuity of the confining rock mass; proximity to faults and tectonic history of the area; proximity to valuable resources such as potable water, oil and gas, and mineral deposits; and presence of unplugged or inadequately plugged wells in the vicinity of the disposal site. Of course, the detailed investigation should be conducted when disposal sites are narrowed down to a few suitable sites. Detailed investigation will require access to sufficient well logs to create geological subsurface models, lab testing equipment for identifying strength parameters, and field testing technology for identifying unplugged wells in the vicinity of the disposal site.

The following sections will discuss scoring and weighting for criteria in the MCA system. The criteria are scored out of 100 and weights are out of 1 as the total sum of weights for the criteria is 1.

4.7.1 Scoring and Weighting: Permeability

Permeability is given the highest weight of 0.25 as the overall goal of the project is to transmit brine through the formation. Table 4 shows the permeability scoring approach and Figure 53 displays the scoring on the graph. Permeability values of more than 100 mD are preferred for large volume of brine storage. In southwestern Ontario, permeability values for the potential disposal sites average around 50 mD; however, near the Sarnia region, the Lucas Formation contains karstic features that have much larger permeability. Since the location of karst is not mapped yet, the sites that show a potential for karst are given an additional weight of 0.10. This additional weight will allow the potential karstic sites to be rated higher when comparing to non-karstic sites from the same formation or other formation.

Table 4: Criterion scoring for permeability.

Permeability (mD)	Score
<10	0
10 – 50	0 - 20
50 - 100	20 - 40
100 – 500	40 - 60
500 – 1000	60 - 80
1000 - 2000	80 - 100
>2000	100

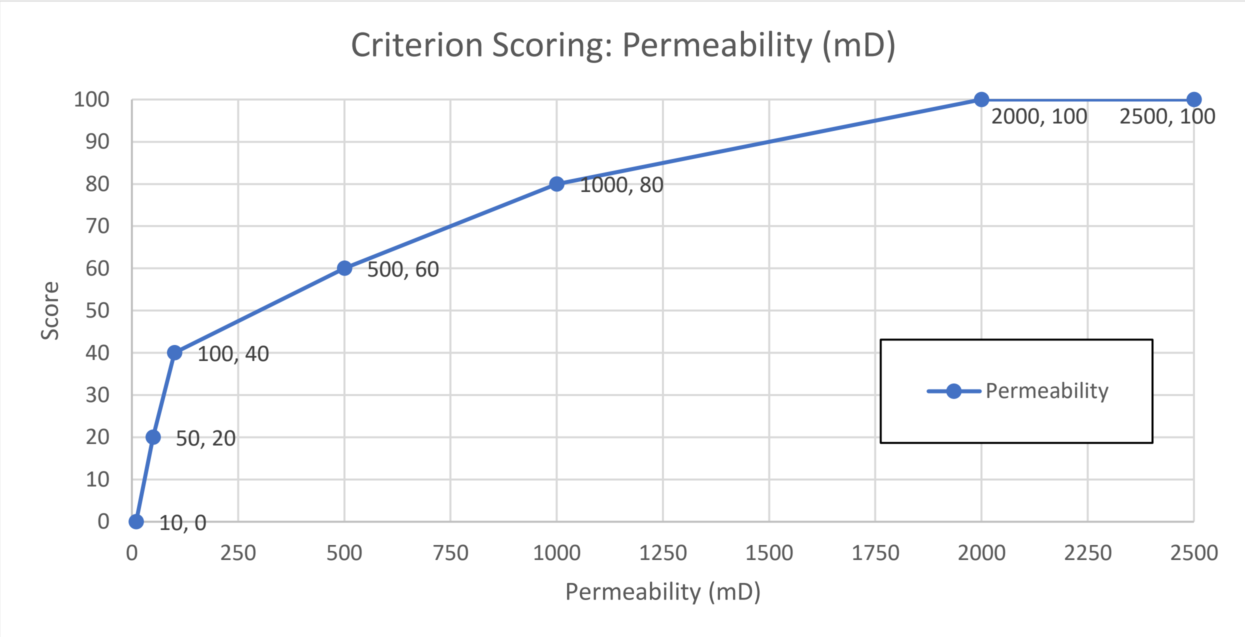

Figure 53: Graph displaying scoring for permeability.

4.7.2 Scoring and Weighting: Porosity

Porosity is assigned a weighting factor of 0.20 and is an important characteristic as it signifies the storage capacity of a formation. Porosity values of 15 % or greater are preferred for large disposal operations. In southwestern Ontario, porosities up to 20 % are encountered in the Lucas Formation and the Cambrian strata. Table 5 shows the scoring for porosity and Figure 54 displays the scoring on the graph.

Table 5: Criterion scoring for porosity.

Porosity (%)	Score
< 5	0
5 – 10	0 – 40
10 – 15	40 – 60
15 – 20	60 – 80
20 – 30	80 – 100
> 30	100

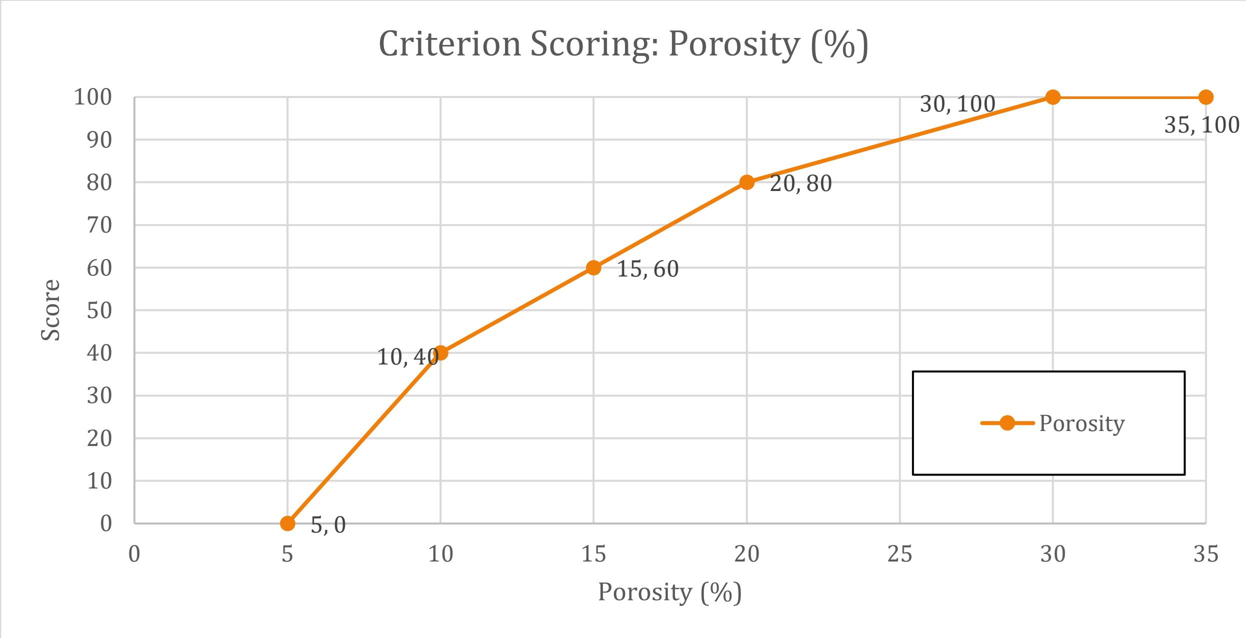

Figure 54: Graph displaying scoring for porosity.

4.7.3 Scoring and Weighting: Thickness

The thickness of the formation is the third most important parameter as the injection pressure and storage capacity are directly related to thickness. It is given a weighting of 0.15. Table 6 shows the thickness scoring approach and Figure 55 displays the scoring on the graph. Thickness of greater than 15 m is given a high score as a disposal formation with 15 m of thickness and a large areal extent can store an adequate volume of brine. Potential disposal formations in southwestern Ontario are thick and receive a high score in this category. As a reference, the Lucas Formation can be up to 96 m thick in the Sarnia region.

Table 6: Criterion scoring for thickness.

Thickness (m)	Score
< 5	0
5 – 10	0 – 25
10 – 15	25 – 50
15 – 20	50 – 75
20 – 25	75 – 100
> 25	100

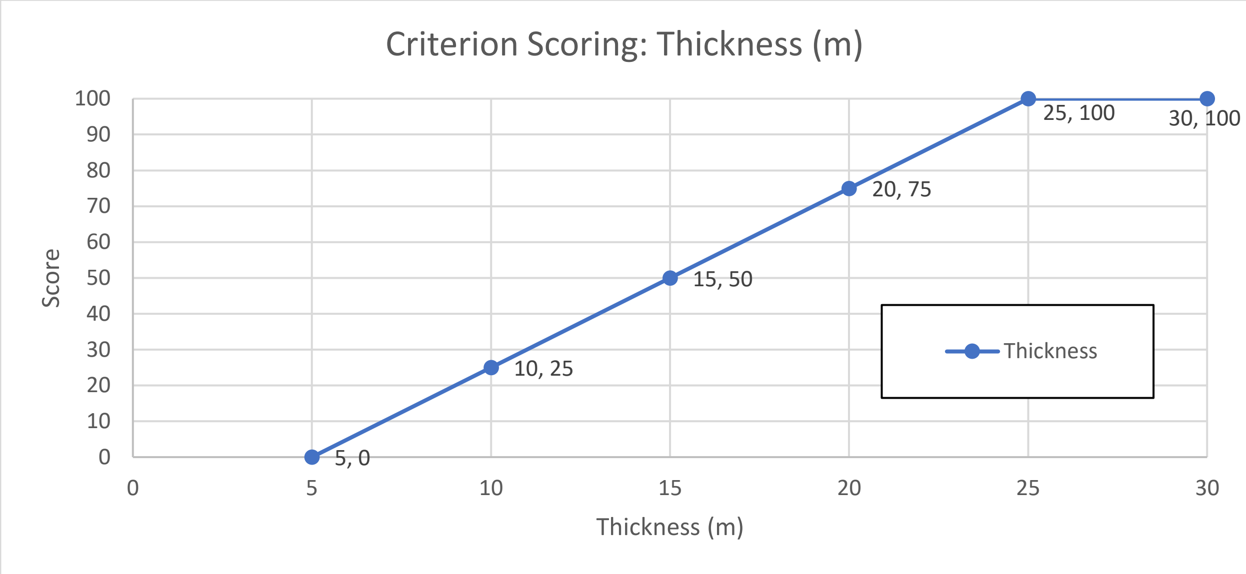

Figure 55: Graph displaying scoring for thickness.

4.7.4 Scoring and Weighting: Depth

Depth to the disposal formation is given a weight of 0.15. The shallower limit of depth is an important number as some environmental issues are related to shallow formations. At shallow depths, injection pressures must be kept in check as the caprock can be breached if the formation stresses are low and the injection pressures high (exceeding the fracture pressure of the strata). Also, freshwater is encountered at shallow depths, and it must be protected. Therefore, disposal strata at depths of less than 120 m are given a score of 0. In fact, disposal at less than 180 m should be performed with extreme caution and should be carried out with a strong monitoring program. Table 7 shows the scoring for depth and Figure 56 displays the scoring on the graph. Formations deeper than 300 m are given a high score as they can support relatively high injection pressures and do not typically pose a threat to freshwater sources. The deeper limit of depth is not as important as the shallower limit; one issue related to the deeper limit is that drilling costs are high for deeper caverns. In southwestern Ontario, the shallower limit of depth is an issue. The Lucas Formation in the Sarnia region is located at shallow depth, and injection in those areas must be performed with caution.

Table 7: Criterion scoring for depth.

Depth (m)	Score
< 120	0
120 - 150	0 – 20
150 - 180	20 – 40
180 - 300	40 – 80
300 - 400	80 – 100
400 – 800	100
800 – 1300	100 – 80
1300 – 1800	80 – 60
1800 – 2300	60 – 40
> 3300	0

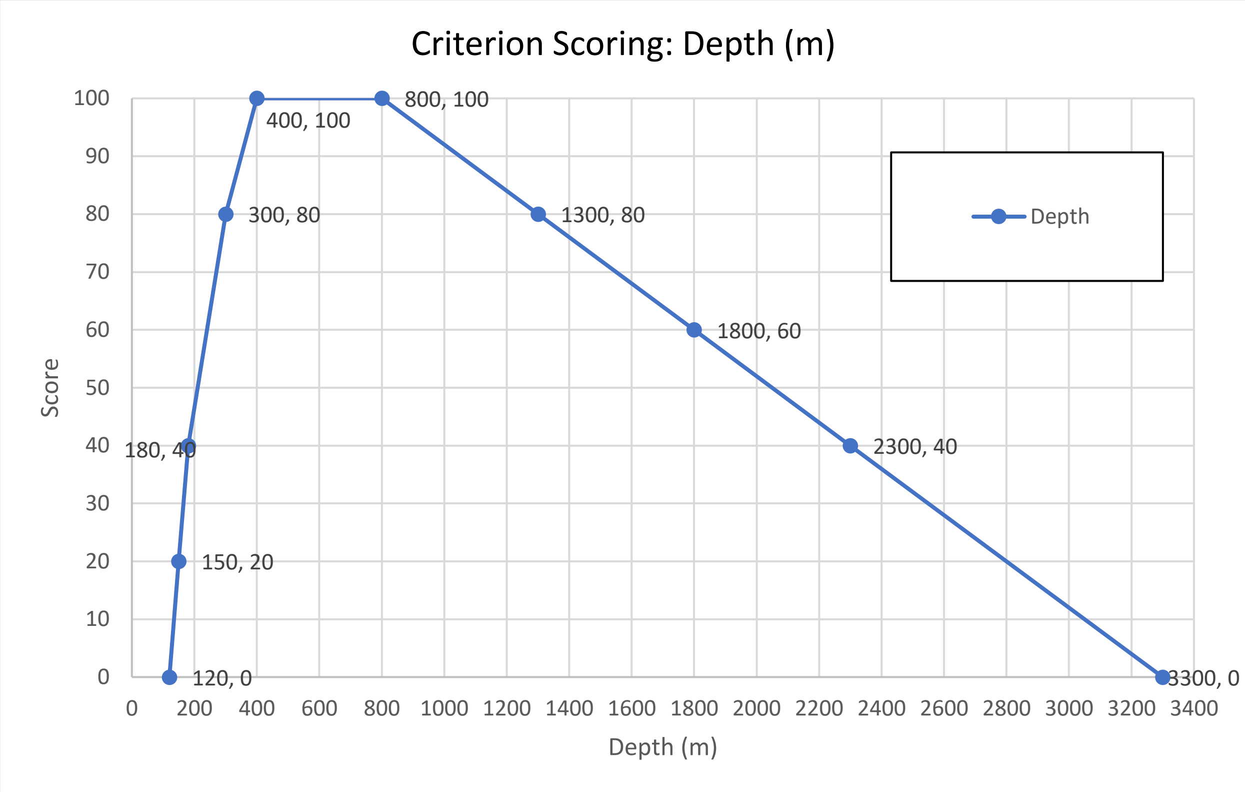

Figure 56: Graph displaying scoring for depth.

4.7.5 Scoring and Weighting: Disposal Formation Lithology

Disposal formation lithology is assigned a weight of 0.10, and it gives an initial measure of the disposal potential in the formation. The ideal formation should consist of sandstone, limestone or dolomite. Compared to the other rocks (e.g., shales, mudstones, etc.), these rocks tend to have larger permeability and porosity values. Table 8 displays the scoring chart for the disposal formation lithology. Formations containing medium to coarse grained sandstone and carbonates are given high scores; whereas formations containing shale interbeds are given a relatively low score.

Table 8: Criterion scoring for disposal formation lithology.

Disposal Formation Lithology	Score
Medium to coarse-grained sandstone; porous carbonates (shelf setting)	100
Fine to medium-grained sandstone; carbonates: limestone and dolomite	80
Sandstone with shale interbeds	60
Carbonates with shale interbeds	40
Fractured shale	20
Shale; dense crystalline limestone; igneous or metamorphic rocks	0

4.7.6 Scoring and Weighting: Caprock lithology

Caprock lithology is an important criterion as the caprock acts as a barrier to the formation fluid and stops the fluid from escaping the disposal formation. It is assigned a weighting factor of 0.15. An ideal caprock is impermeable, strong, thick, and laterally extensive. In this study, the caprock lithology is selected as a criterion as it provides a qualitative idea of the strength and permeability characteristics of the caprock. In future studies, where a detailed investigation is required, the thickness and lateral extent of the caprock should also be considered. Typically, the caprock in southwestern Ontario, for the Lucas Formation and the Cambrian strata, are laterally extensive and meet the minimum thickness requirement of 8 m.

Table 9 displays the scoring chart for the caprock lithology. Shale and dense rocks are given the highest score due to their ability to trap fluid in the formation. Even fine-grained rocks can provide an acceptable seal since the pore radius is small, and that limits flow through the pores.

Table 9: Criterion scoring for caprock lithology.

Caprock Lithology	Score
Shale	100
Dense crystalline carbonates; shale and carbonate interbeds	80
Dense carbonates with shale interbeds	60
Dense sandstone or siltstone	20
Fractured rock mass	0

4.8 Data Collection and Interpretation

4.8.1 Depth and Isopach Data

Depth and isopach maps for the Lucas Formation and the Cambrian age strata were generated from the data obtained from the Ontario's Oil, Gas and Salt Resources (OGSR) library. The data repository of the OGSR library holds records of thousands of wells drilled in Ontario. The depth maps were generated from the "depth to the formation top" data and applying the Kriging function in the ArcMap. The isopach maps were generated by subtracting the "depth to the formation top" data from the "depth to the formation bottom" data and applying the kriging function in the ArcMap.

4.8.2 Porosity and Permeability Data

Petrophysical properites, i.e., porosity and permeability, are ranked high in terms of factors that influence a site's brine disposal potential. Porosity data can be acquired relatively easily from well logs through the neutron logs and density logs; these logs are readily available from the OGSR library. However, permeability data are scarce due to lack of core logging and well testing.

From experience in the oil and gas sector, it has been demonstrated that for a given formation a relationship usually exists between porosity and permeability. Nelson (1994) argues that in most sedimentary rocks, it can be said that the logarithm of permeability (log k) is linearly proportional to porosity (ϕ); the log k- ϕ relationship can be expressed by the equation: $\log k = m\phi + b$. The intercepts (b) and slopes (m) can vary depending on depositional and diagenetic factors. These factors include grain size, grain sorting, surface area, pore dimension, and cementation.

Figure 57 displays common processes and factors that affect the porosity-permeability relationship. Compaction due to overburden stress reduces porosity and permeability after initial deposition. Alternatively, dissolution increases porosity and permeability of a reservoir. Dissolution of the carbonate reservoir in the Lucas Formation has resulted in karstic features with high porosity and permeability. Larger grain size increases permeability even though porosity is decreased; whereas finer grain size decreases permeability even though porosity is increased. Finally, cementation or presence of clay decreases the porosity and permeability of the reservoir.

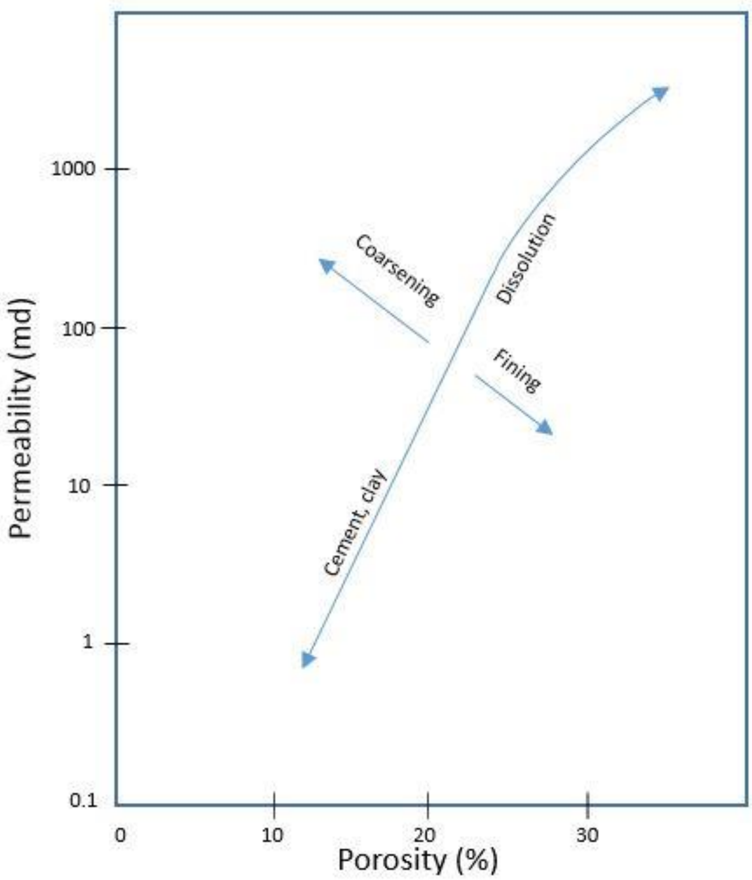

Figure 57: Factors that affect porosity-permeability relationships (Adapted from Nelson, 1994).

The empirical equations and porosity-permeability relation graphs are created using one or more of the following factors: grain size, pore radius, surface area, and water saturation (Nelson, 1994). If this information is not available, then the porosity-permeability relationship from a similar formation can be utilized to obtain an estimate of permeability. In this study, wherever core logs are not available, the permeability values are estimated from porosity-permeability graphs of other formations with similar properties.

For sites in the Cambrian strata, where core logs are not available, the permeability values are estimated from the porosity-permeability relationship of sandstones from the Jurassic Dogger Beta sandstone (Figure 58). The lithology and the diagenetic history of this formation is similar to the Cambrian strata. In fact, the log k - ϕ relationship from the Jurassic Dogger Beta sandstone matches very closely with the log k - ϕ relationship obtained from a core log for the Cambrian strata in Lambton County (Figure 59).

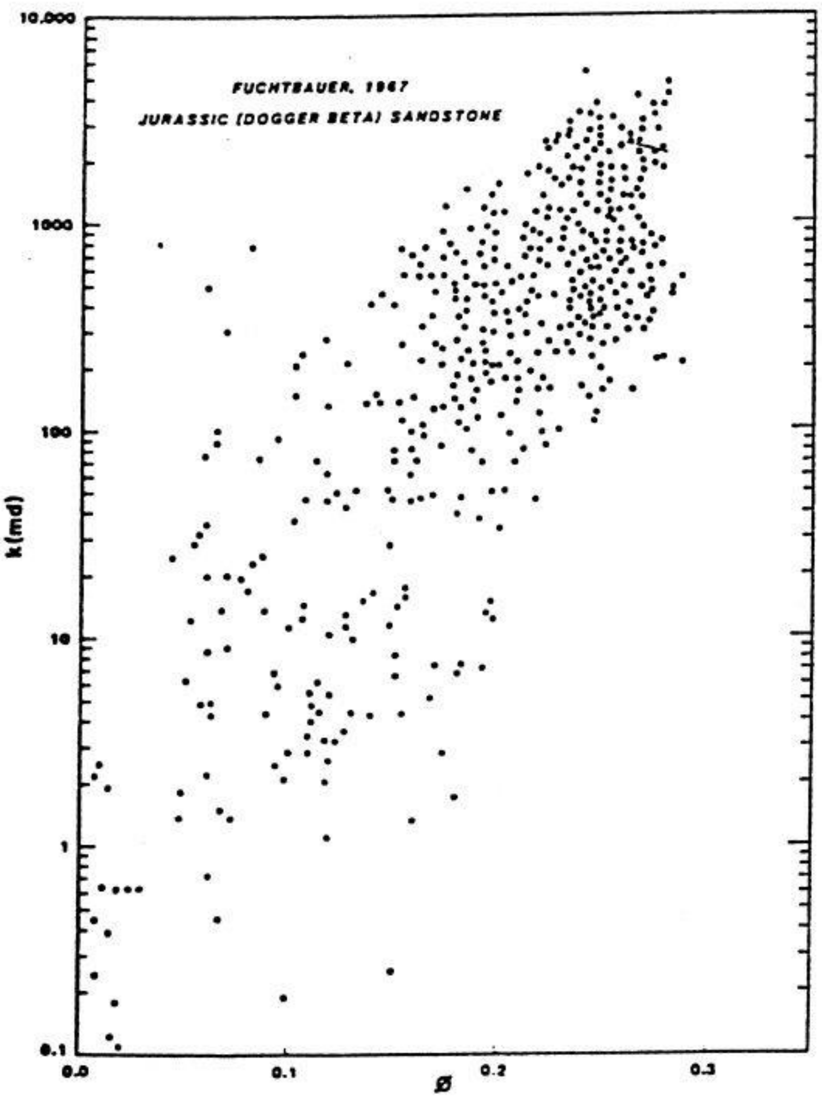

Figure 58: Porosity-permeability relationship used for the Cambrian strata based on the relationship published by Fucbtbauer (1967).

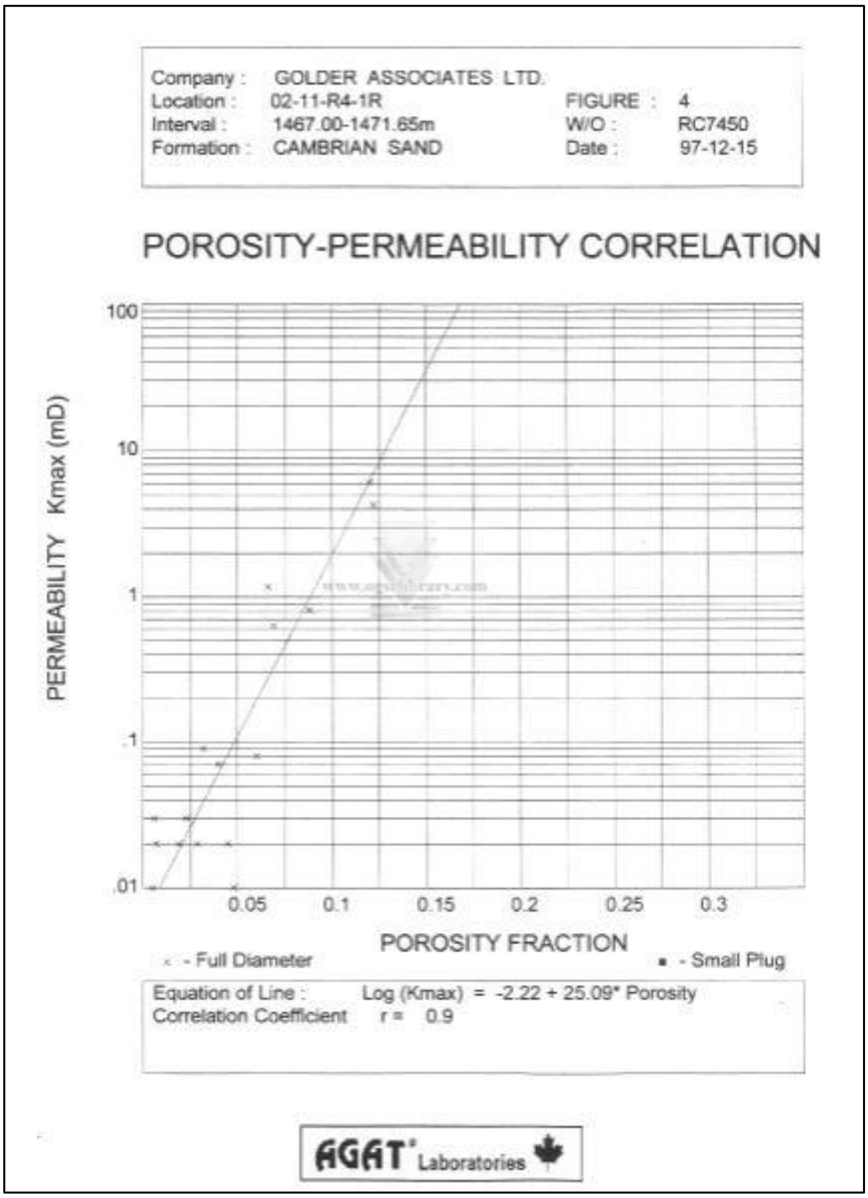

Figure 59: Porosity-permeability relationship of a core from Lambton County (source: OGSR library database).

The Lucas Formation is mainly comprised of limestones and dolostones, and the porosity-permeability relationship can be estimated from Figure 60. Nelson (1994) suggests that not much information is available for porosity-permeability relationship in carbonate rocks. However, given particle size and porosity, a reasonable estimate of permeability can be made from the porosity-permeability relationship published by Lucia (1983) (Figure 60). In reality, estimating permeability in the Lucas Formation is not a trivial task as the formation is dominated by karst. As discussed before in the section on karst, the location of karst is not entirely mapped yet, and a large part of southwestern Ontario falls under the 'unknown' category on the karst map published by Ontario Geological Survey (Figure 49). Additional weighting is assigned to sites that have potential for karst. When comparing sites for detailed investigation, the disposal companies will need to perform a site-specific investigation to obtain important information on permeability.

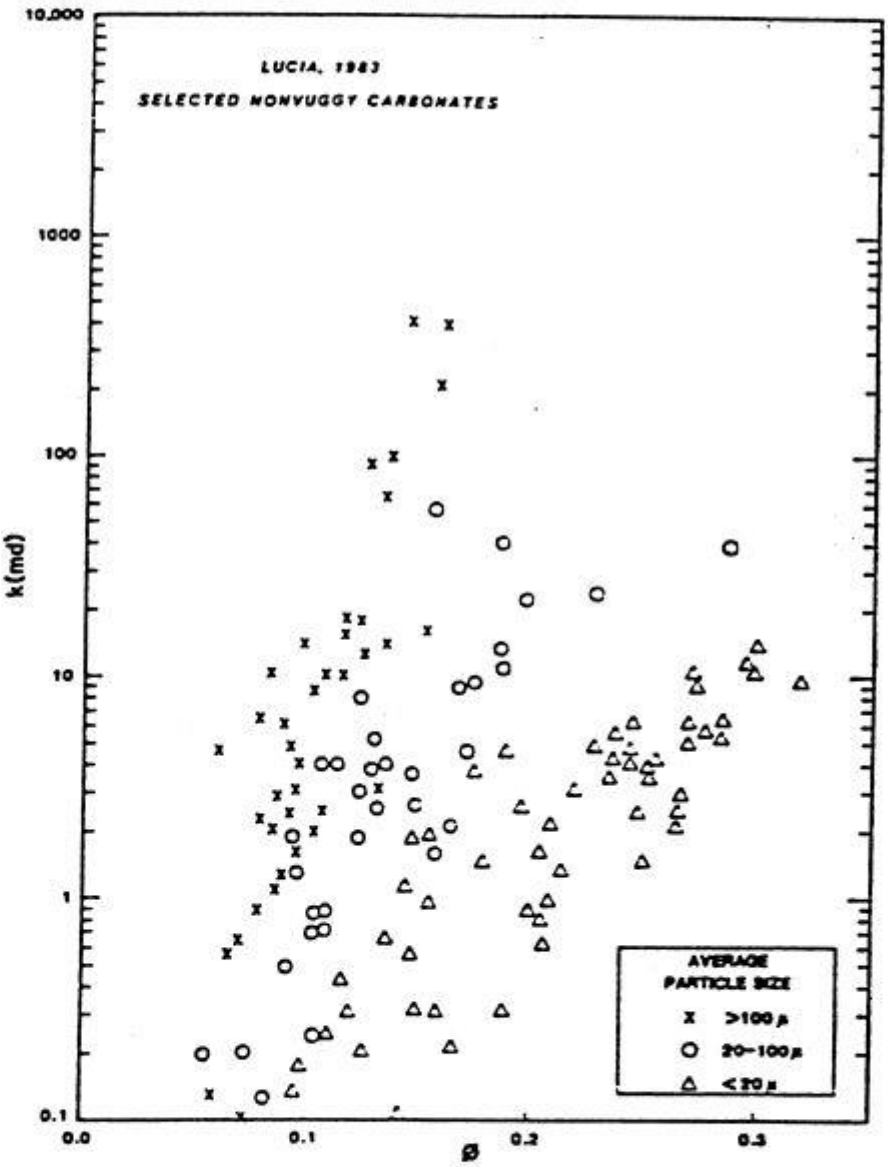

Figure 60: Porosity-permeability relationship used for the Lucas Formation based on the relationship published by Lucia (1983).

4.8.3 Other Data: Petroleum Pools, Disposal Formation Lithology and Caprock lithology

The OGSR library was consulted to obtain maps of the petroleum pools. Disposal formation lithology and caprock lithology were obtained from a book by Armstrong and Carter (2010), the subsurface Paleozoic stratigraphy of southern Ontario, and well logs from the OGSR library.

4.9 Results and Discussion

The MCA evaluation system was applied to various strategically chosen sites in southwestern Ontario. Appendix C shows the MCA evaluation tables for the sites in the Lucas and the Cambrian Formations. Appendix D shows examples of well cards that were used in the MCA evaluation system; only a few well cards are presented in the appendix as it is not practical to include all the well cards used in the study. The sites evaluated in the MCA system have gone through the initial suitability test and passed the decision tree shown in section 4.6.

An attempt was made to select and evaluate at least one site per township. However, the well logs are spread unequally due to a large concentration of wells in the potential oil and gas areas, and lack of drilling in the other areas. To counter this situation, interpolation is used around the sites with sufficient data. The disposal potential results are presented by formation. Therefore, two result maps are generated: 1) Cambrian strata disposal potential result (Figure 61) and 2) Lucas Formation disposal potential result (Figure 63).

The evaluation results were divided into 4 categories:

- S1 – Suitable, Level 1: This category was assigned to sites that achieved a score of more than 65 in the MCA evaluation system. Typically, to be a part of this category, sites have to display relatively high permeability and porosity values.
- S2 – Suitable, Level 2: This category was assigned to sites that scored between 45 and 65 in the MCA evaluation system. Sites in this category tend to have lower permeability and porosity values as compared to the S1 category.
- P – Potentially Suitable: This category is assigned to sites that lack porosity and permeability data, but otherwise, show potential for disposal based on depth, thickness, disposal formation lithology, and caprock lithology.
- X – Unsuitable: This category is assigned to sites that do not meet the minimum criteria for one or more of the following parameters: depth, thickness, permeability, porosity, disposal formation lithology, and caprock lithology.

4.9.1 Cambrian Age Strata

During the late 1960s, industrial waste and brine from a few disposal wells escaped to the surface in the Sarnia region. All of these wells were located in the Lucas Formation. This prompted industry to look into alternative disposal options, such as, utilizing the Cambrian age strata (Kent, Brown and Bentley, 1986).

One of the major advantages of the Cambrian strata over the Lucas Formation is its relatively greater depth. The majority of the areas in the Lucas Formation received a poor score in the depth criterion as the Lucas Formation is less than 120 m in most of southwestern Ontario. However, the depth of the Cambrian strata is greater than 500 m in most of southwestern Ontario and does not pose groundwater or surface water contamination issues.

The general disadvantages of the Cambrian strata over the Lucas Formation are limited thickness, high formation pressure, and low permeability. A large part of southwestern Ontario is not suitable for disposal into the Cambrian strata due to the thickness of the strata being less than 5 m. It is also reported that the Cambrian strata is over pressurized, which might lead to large operational costs. Furthermore, the permeability values in the Cambrian strata are relatively less than the Lucas Formation as it does not contain karstic networks.

Figure 61 displays the areas that fall under the four disposal categories: suitable – level 1, suitable – level 2, potentially suitable, and unsuitable.

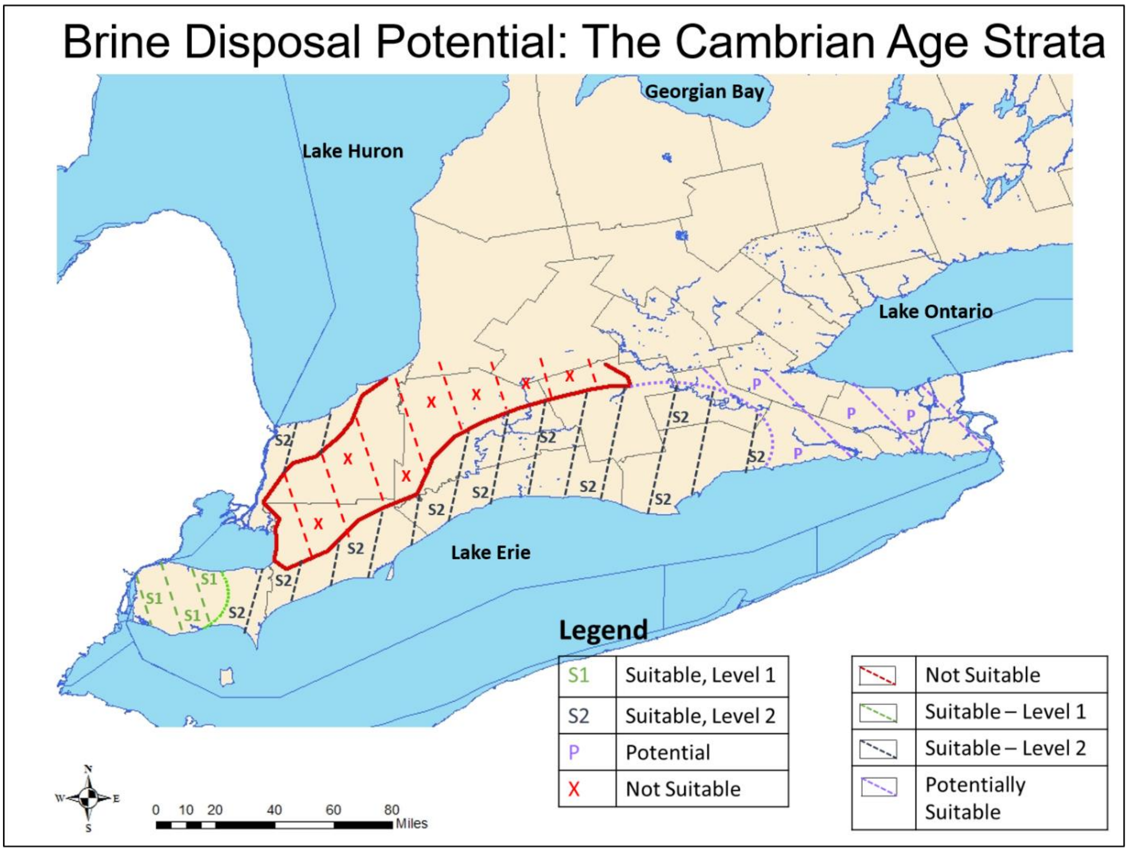

Figure 61: Brine disposal potential result - the Cambrian age strata (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

The Cambrian age areas with high disposal potential, suitable- level 1, are concentrated in Essex County. Table 10 shows the evaluation table for one of the sites in Essex County. Sites in Essex County contain relatively high permeability, greater than 100 mD, as compared to the average permeability of about 50 mD for the rest of southwestern Ontario. Essex county also scores high in the depth criterion with depths ranging close to the 1000 m mark; at this depth, the disposal site will be far away from freshwater sources, and still shallow enough that the drilling and operational costs are not particularly high. The county also scores perfect in the thickness criterion with the formation thickness much larger than 25 m.

Table 10: MCA evaluation table for the Cambrian strata in Essex County.

County	Essex			
Township	Colchester South			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	883	97	0.15	14.55
Thickness (m)	75	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				71

Areas with mediocre disposal potential, suitable – level 2, consist of Elgin County, Norfolk County, Haldimand County, Brant County, and parts of Lambton County, Essex County, Kent County, Middlesex County, and Oxford County. Sites in this category typically score lower in permeability and porosity criteria. The township of Sarnia, a potential CAES facility, falls under this category. Table 11 shows the evaluation table for the Cambrian strata in the Township of Sarnia. The site in Sarnia scores 58 out of 100, and the low score is attributed to low permeability and porosity values in the Sarnia region; permeability of 30 mD and porosity of 15 % are recorded for this site. Evaluation tables for other sites that fall into 'suitable, level 2' category are shown in Appendix C.

Table 11: MCA evaluation table for the Cambrian strata in the Township of Sarnia (Lambton County).

County	Lambton			
Township	Sarnia			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1430	75	0.15	11.25
Thickness (m)	38	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				58

Some areas of the Cambrian strata lack porosity and permeability data, but still show a potential for disposal based on depth, thickness, disposal formation lithology and caprock lithology; these areas are termed as ‘potentially suitable.' From Figure 61, these areas include Welland County, Lincoln County, and Wentworth County.

A large part of southwestern Ontario also falls under the ‘unsuitable’ category. The areas in this category include parts of Lambton County, Kent County, Middlesex County, and Oxford County. These areas are not suitable for disposal because they do not meet the minimum thickness criteria. As displayed in the isopach map of the Cambrian strata (Figure 45), the strata is less than 5 m in all of these areas. Areas that contain oil and gas fields are also not suitable for brine disposal. Figure 62 displays proven petroleum fields in the Cambrian strata.

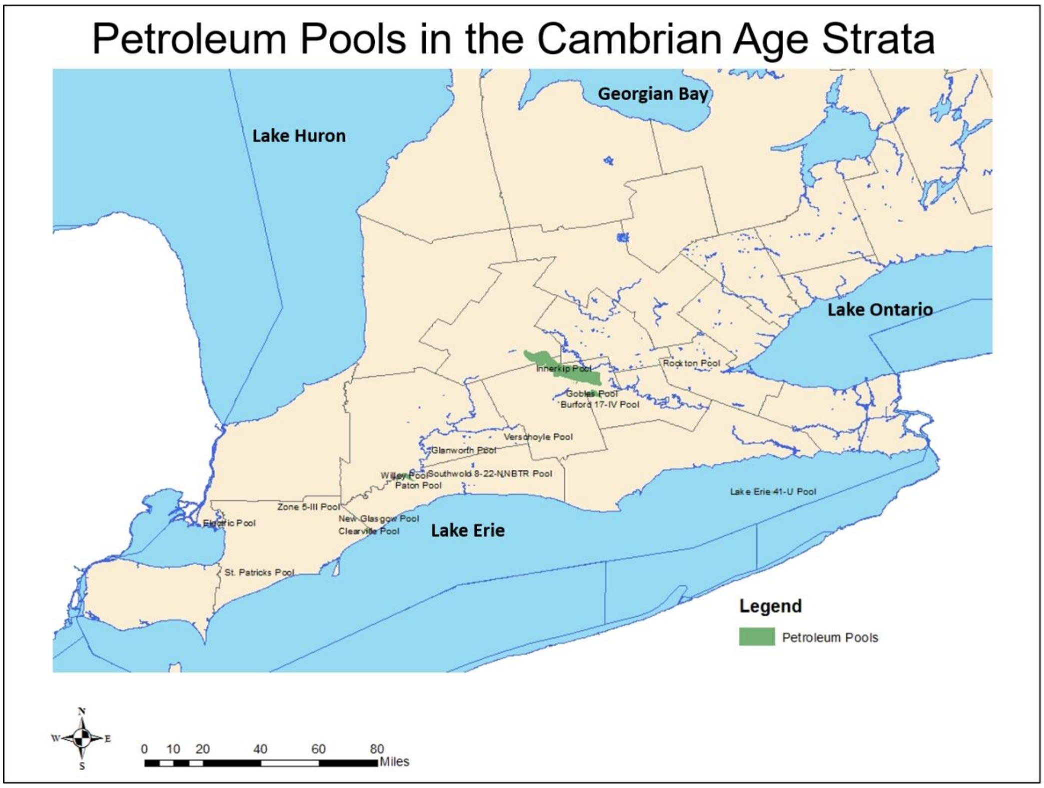

Figure 62: Petroleum pools in the Cambrian strata (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

4.9.2 Lucas Formation

Until now, the Lucas Formation has been extensively utilized for brine disposal. Companies prefer disposal into the Lucas Formation due to its karstic nature; areas with karstic networks or ‘lost circulation’ zones provide high permeability values and storage space for large volumes of brine. Even though the karst networks have not been mapped yet, previous drilling and disposal operations have shown the occurrence of karst in the Lucas Formation.

A major limitation of disposal into the Lucas Formation is its shallow depth. In fact, a large part of southwestern Ontario is not suitable for disposal into the Lucas Formation, as it does not meet the minimum depth requirement. Disposal at shallow depth comes with various environmental issues due to lower caprock strength at shallow depth and a higher risk of caprock breach.

Figure 63 displays the areas in the Lucas Formation that fall under the four disposal categories: suitable – level 1, suitable – level 2, potentially suitable, and unsuitable.

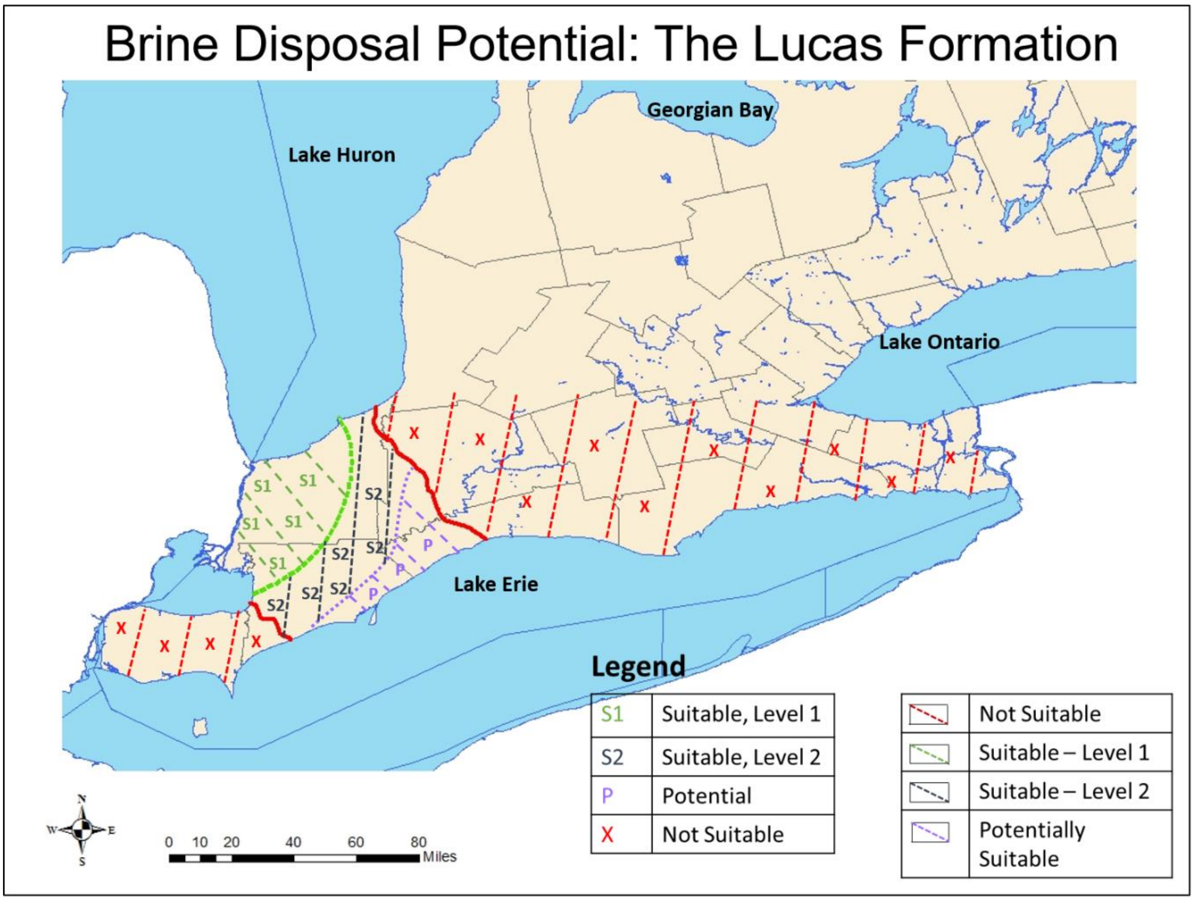

Figure 63: Brine disposal potential result - the Lucas Formation (Map Author: University of Waterloo; Data Provider: Ontario Oil, Gas and Salt Resources Library).

The majority of Lambton County and the northwest corner of Kent County fall into the 'suitable – level 1' category. Since Sarnia has the thickest salt beds and is a potential site for CAES facilities, evaluation results from a site in Sarnia are discussed. Through the past disposal operations in the Sarnia region, it was discovered that the formation is karstic and displays high permeability. Table 12 shows the MCA evaluation system for a site in the Sarnia Township; the site scores 73 out of 100. The site has relatively high permeability of 100 mD as compared to the average range of 10 to 50 mD in Lambton County. An additional 10 points are added to the total score due to the area being potentially karstic. In addition to permeability, the site scores high in all other criteria, except depth. As is the case with most of the sites in the Lucas Formation, the site in Sarnia scores low in depth, with the depth of 137 m. At shallow depth, such as in this case, the operator would need to be very cautious with the injection pressures so that the caprock integrity is not breached.

Also, an appropriate monitoring system must be established with frequent monitoring of freshwater sources and the changing reservoir conditions, such as formation pressure.

Table 12: MCA evaluation table for the Lucas Formation in the Sarnia Township

County	Lambton			
Township	Sarnia			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	137	12	0.15	1.8
Thickness (m)	95	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	20	80	0.2	16
Reservoir Lithology	Limestone and Dolomite (Potentially Karstic)	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				73

Areas with level 2 suitability include parts of Lambton, Kent, Middlesex, and Elgin Counties. Areas in this category score less than 65 on the evaluation system, and the low score is due to depth, permeability, and porosity criteria. Table 13 shows the evaluation table for a site in Kent County that falls under 'suitable – level 2' category. The site scores 62 out of 100, and the low score is attributed to the shallow depth and low permeability; the depth to the Lucas Formation at this site is 130 m and a permeability value of 25 mD is recorded for this site. Appendix C shows evaluation tables for other sites that fall under 'suitable – level 2' category.

A few areas in parts of Kent, Elgin, and Middlesex Counties lack porosity and permeability data, but still show disposal potential based on depth, thickness, disposal formation lithology, and caprock lithology. These areas belong to the 'potentially suitable' category.

Table 13: MCA evaluation table for the Lucas Formation in Kent County

County	Kent			
Township	Zone			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	130	7	0.15	1.05
Thickness (m)	40	100	0.15	15
Permeability (mD)	25	10	0.25	2.5
Porosity (%)	17	67.5	0.2	13.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				62

A large part of southwestern Ontario, shown in Figure 63, is not suitable for brine disposal into the Lucas Formation. The areas in this category do not meet the minimum depth criteria. Figure 48 displays the depth map of the Lucas Formation and it can be seen that the Formation is shallower than 120 m in the following areas: Essex County, Norfolk County, Oxford County, Brant County, Haldimand County, Wentworth County, Lincoln County, Welland County, and parts of Kent County, Elgin County, and Middlesex County. Areas that contain oil and gas fields are also not suitable for brine disposal. The hydrocarbon pool map of the Lucas Formation is not available at this time.

4.9.3 Other Potential Disposal Formations

As discussed in the preceding paragraphs, the Cambrian age strata and the Lucas Formation contain large areas that have the best potential for brine disposal. Apart from the Cambrian strata and the Lucas Formation, some other formations might have limited disposal potential. McLean (1968) suggests that these formations include the Guelph Formation, Bass Islands Formation, and Bois Blanc Formation.

The Guelph Formation is comprised of platform and reefal dolostones and limestones (Armstrong and Carter, 2010). The reefs exhibit well developed vuggy porosity and hold hydrocarbon deposits in southwestern Ontario. In fact, this formation is famous for having historically produced large quantities of oil and gas. In limited areas, where oil and gas deposits are not encountered, the Guelph Formation can offer suitable characteristics for brine disposal. In fact, if allowed by the regulations set by the Ministry of Natural Resources and Forestry, brine can be disposed in depleted oil and gas reefs of the Guelph Formation.

The Bass Islands Formation is comprised of very fine to fine crystalline dolostones. Armstrong and Carter (2010) note that no oil and gas has been encountered in the Bass Islands Formation. Core samples display little to no porosity; however, a few meters in the upper part of the formation have regionally formed a sulfurous water aquifer due to sand-filled joints, open fractures, and karstic features that were formed during regional exposure and weathering (Armstrong and Carter, 2010). These regions might have brine disposal potential. A detailed investigation is needed to confirm the location and potential of these aquifers to store suitable quantities of brine.

The Bois Blanc Formation consists of fine to medium grained cherty limestone and dolostone. Core logs display little to no porosity. However, in the lower part of the Bois Blanc strata, the formation contains the Springvale Member, which is comprised of quartzitic sandstone and minor sandy carbonates. The Springvale Member can locally reach thickness of 30 m in the sinkholes formed by dissolution of Salina Group salt beds (Armstrong and Carter, 2010). McLean (1968) mentions that water recoveries were recorded in the Springvale Member and some areas might be suitable for brine disposal. These claims must be checked with detailed investigation to see if large quantities of brine can be accommodated in the Springvale Member of the Bois Blanc Formation.

4.10 Conclusions and Recommendations

A study of brine disposal potential in southwestern Ontario was warranted due to projected use of salt caverns for compressed air energy storage (CAES) and current utilization of salt caverns for storing liquid and gaseous hydrocarbon products. The main purpose of this study was to evaluate the potential of brine disposal in southwestern Ontario; i.e., the study aimed to identify sites that are suitable, potentially suitable, and unsuitable.

Multi-criteria analysis (MCA) was utilized to develop an evaluation system to compare various strategically chosen sites throughout southwestern Ontario. The process included assigning weights and scoring to criteria that would affect brine disposal site selection. The criteria included permeability, porosity, depth, thickness, disposal formation lithology, caprock lithology, and karst potential. Criteria weighting and scoring were generated from academic and industrial expert opinions.

The study mainly focused on two rock strata: the Lucas Formation and the Cambrian age strata. These strata show suitable disposal characteristics that are required for large quantities of brine disposal. In fact, the Lucas Formation has been extensively used for disposal purpose in the past. Due to environmental issues in the Lucas Formation in the early 1960s, the Cambrian strata was looked as alternative disposal formation. Apart from the Lucas Formation and Cambrian strata, other formations that show limited brine disposal potential are the Guelph Formation, Bass Island Formation, and Bois Blanc Formation.

The MCA evaluation system was applied to various strategically chosen sites in southwestern Ontario. The results were divided into 4 categories: suitable – level 1, suitable – level 2, potentially suitable, and unsuitable. Due to uneven distribution of geologic wells, manual interpolation was used to display the MCA results.

Companies have preferred to dispose brine in the Lucas Formation due to the presence of karstic features. Karst features generally are associated with high permeability and make the Lucas Formation suitable for disposal of large quantities of brine. However, the shallow depth of the formation is a cause of concern due to environmental issues that can arise from caprock or wellbore breach and contamination of freshwater formations. The MCA results showed that the most suitable areas for disposal into the Lucas Formation are Lambton County and the northwest corner of Kent County. The sites that show mediocre potential consist of parts of Lambton, Kent, Middlesex, and Elgin Counties. Due to the shallow depth of the formation, a large part of southwestern Ontario is unsuitable for brine disposal in the Lucas Formation. Areas in the 'unsuitable' category do not meet the minimum depth requirement of 120 m.

The Cambrian age strata can prove to be an attractive alternative to disposal into the Lucas Formation. The Cambrian strata is located deeper than 500 m in most of southwestern Ontario and does not pose depth related environmental issues that are encountered in the Lucas Formation. However, as compared to the Lucas Formation, the Cambrian strata have relatively low permeability, high formation pressure, and limited thickness. The most suitable area for disposal in the Cambrian strata is Essex County. A major part of southwestern Ontario shows mediocre potential for disposal into Cambrian strata; this area consists of Elgin County, Norfolk County, Haldimand County, Brant County, and parts of Lambton County, Essex County, Kent County, Middlesex County, and Oxford County. Due to limited thickness of the Cambrian strata, a large part of southwestern Ontario does not meet the minimum thickness criteria of 5 m, and is therefore not suitable for disposal.

The Guelph Formation, which is mainly platform and reefal carbonates, in particular, can offer decent disposal potential where oil and gas deposits are not present. This Formation is recognized for producing large quantities of oil and gas, which makes it unsuitable for disposal in much of southwestern Ontario. The Bass Islands Formation and Bois Blanc Formation show very limited disposal potential. The Bass Islands Formation, comprised of very fine to fine crystalline dolostones, contains little to no porosity. However, water recoveries have been recorded from a sulfurous water aquifer in the upper part of the Formation. The Bois Blanc Formation, comprised of fine to medium grained cherty limestone and dolostone, displays little to no porosity. However, water recoveries have been recorded in the lower part of the formation due to the presence of the Springvale Member that is comprised of quartzitic sandstone and minor sandy carbonates. These claims must be checked with detailed investigations to see if large quantities of brine can be accommodated in the Bass Island Formation and Bois Blanc Formation areas where water recovery has been recorded.

A robust monitoring program is required for successful operation of any disposal operation. Early detection of major issues will prevent environmental and operational set-backs, and thereby also protect the investment in the disposal facility asset. A few monitoring procedures are recommended here. However, note that this is not a comprehensive list and the monitoring program might differ between disposal projects. Since southwestern Ontario contains many unplugged and inadequately plugged wells, these wells in a 2.5 km radius of the disposal well must be located through pressure testing and plugged properly. Also, during injection, records should be maintained for injection rates and annulus pressure. This will give an idea aout well plugging, formation plugging, casing leak, or fluid escaping the disposal formation through caprock, faults or unplugged wells. Additionally, Rudd (1972) suggests that observation wells can be placed internally in the disposal formation to check for lateral confinement and outside the disposal formation to check for vertical migration of fluid. An observation well in the overlying permeable formation will be required if the disposal formation is near to the freshwater aquifers, such as disposal operations in the Lucas Formation.

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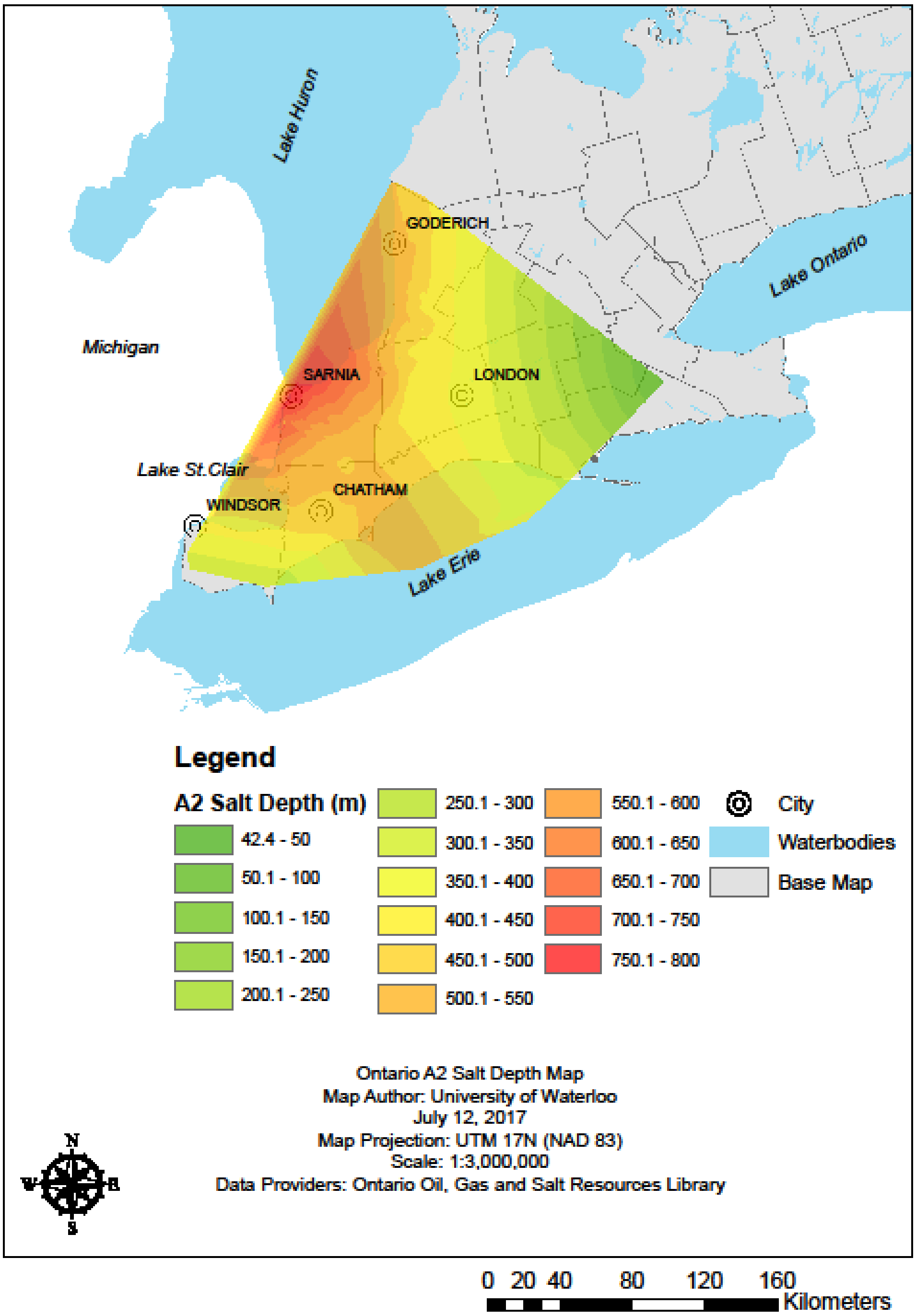
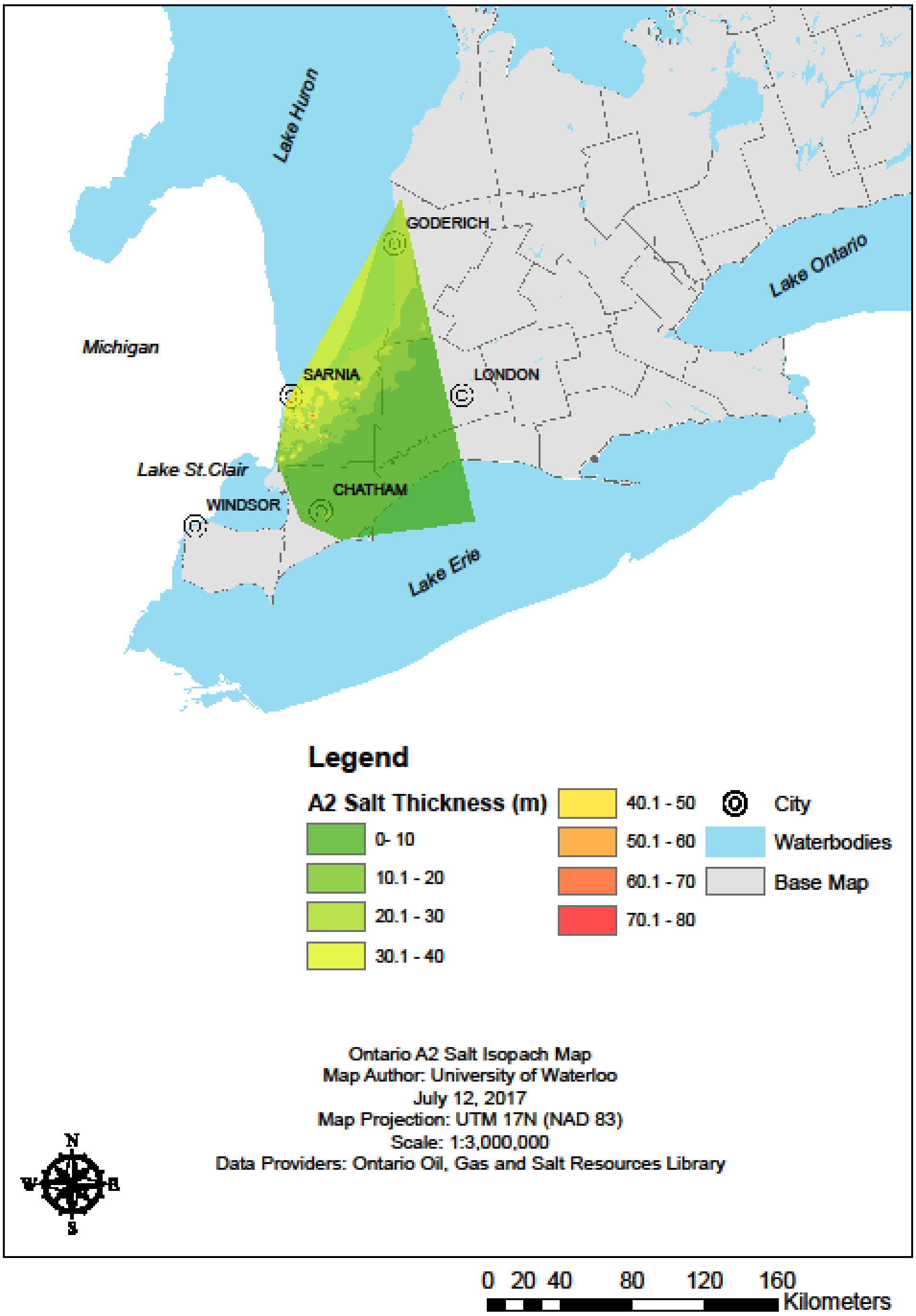
Appendix A: Criteria Data Maps for Ontario, Western Canada, and Maritimes (CAES Siting Study)

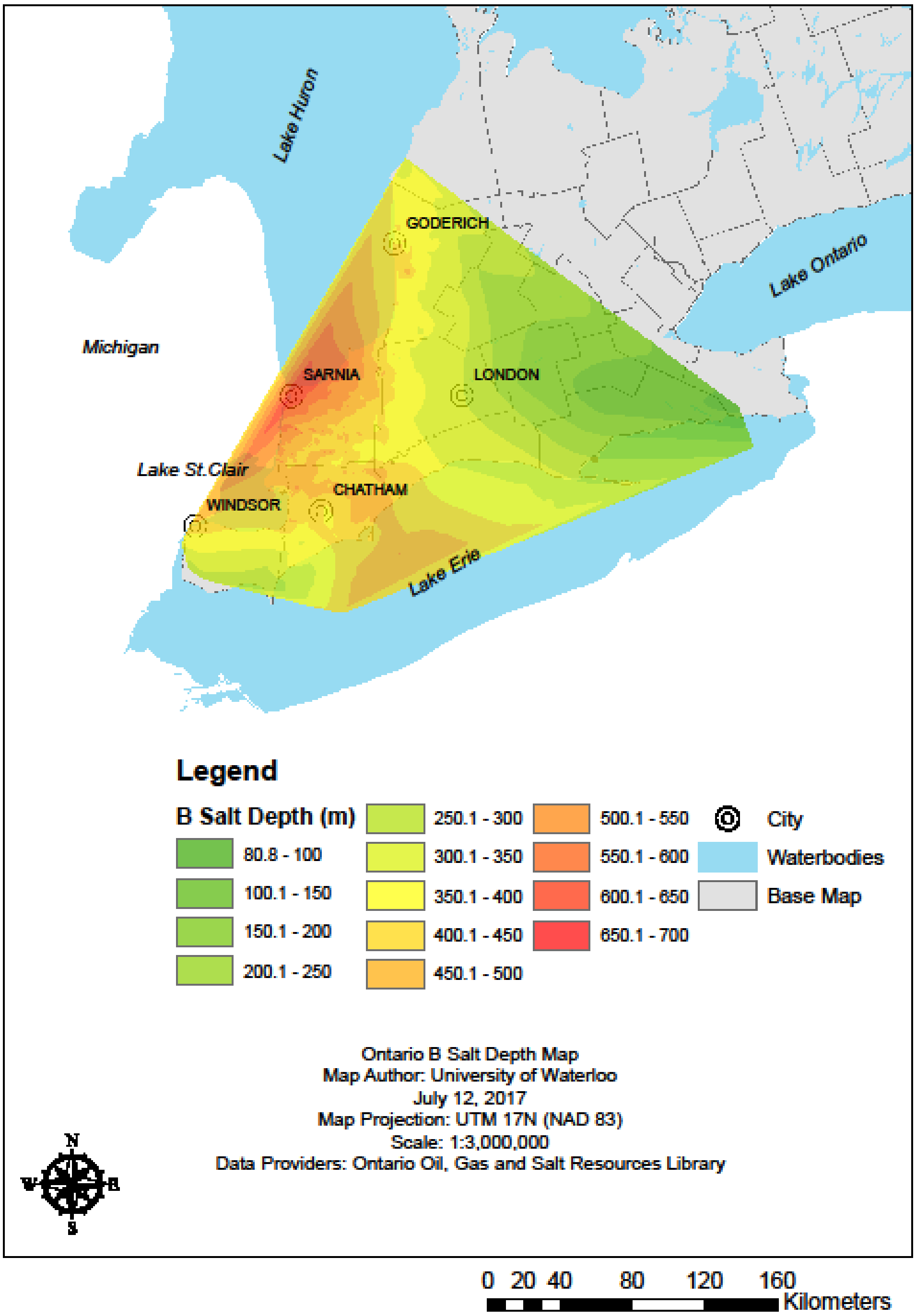
Ontario A2 Salt Depth Map



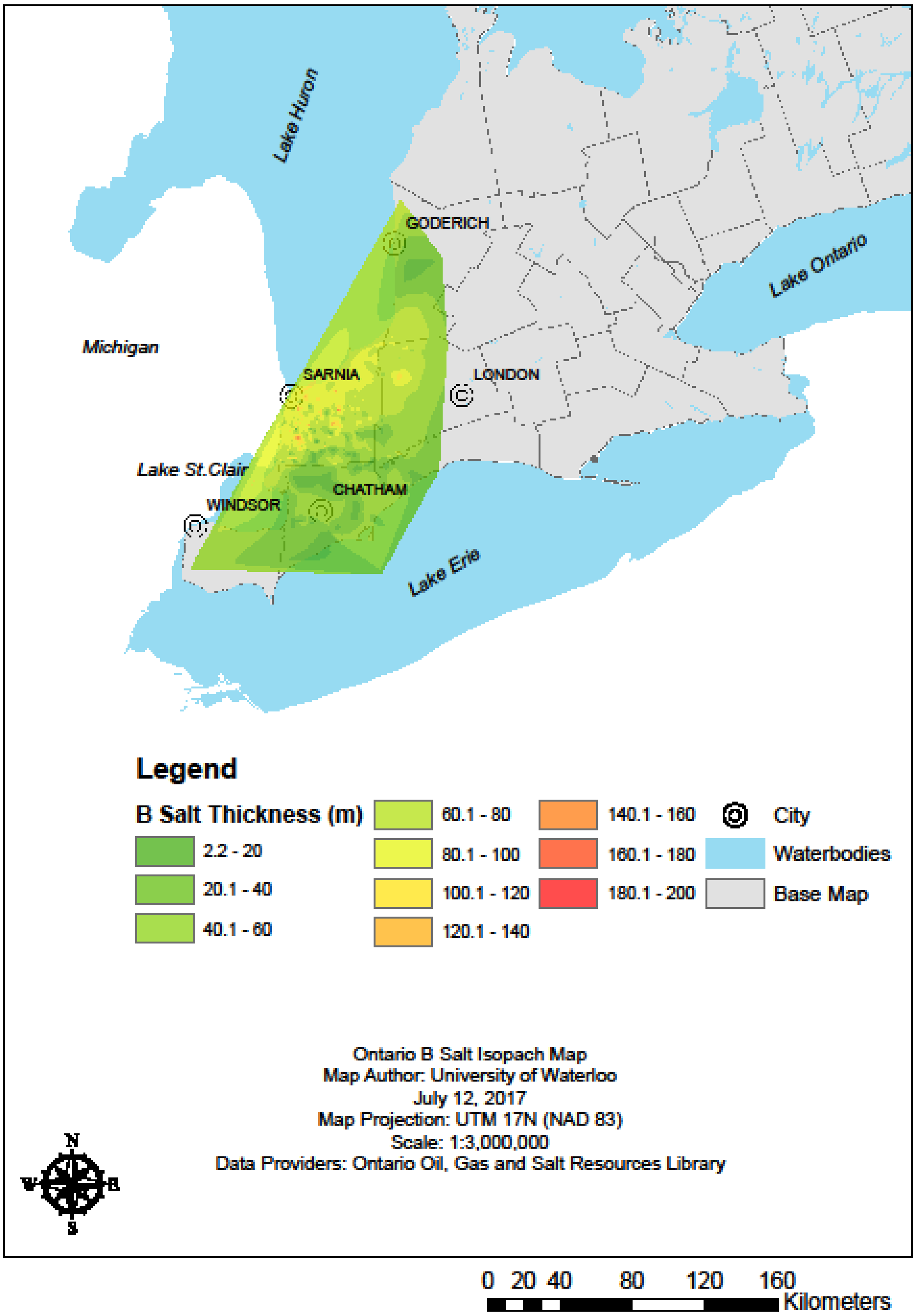
Ontario A2 Salt Isopach Map



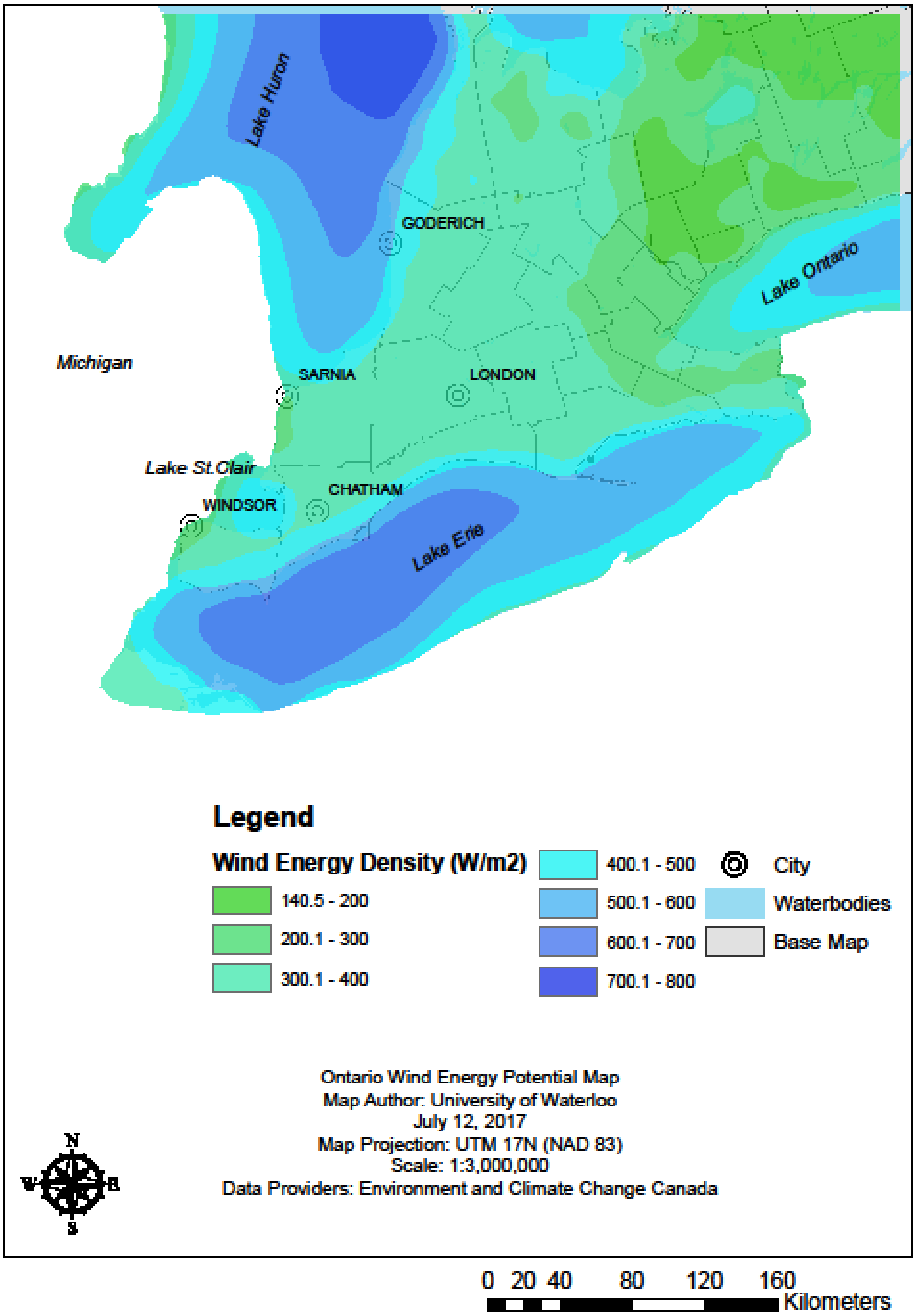
Ontario B Salt Depth Map



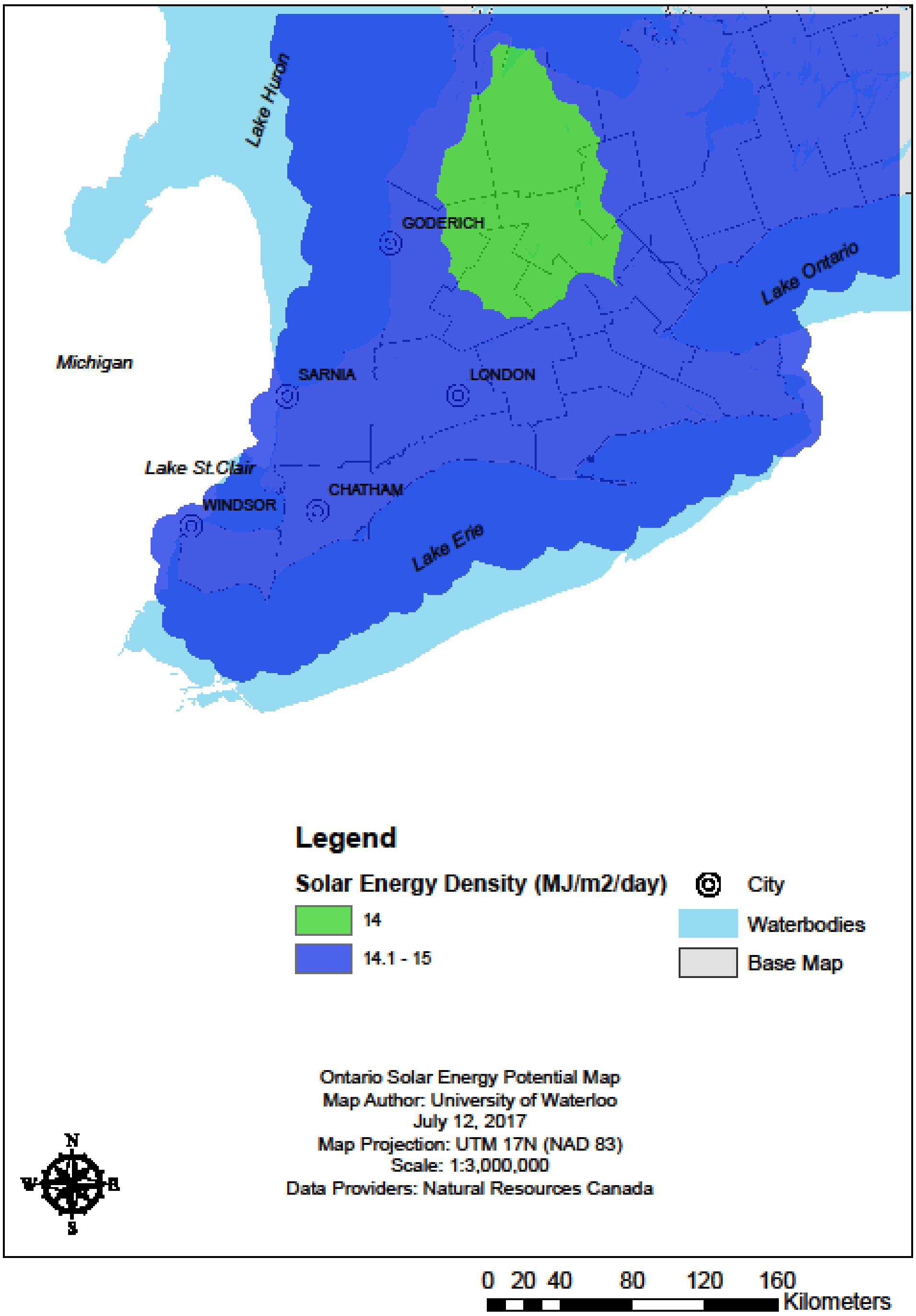
Ontario B Salt Isopach Map



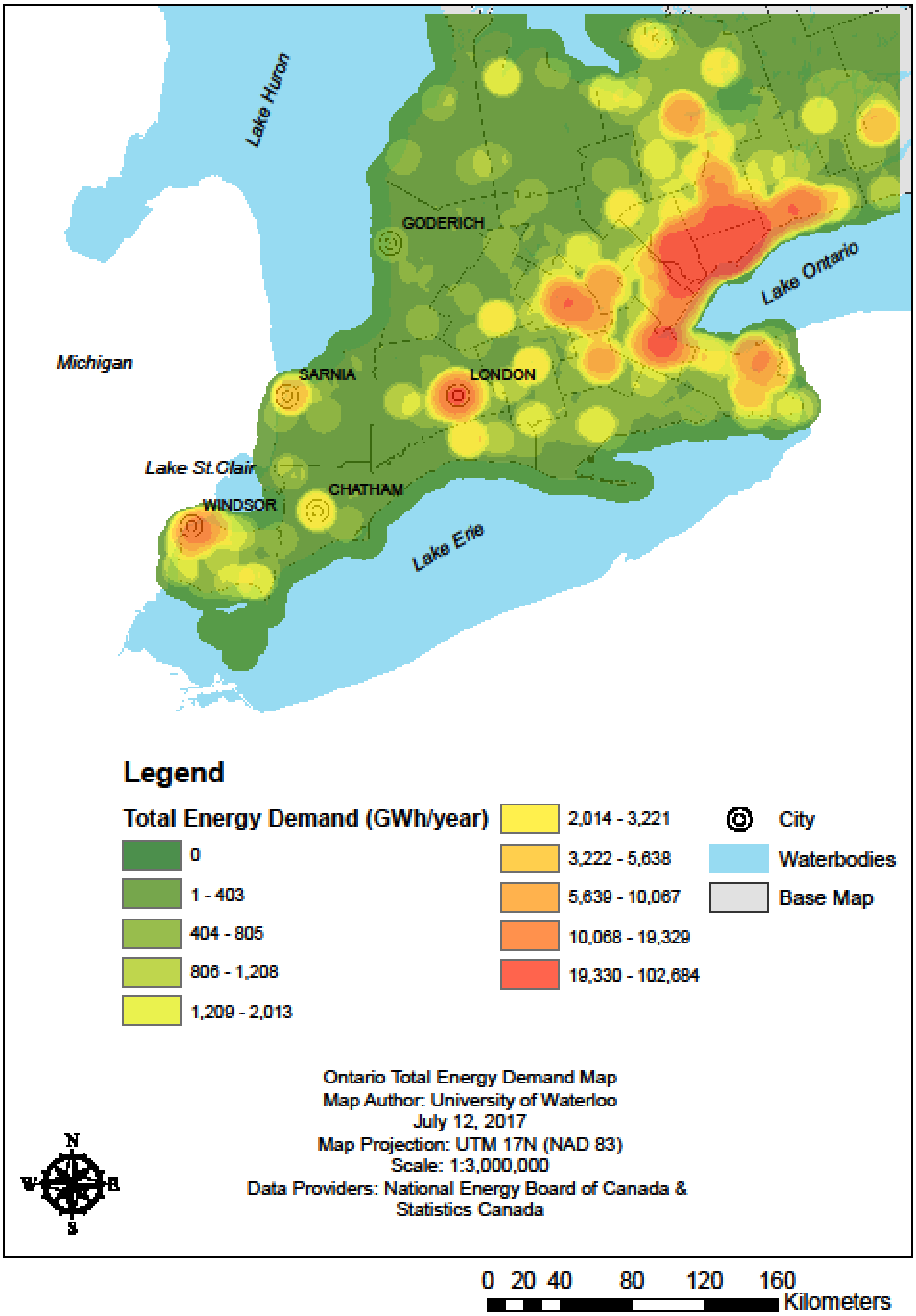
Ontario Wind Energy Potential Map



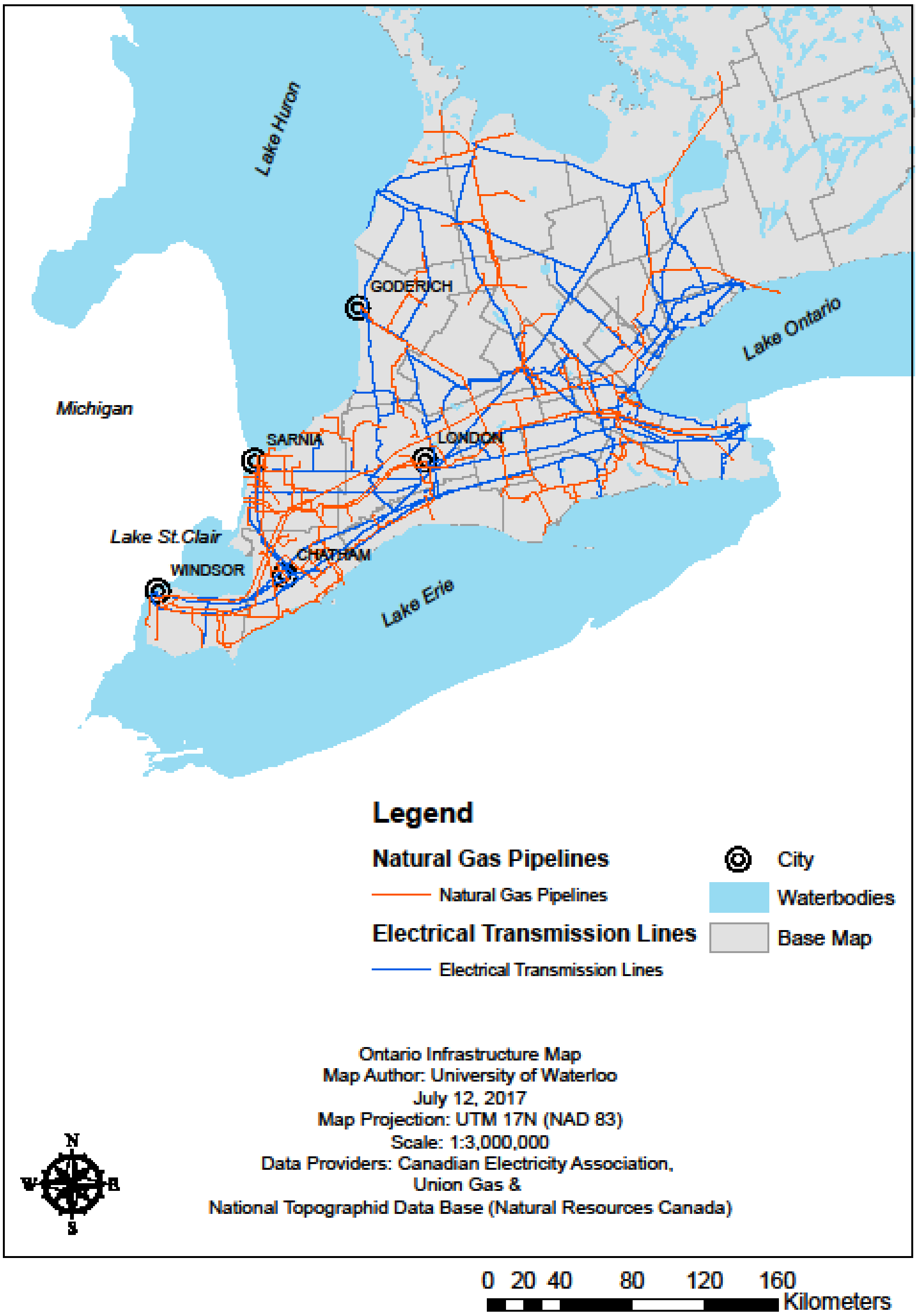
Ontario Solar Energy Potential Map

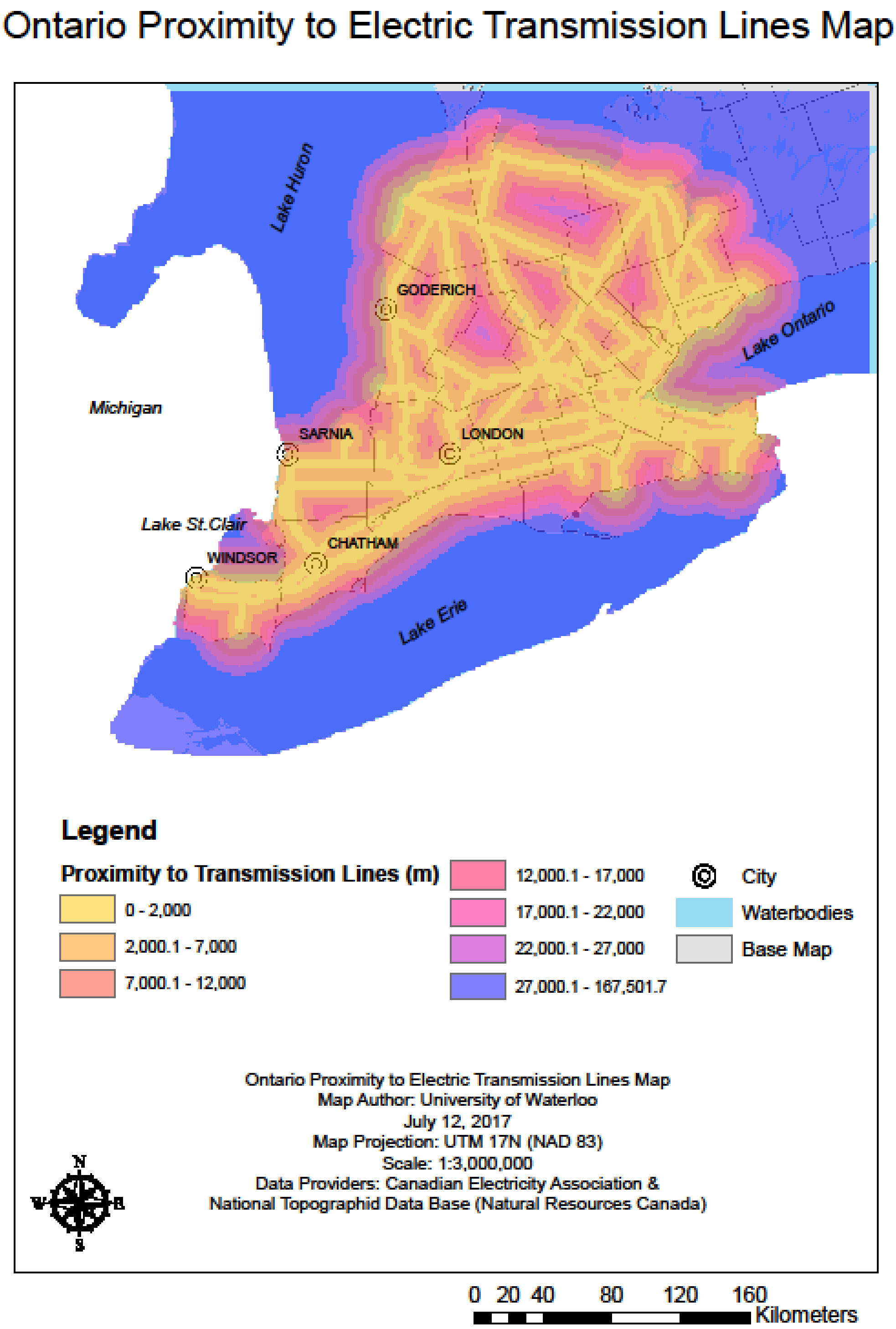


Ontario Total Energy Demand Map

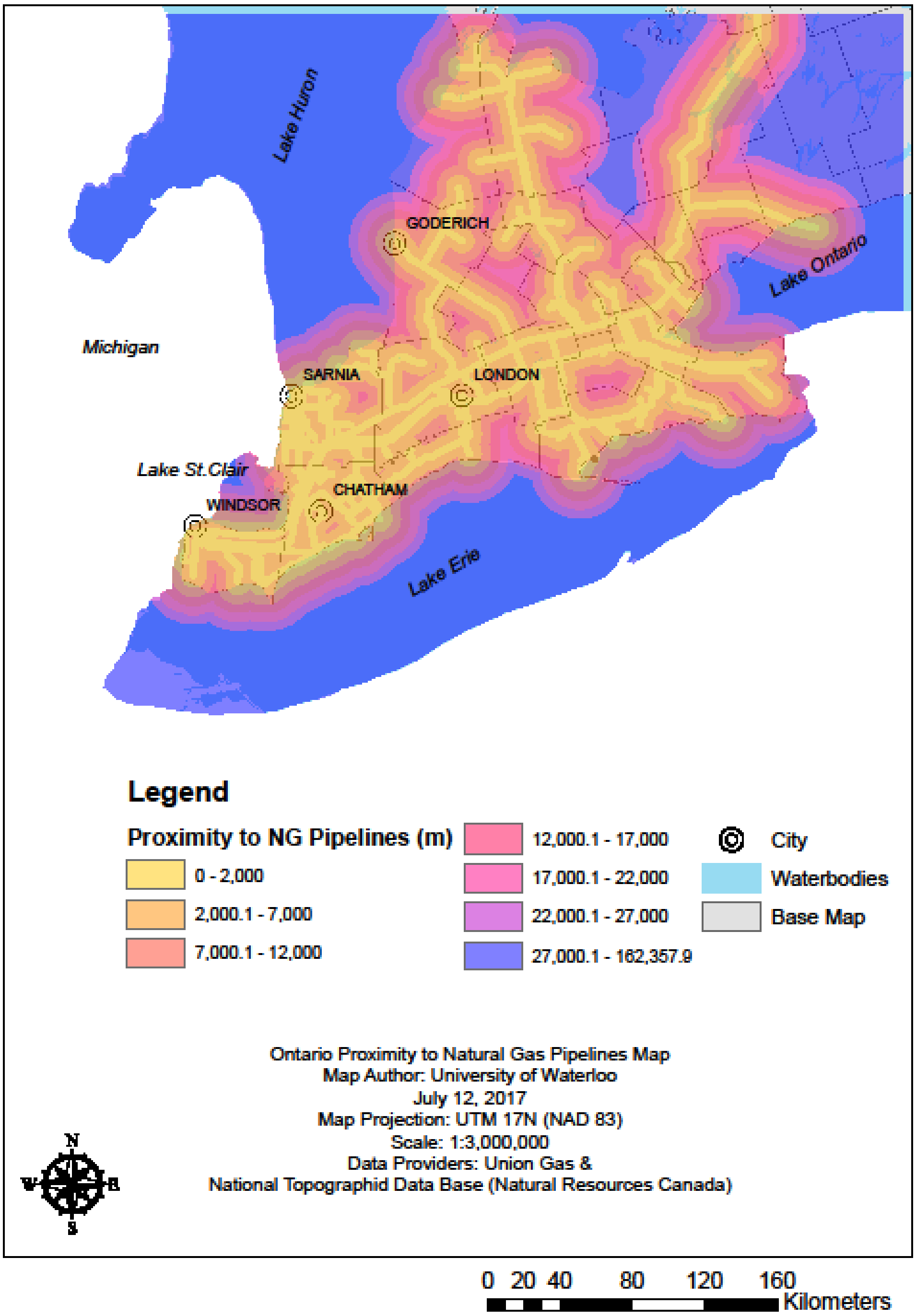


Ontario Infrastructure Map

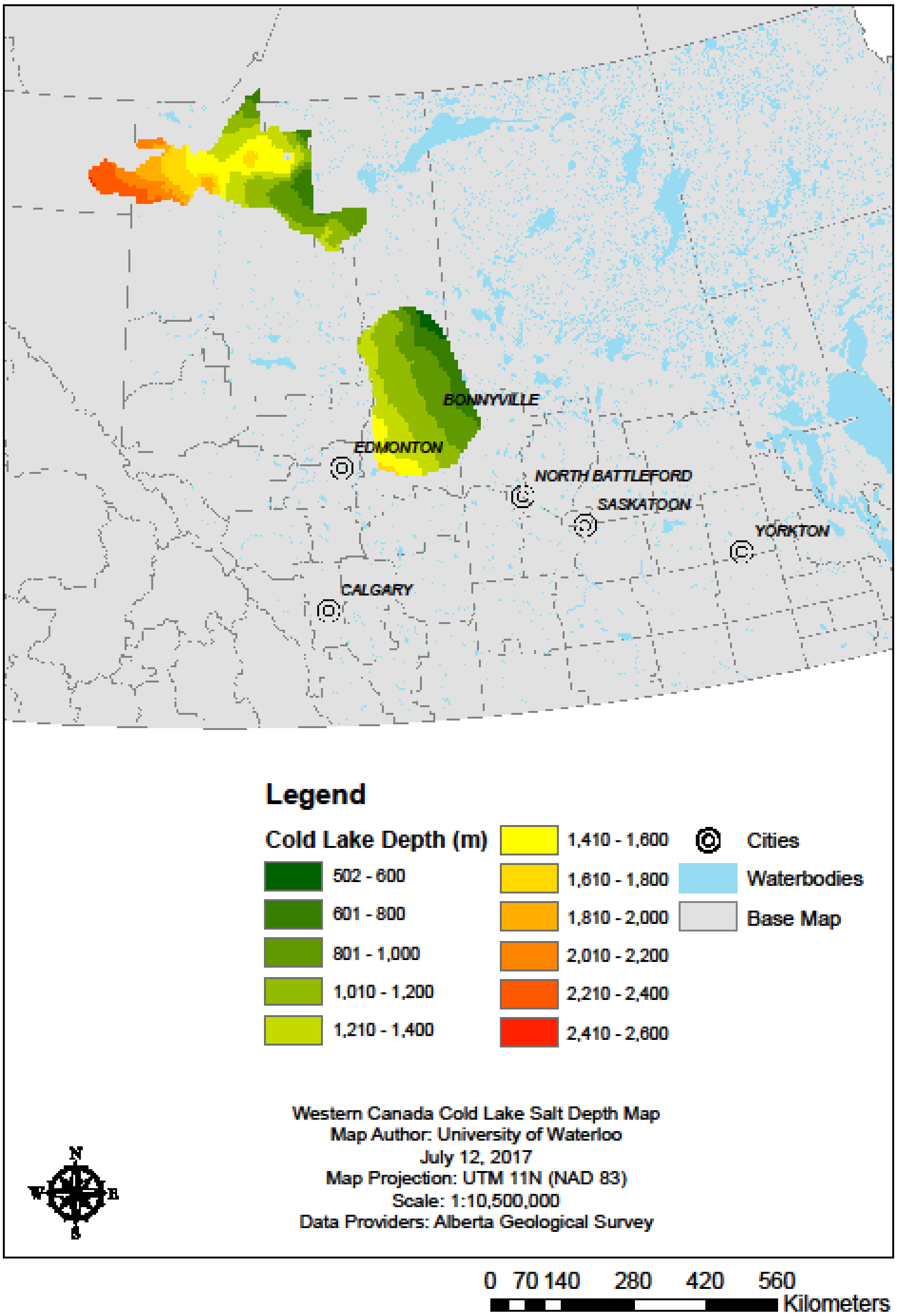



Ontario Proximity to Electric Transmission Lines Map
Lake Huron
GODERICH
Lake Ontario
Michigan
SARNIA
LONDON
Lake St.Clair
WINDSOR
CHATHAM
Lake Erie
Legend
Proximity to Transmission Lines (m)
0 - 2,000
2,000.1 - 7,000
7,000.1 - 12,000
12,000.1 - 17,000
17,000.1 - 22,000
22,000.1 - 27,000
27,000.1 - 167,501.7
City
Waterbodies
Base Map
Ontario Proximity to Electric Transmission Lines Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 17N (NAD 83)
Scale: 1:3,000,000
Data Providers: Canadian Electricity Association &
National Topographid Data Base (Natural Resources Canada)
N
W
E
S
0 20 40 80 120 160
Kilometers

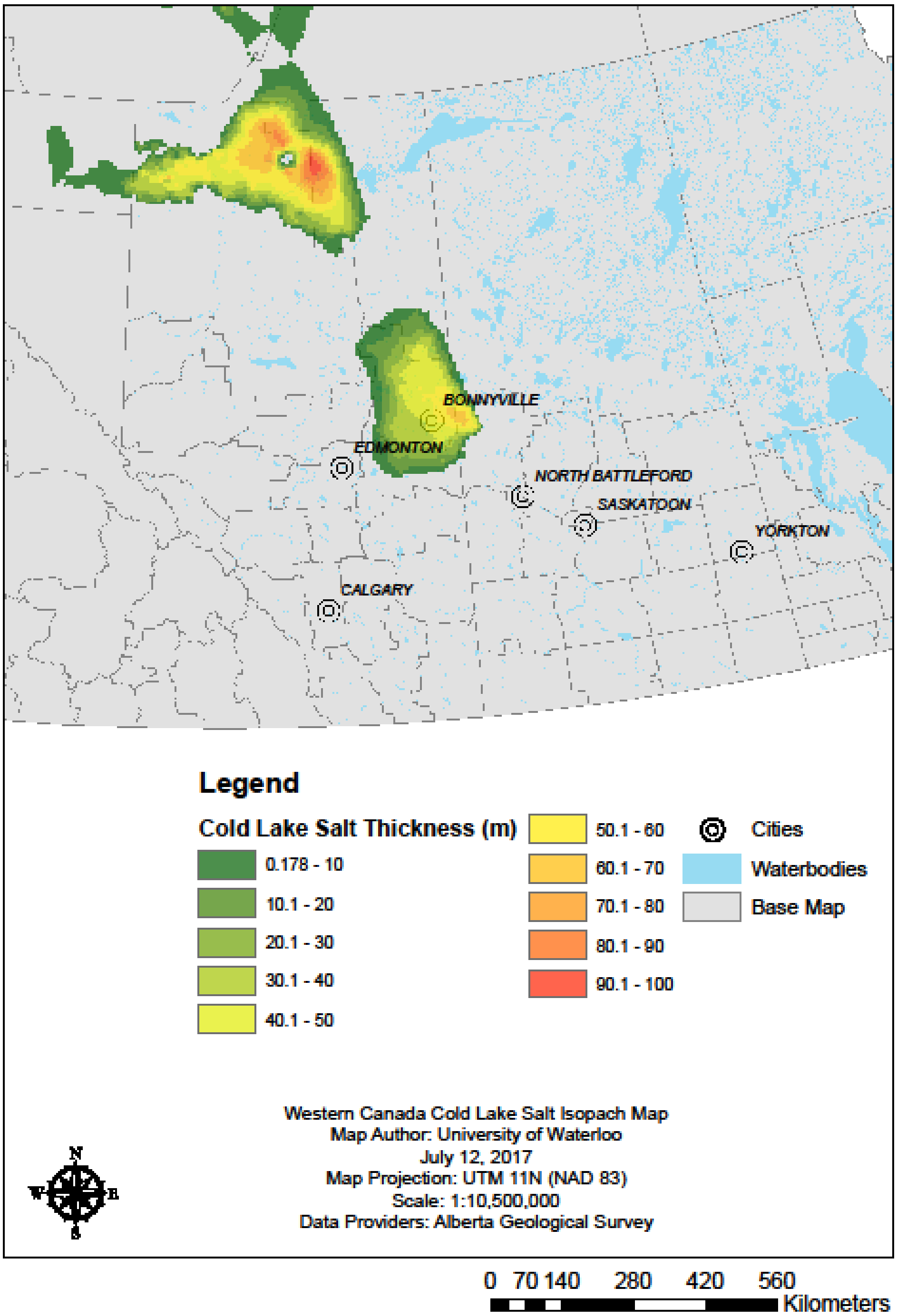
Ontario Proximity to Natural Gas Pipelines Map



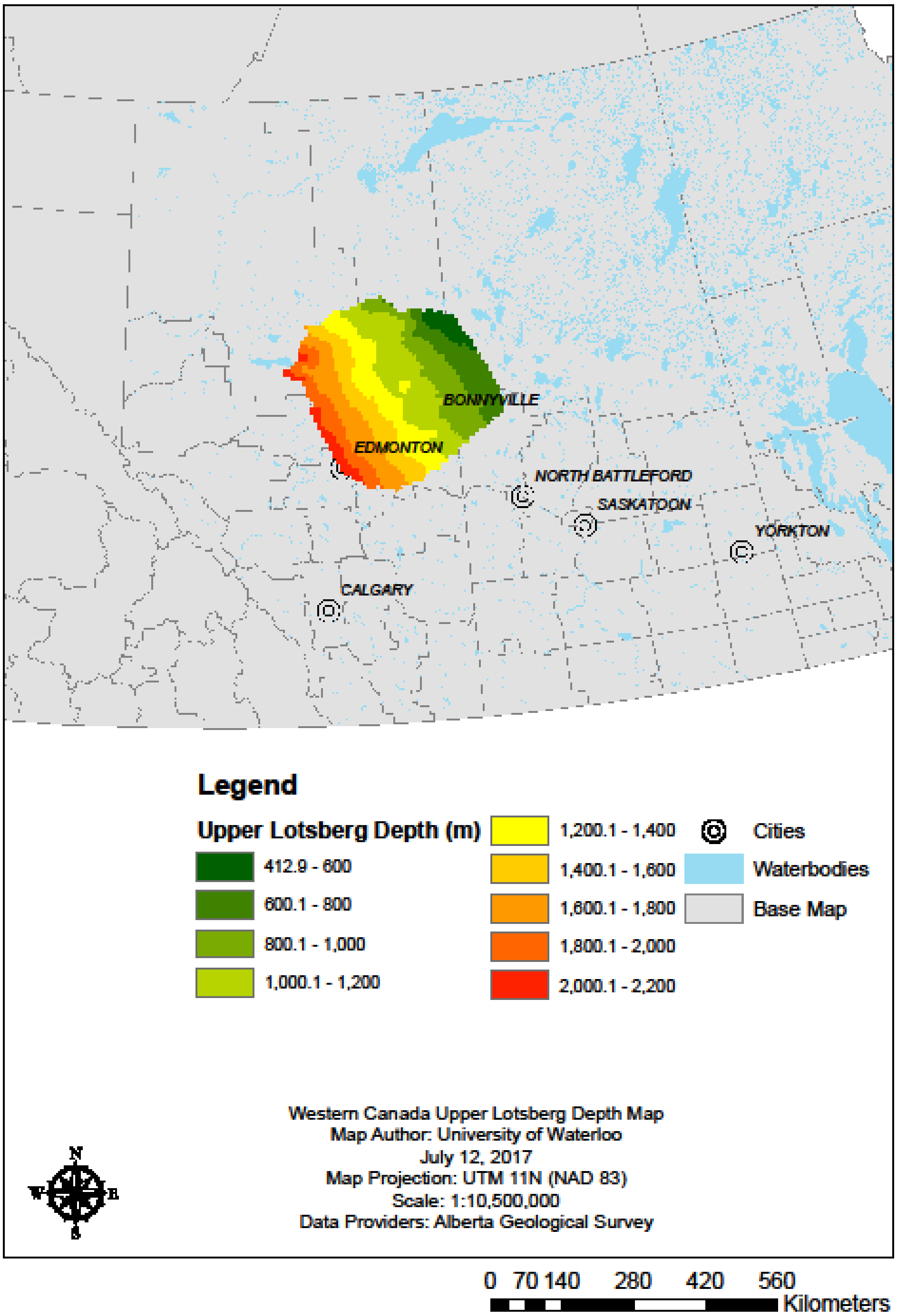
Western Canada Cold Lake Salt Depth Map



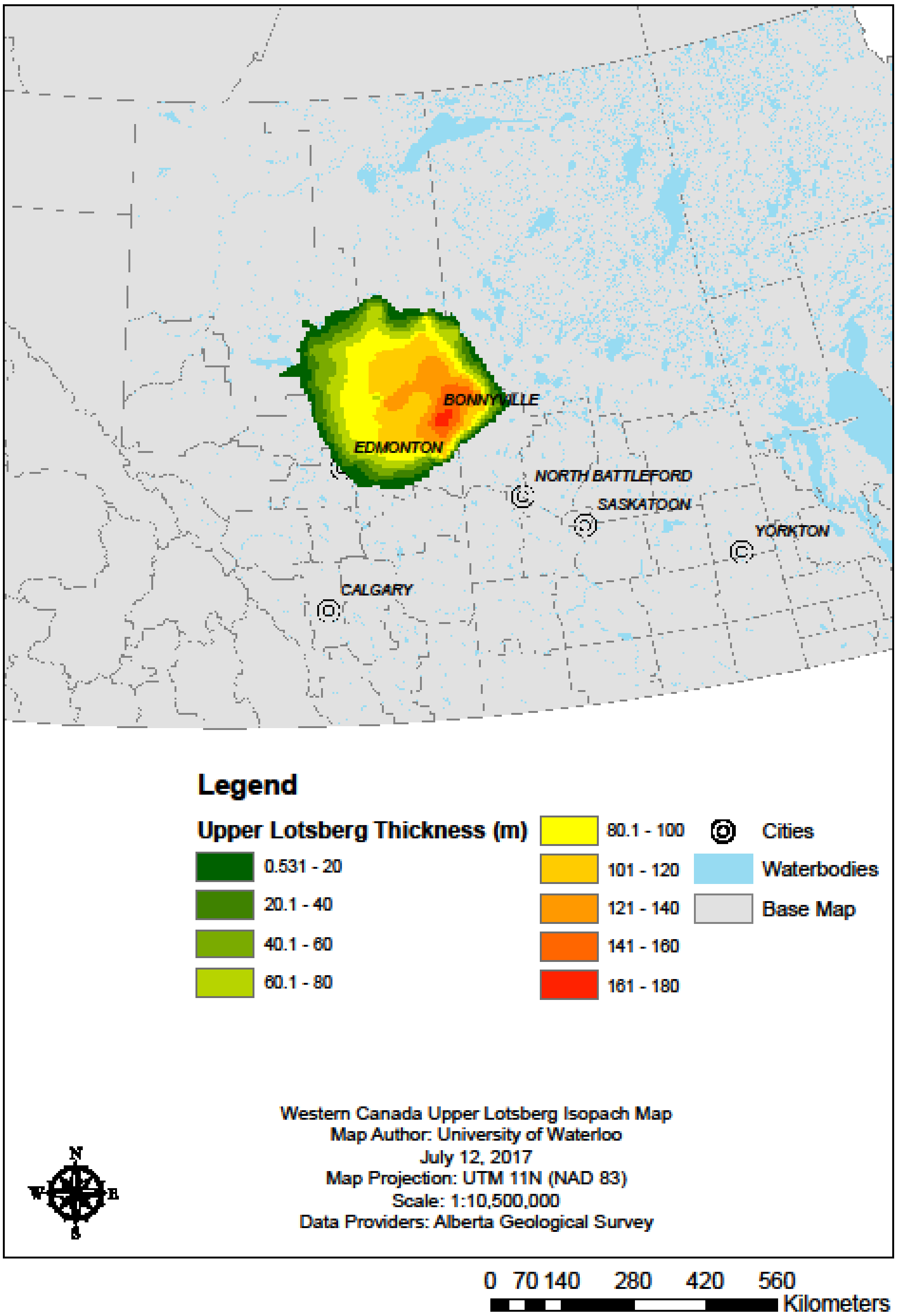
Western Canada Cold Lake Salt Isopach Map



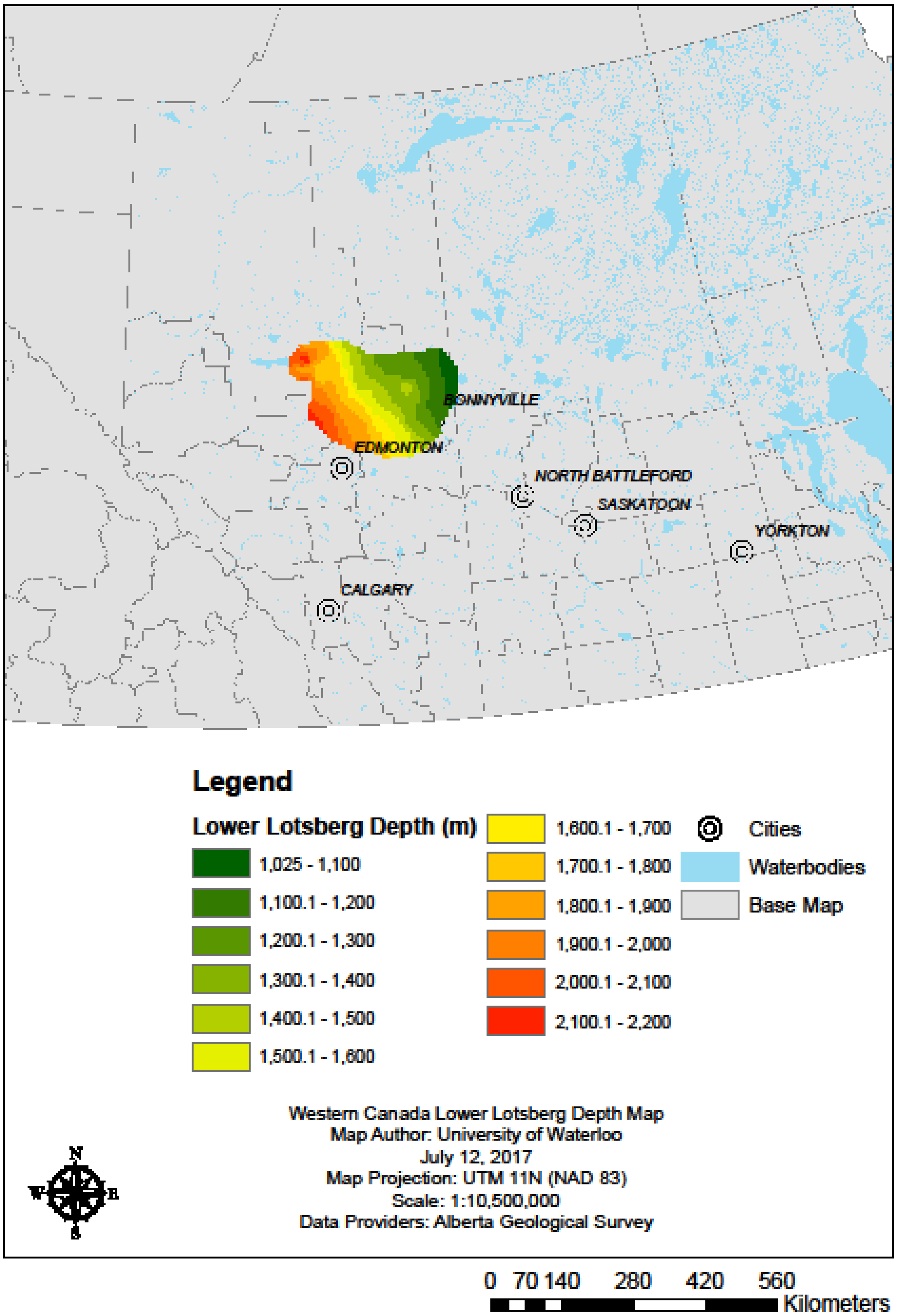
Western Canada Upper Lotsberg Salt Depth Map



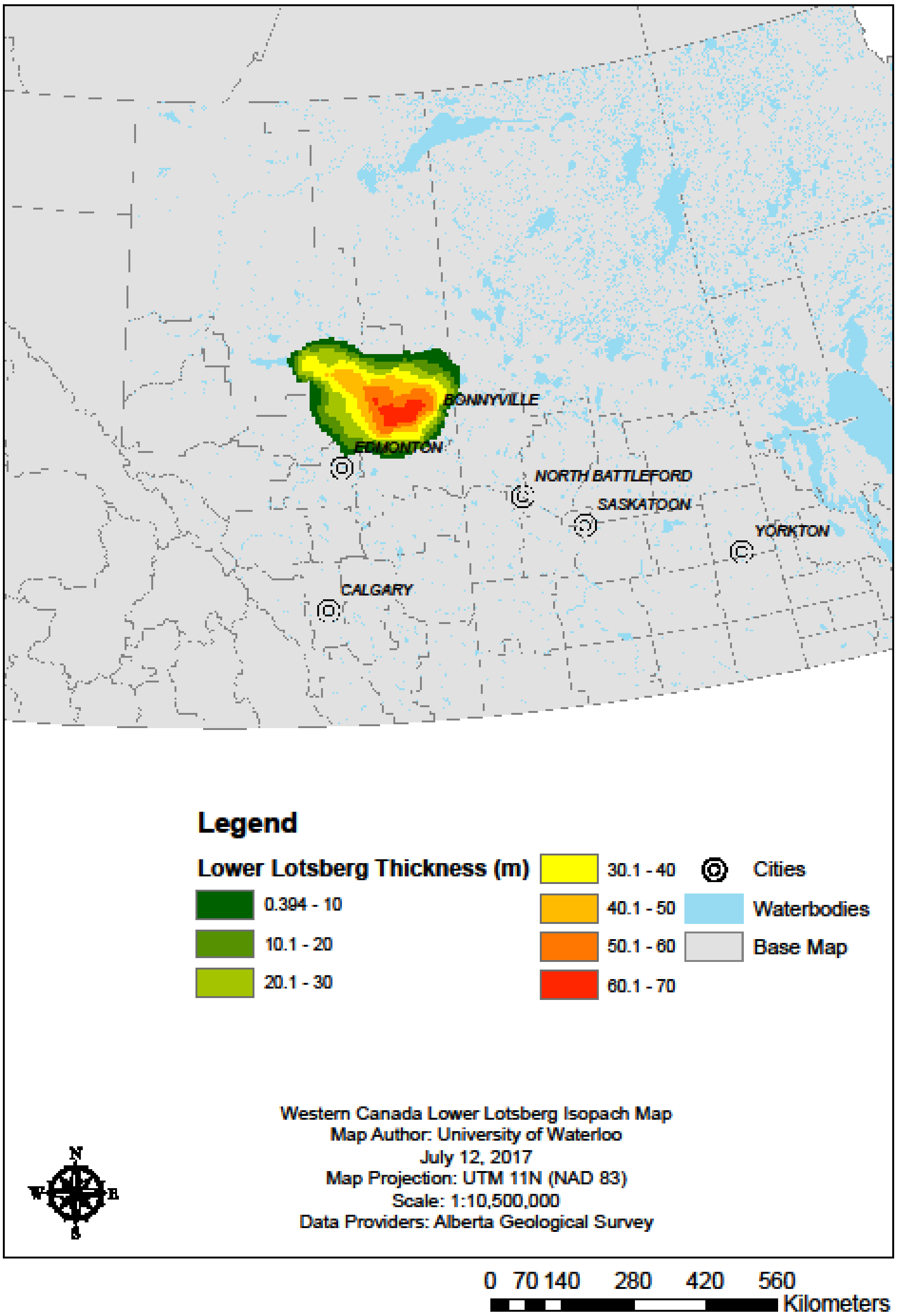
Western Canada Upper Lotsberg Salt Isopach Map



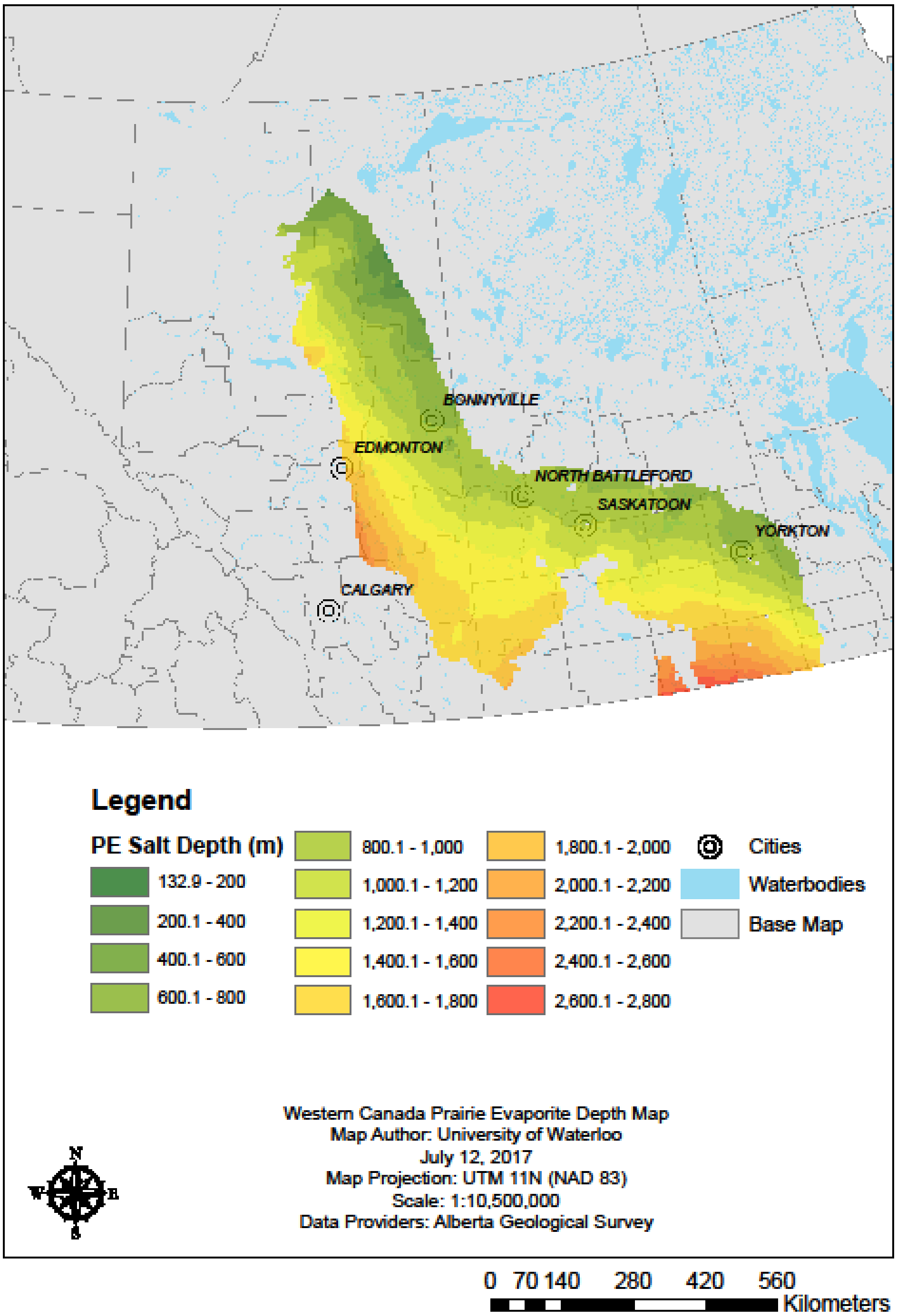
Western Canada Lower Lotsberg Salt Depth Map



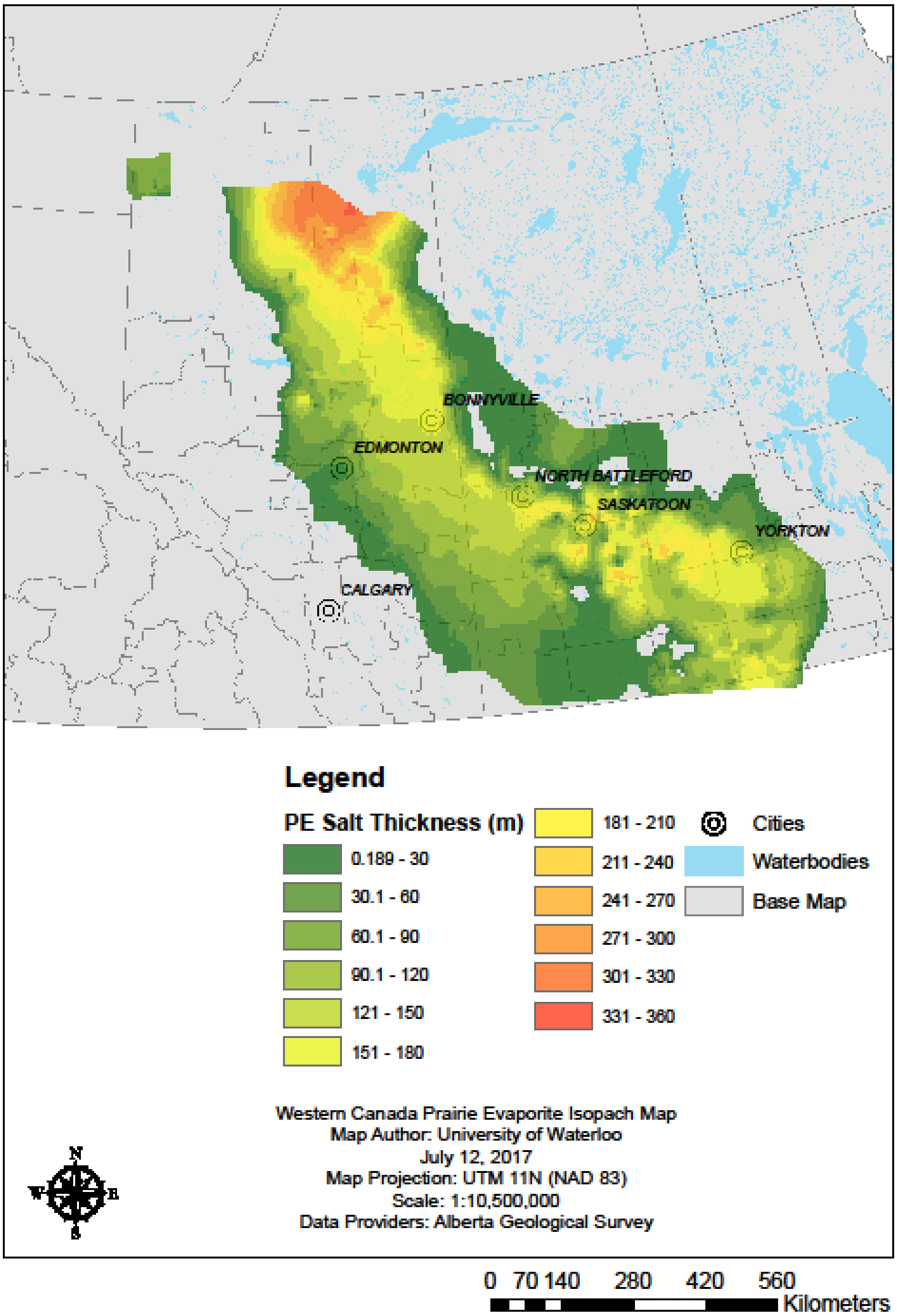
Western Canada Lower Lotsberg Salt Isopach Map



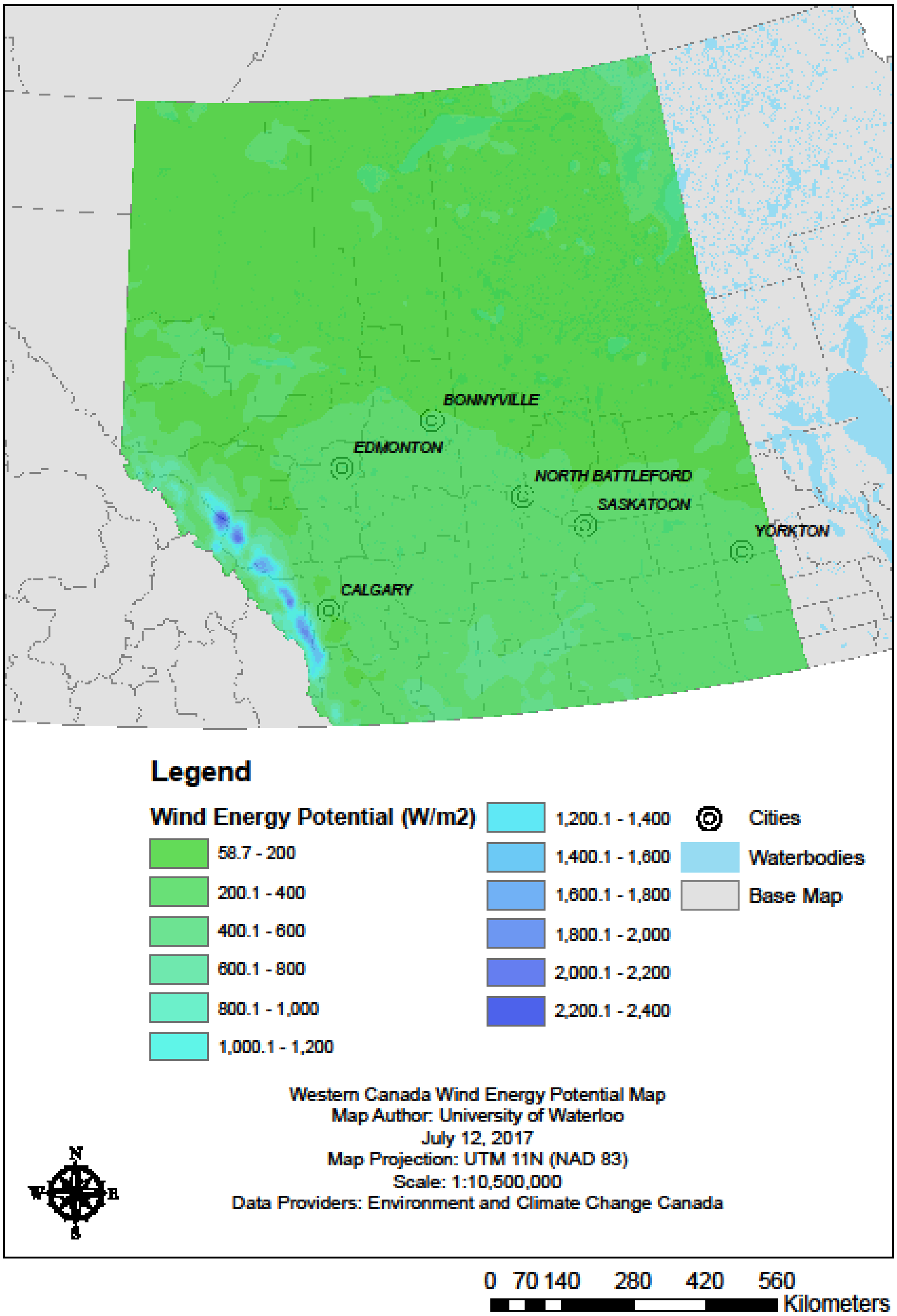
Western Canada Prairie Evaporite Salt Depth Map



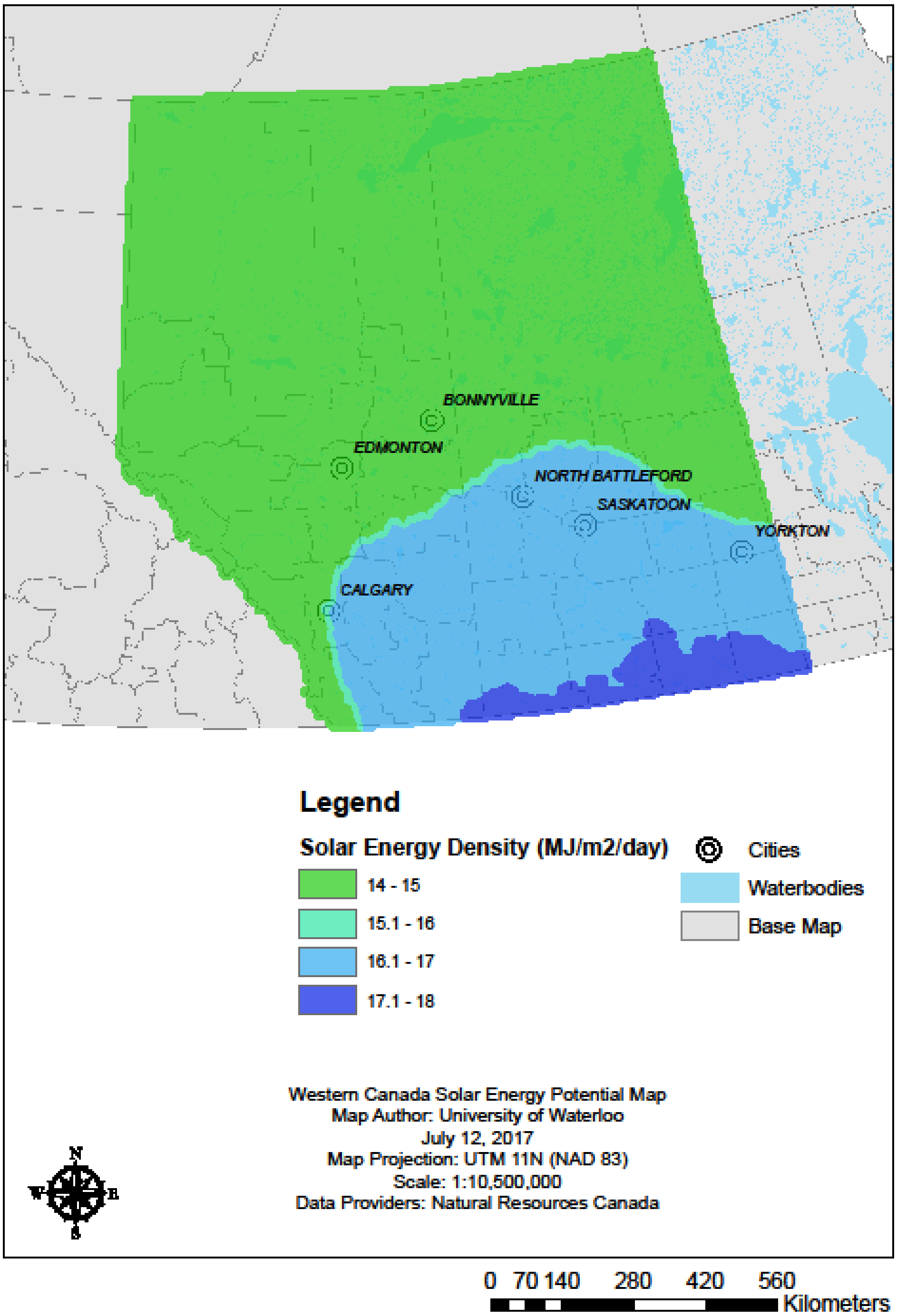
Western Canada Prairie Evaporite Salt Isopach Map



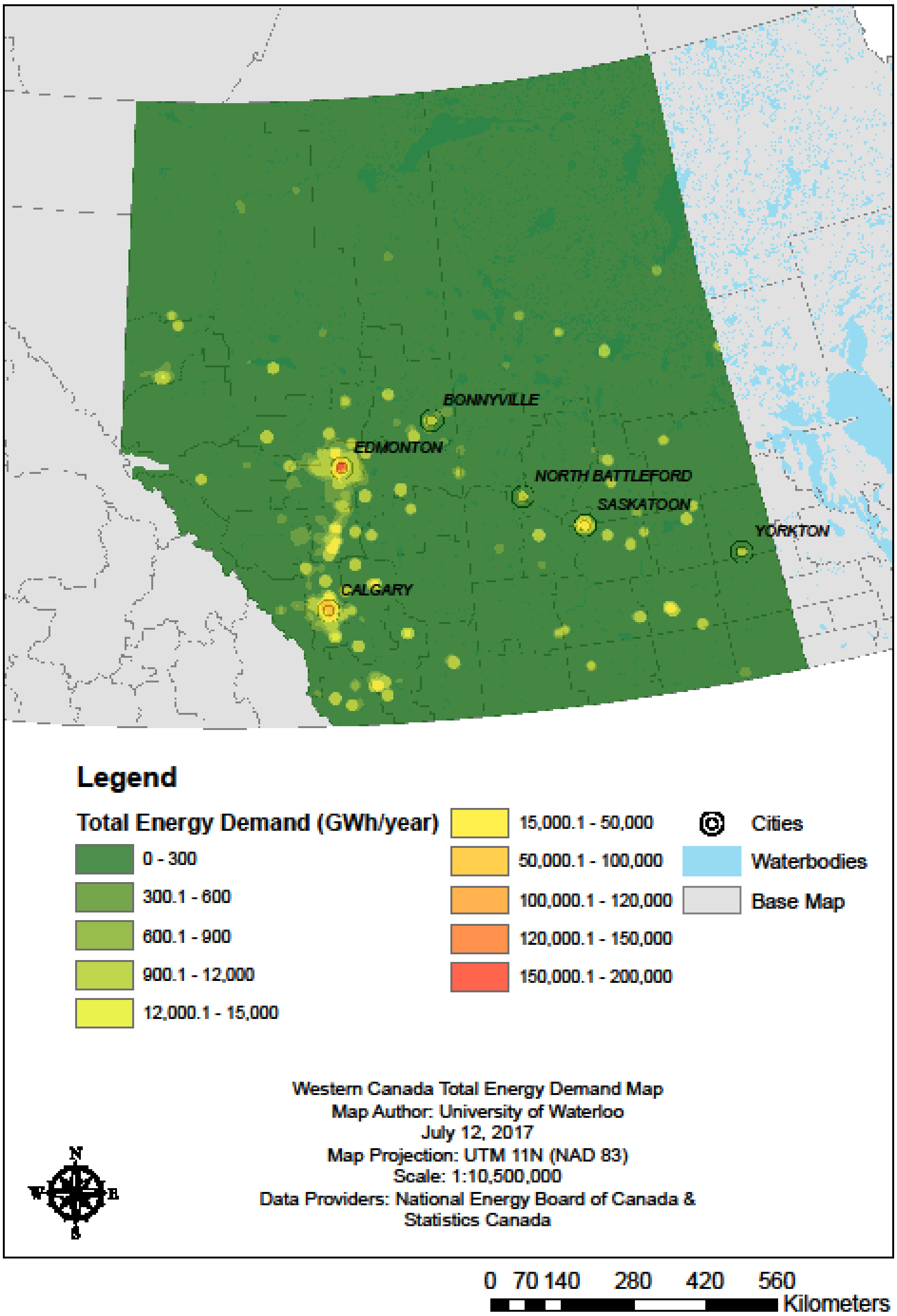
Western Canada Wind Energy Potential Map



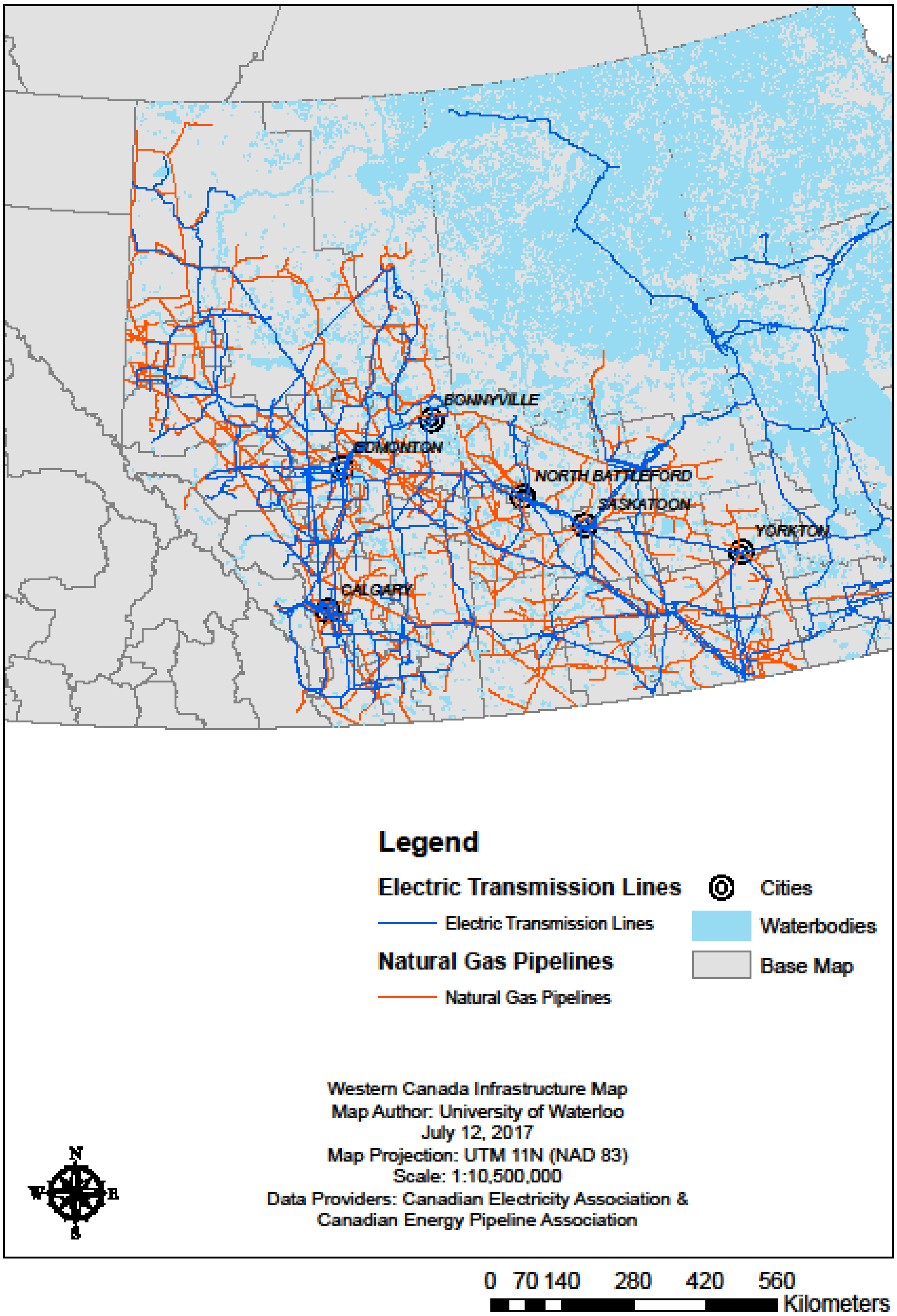
Western Canada Solar Energy Potential Map

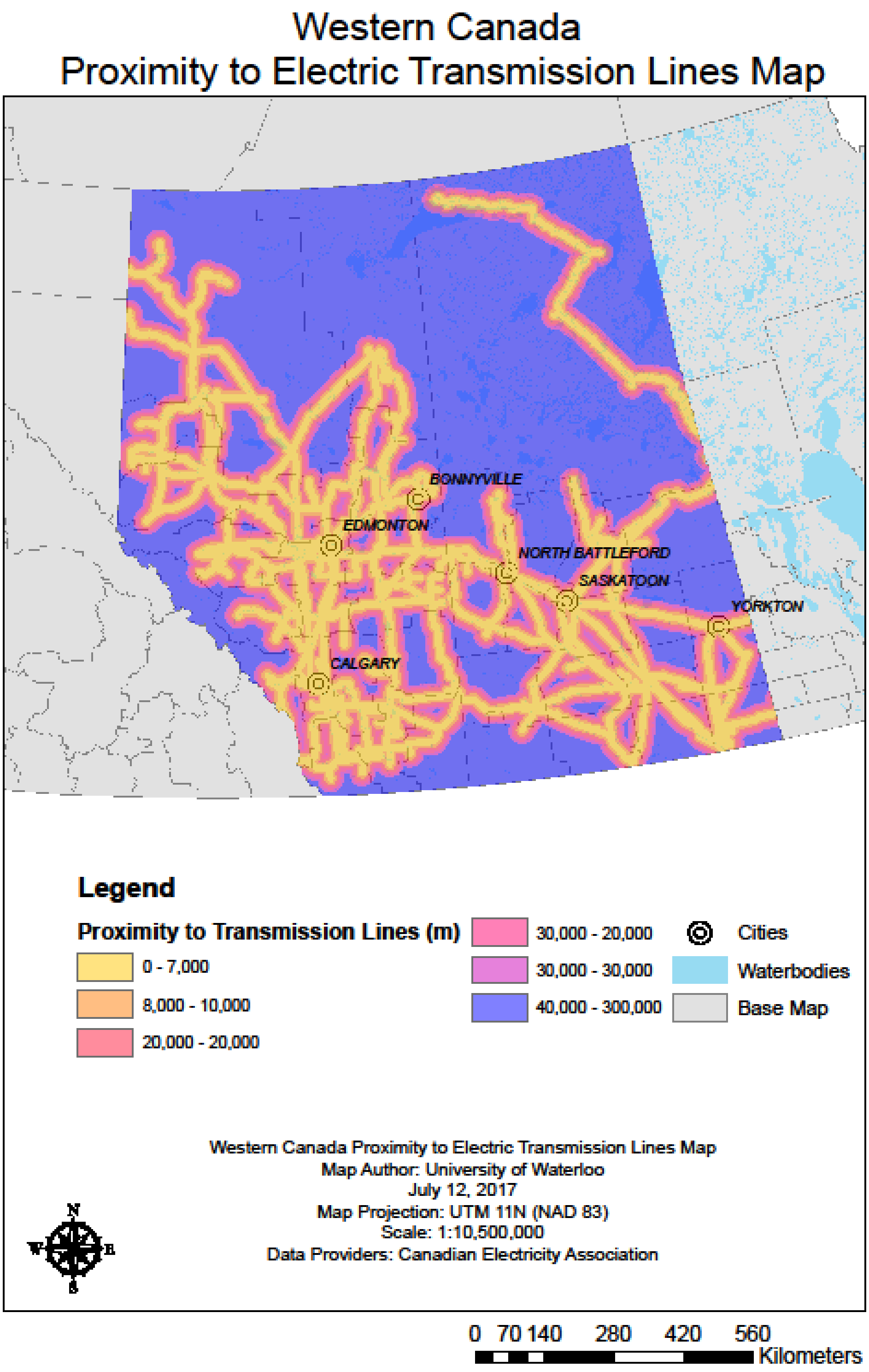


Western Canada Total Energy Demand

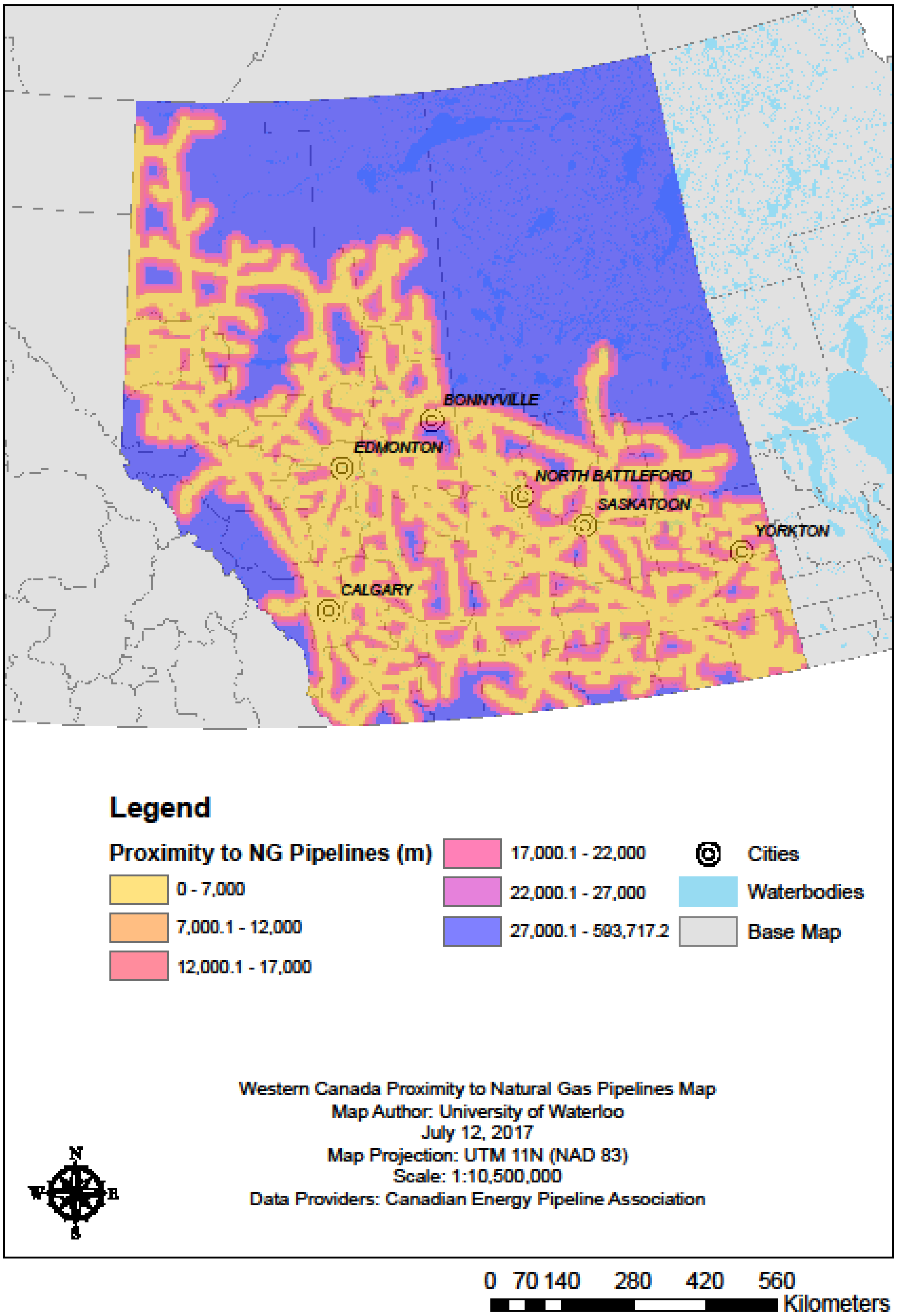


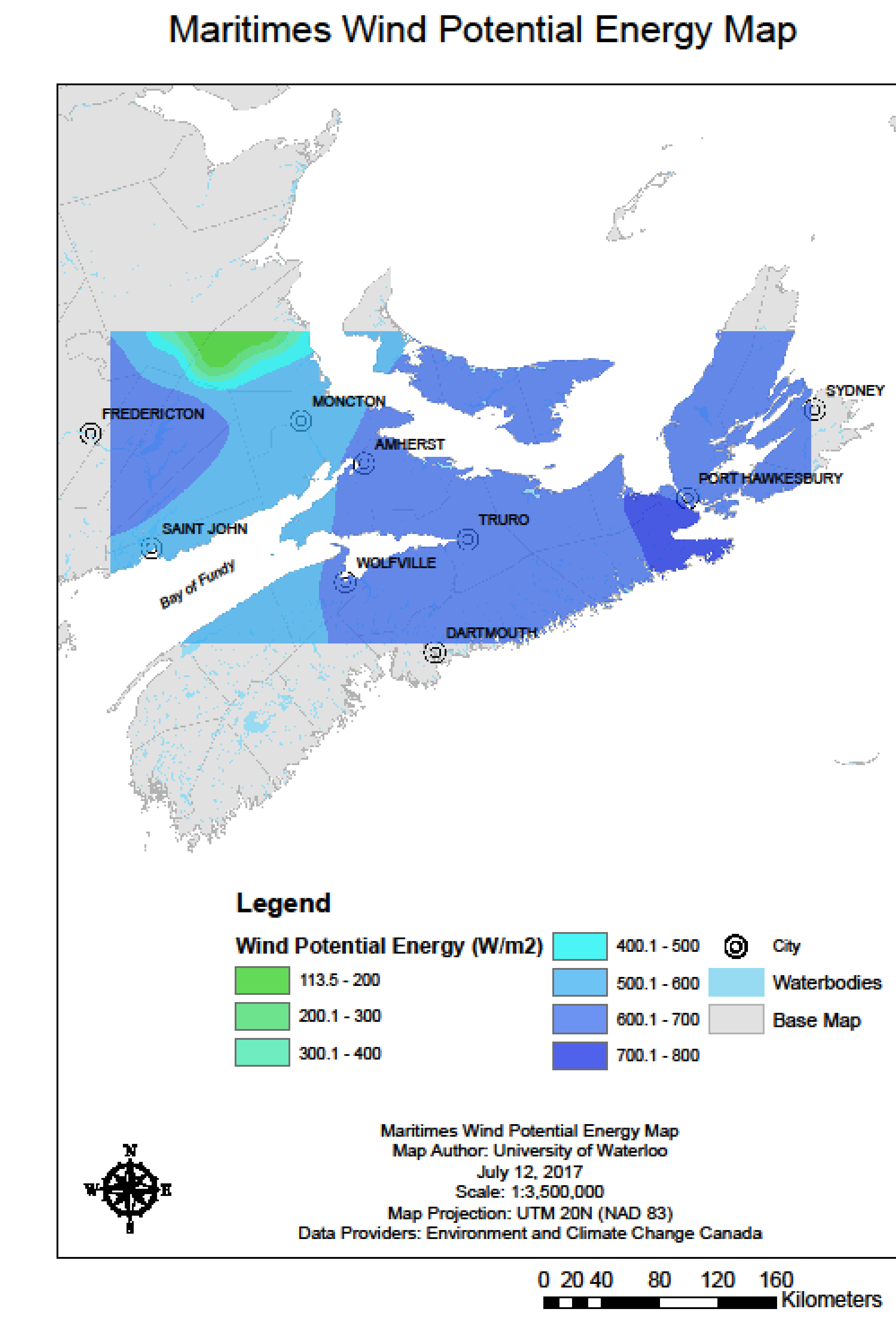
Western Canada Infrastructure Map



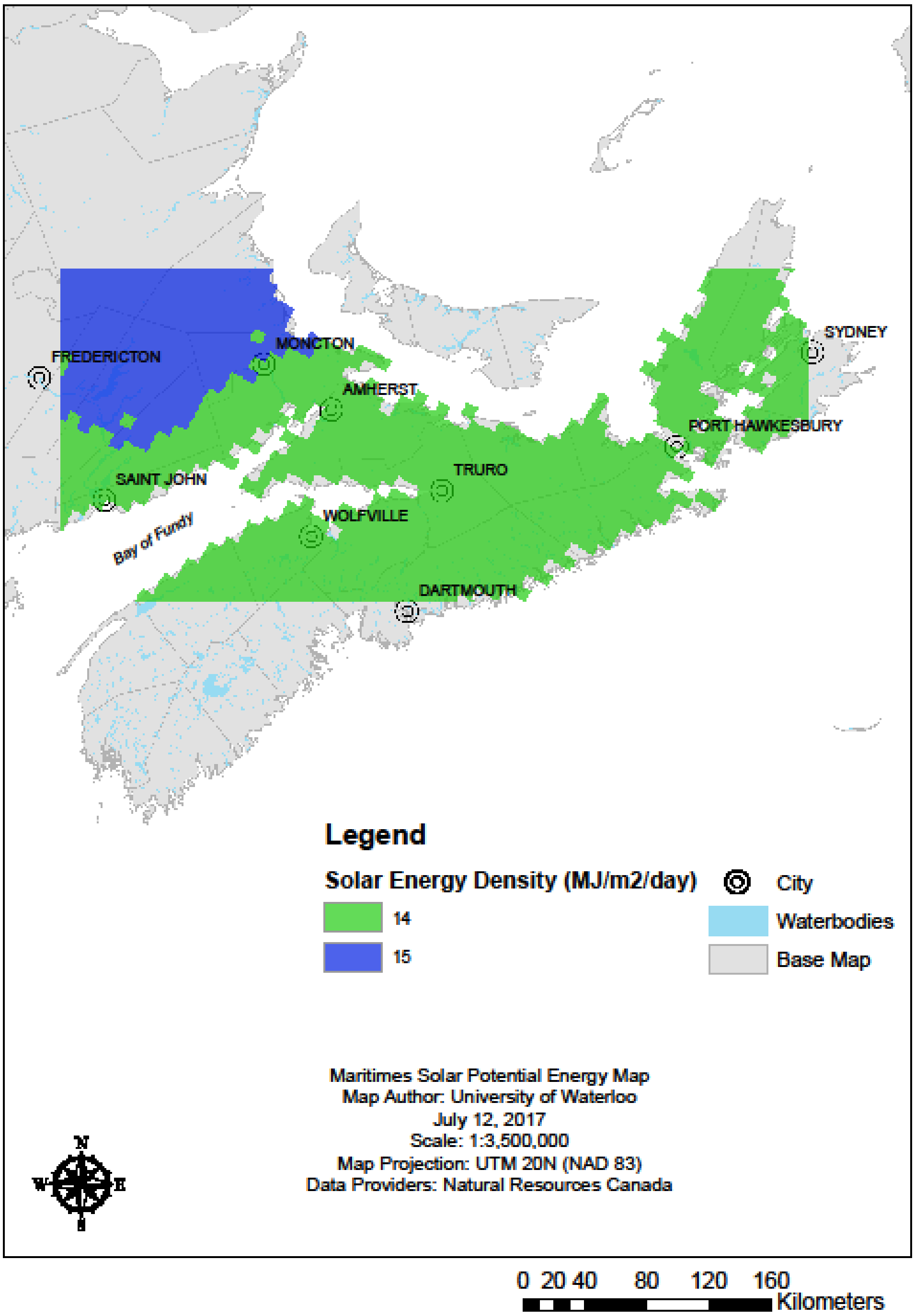

Western Canada
Proximity to Electric Transmission Lines Map
BONNYVILLE
EDMONTON
NORTH BATTLEFORD
SASKATOON
YORKTON
CALGARY
Legend
Proximity to Transmission Lines (m)
0 - 7,000
8,000 - 10,000
20,000 - 20,000
30,000 - 20,000
30,000 - 30,000
40,000 - 300,000
Cities
Waterbodies
Base Map
Western Canada Proximity to Electric Transmission Lines Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000
Data Providers: Canadian Electricity Association
N
W
E
S
0 70 140 280 420 560
Kilometers

Western Canada Proximity to Natural Gas Pipelines

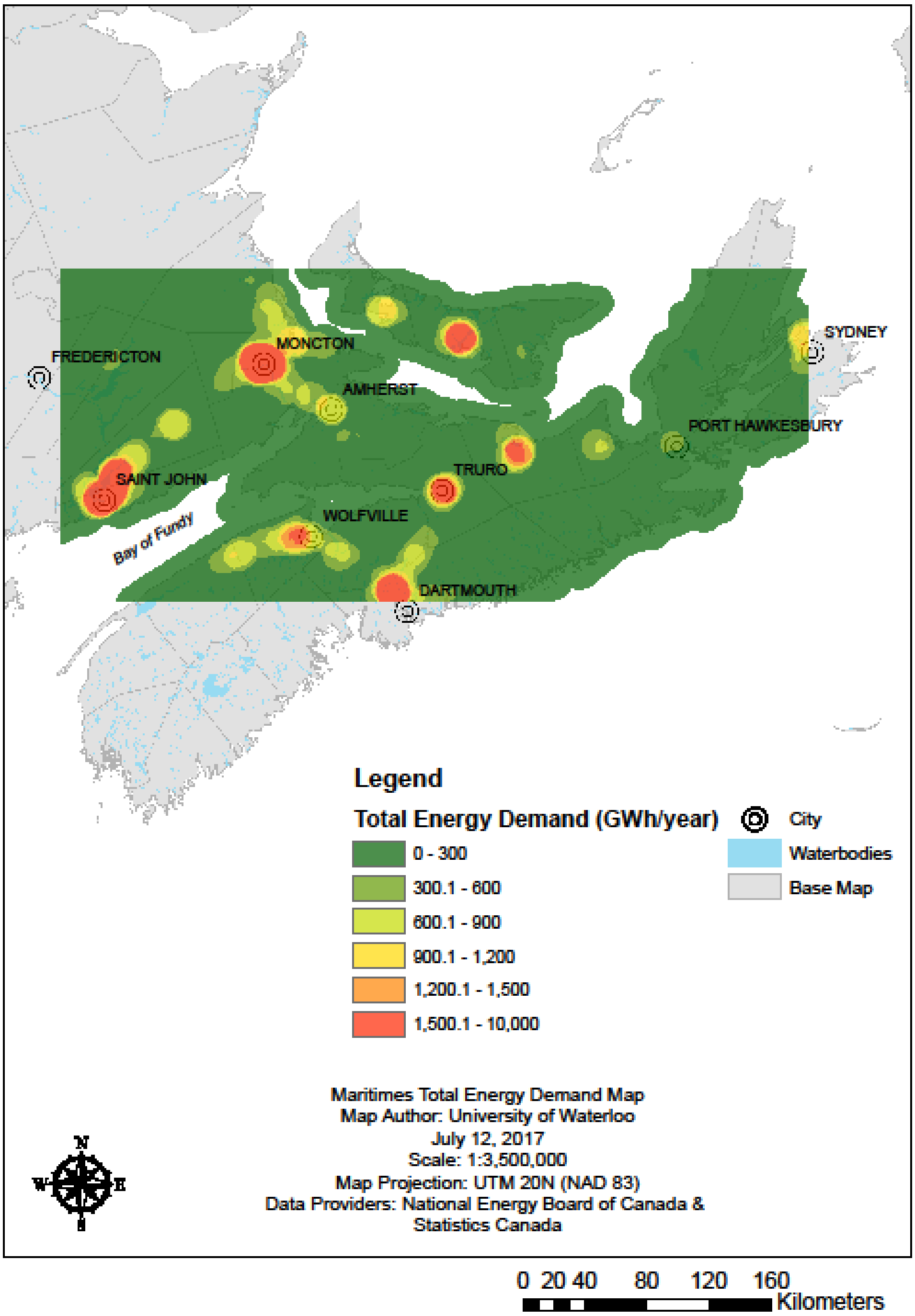



Maritimes Wind Potential Energy Map
FREDERICTON
MONCTON
AMHERST
SYDNEY
PORT HAWKESBURY
TRURO
SAINT JOHN
WOLFVILLE
Bay of Fundy
DARTMOUTH
Legend
Wind Potential Energy (W/m2)
113.5 - 200
200.1 - 300
300.1 - 400
400.1 - 500
500.1 - 600
600.1 - 700
700.1 - 800
City
Waterbodies
Base Map
N
W
E
S
Maritimes Wind Potential Energy Map
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)
Data Providers: Environment and Climate Change Canada
0 20 40 80 120 160
Kilometers

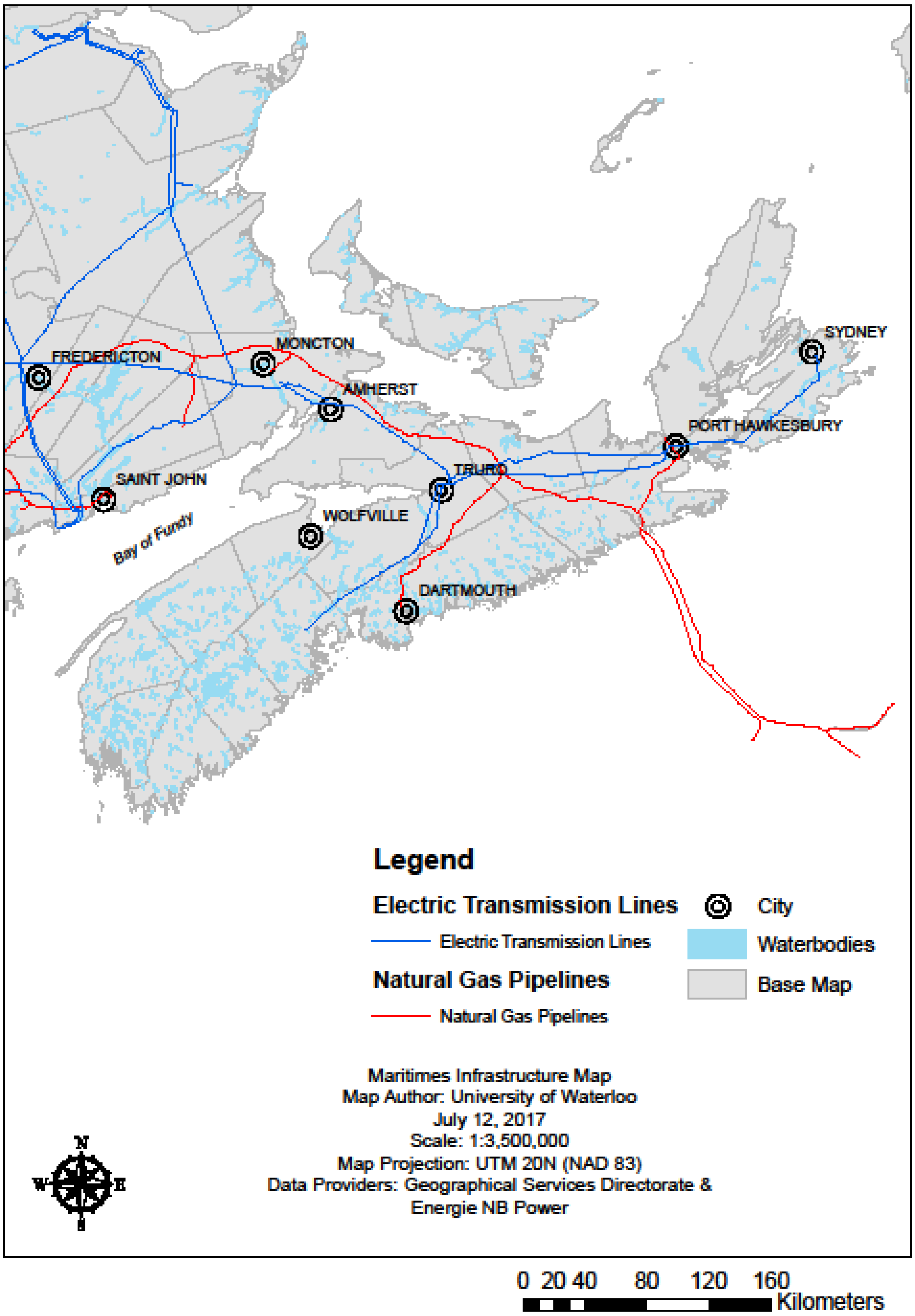
Maritimes Solar Potential Energy Map



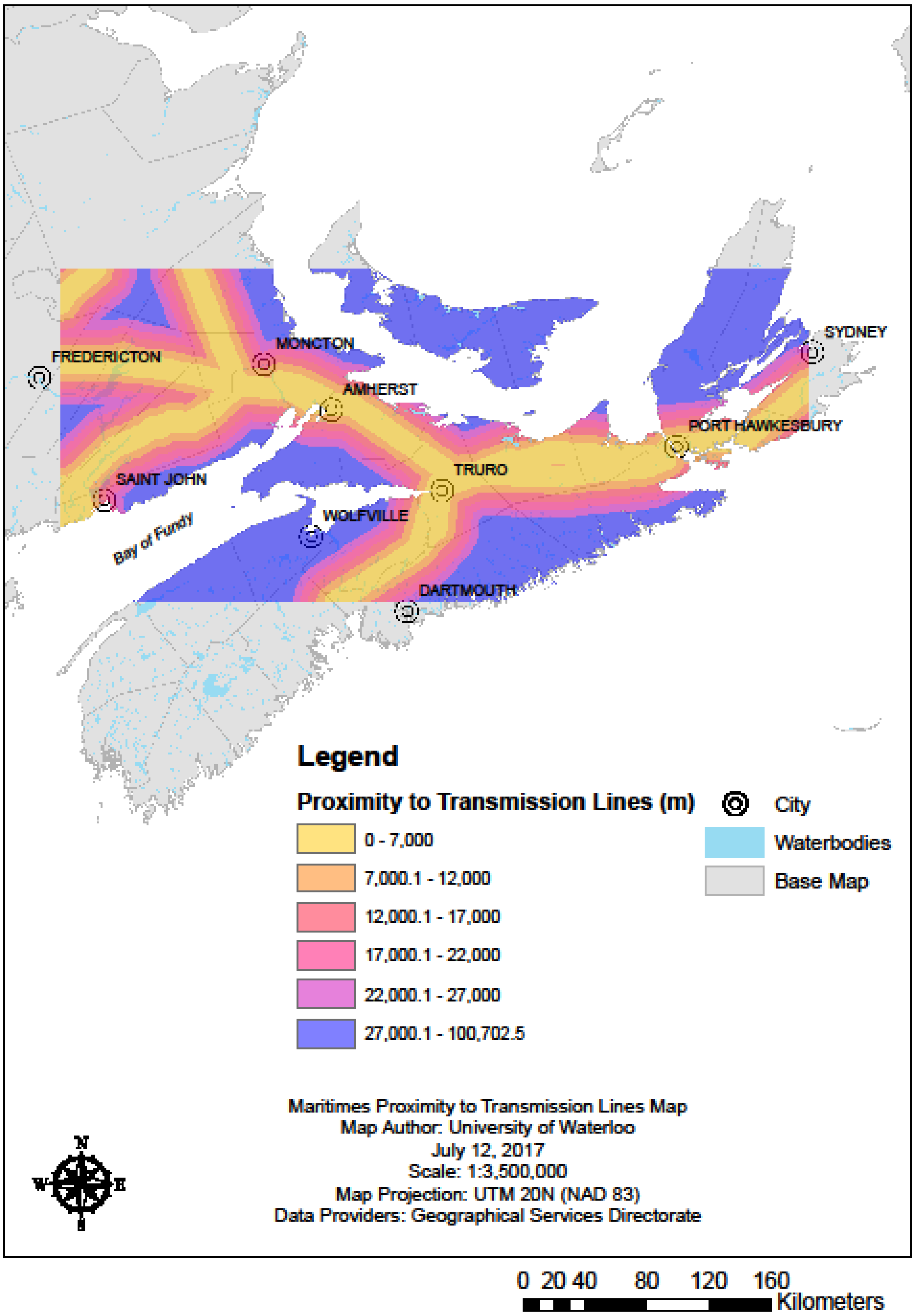
Maritimes Total Energy Demand Map



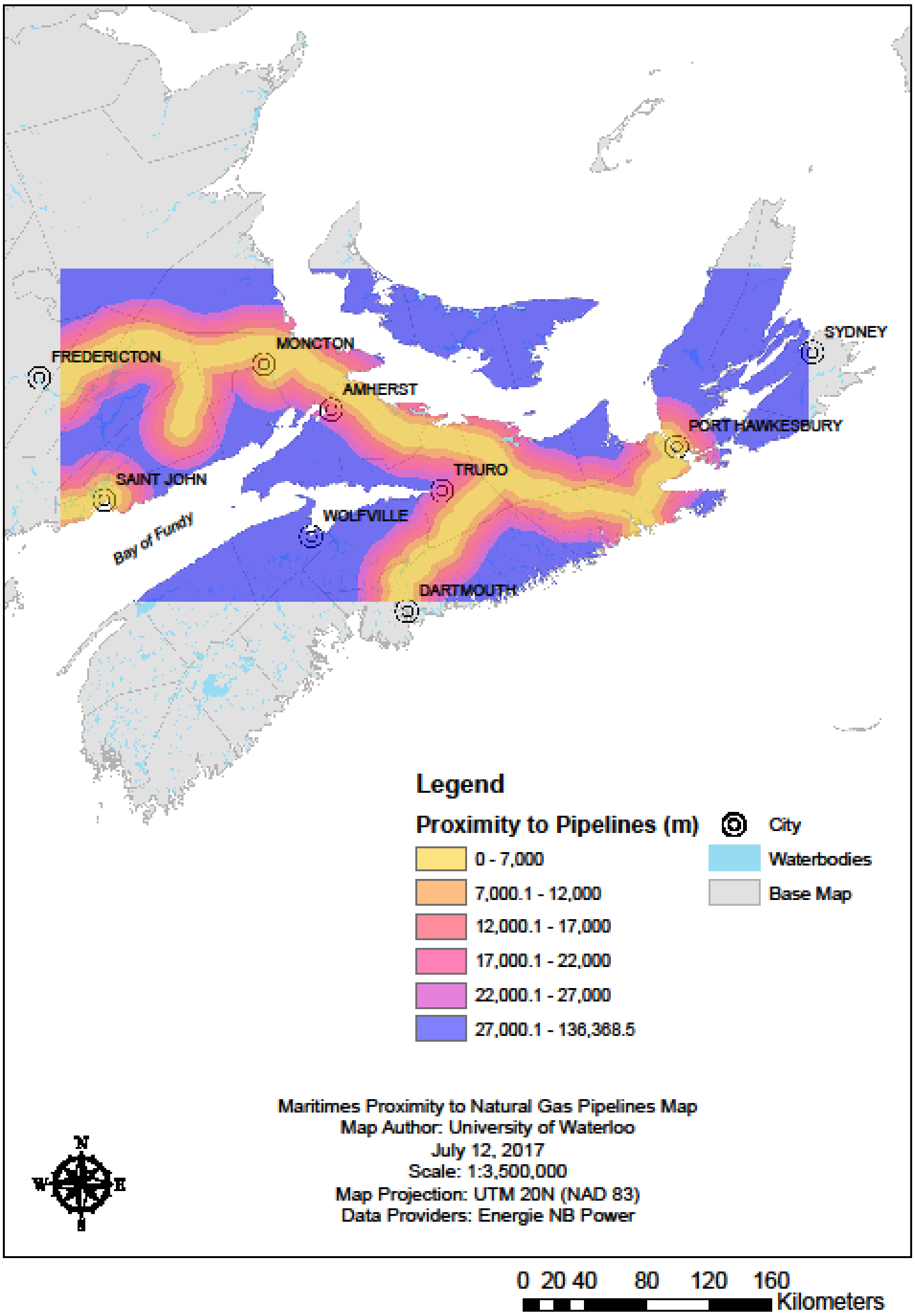
Maritimes Infrastructure Map



Maritimes Proximity to Transmission Lines Map

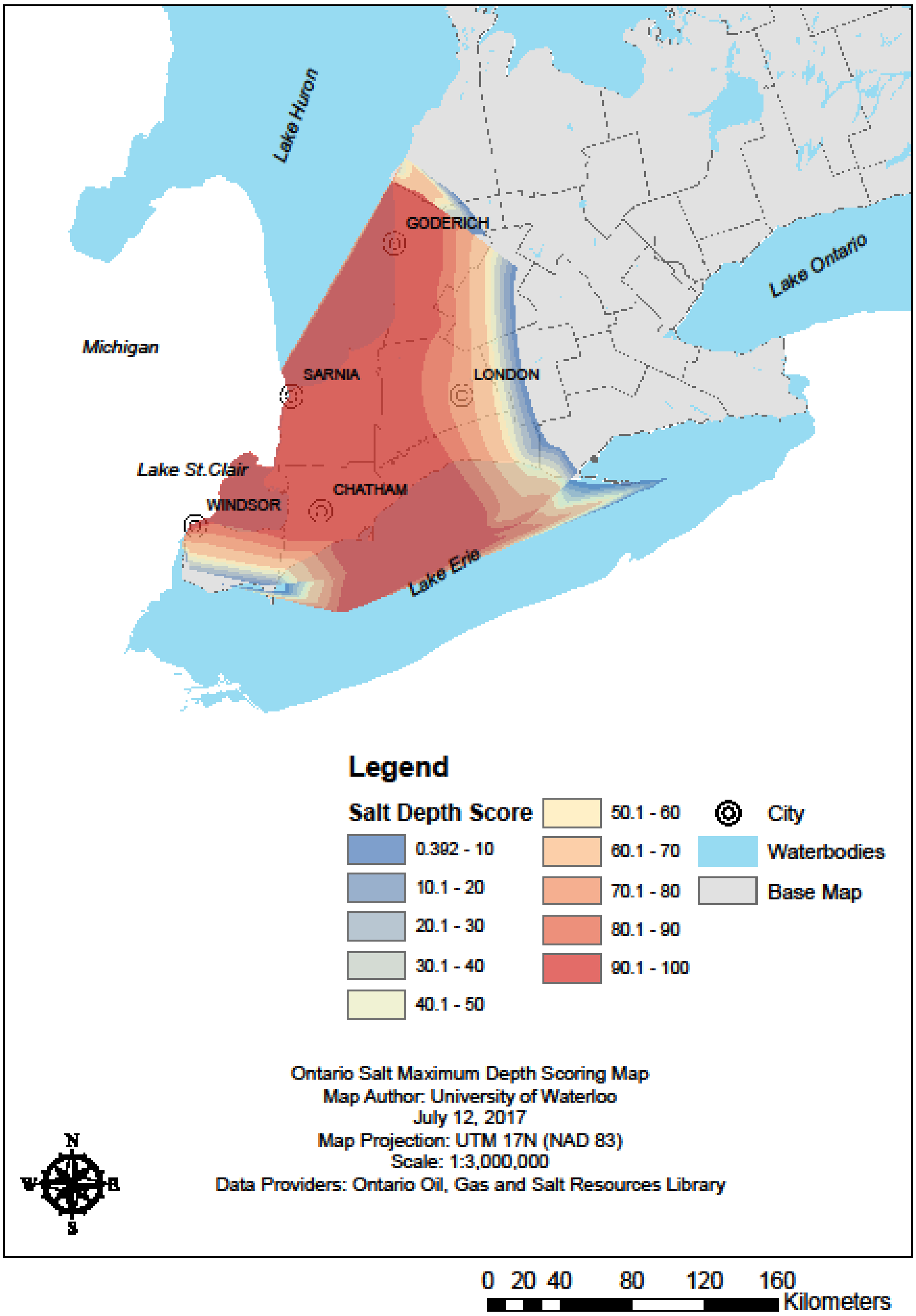


Maritimes Proximity to Natural Gas Pipelines Map

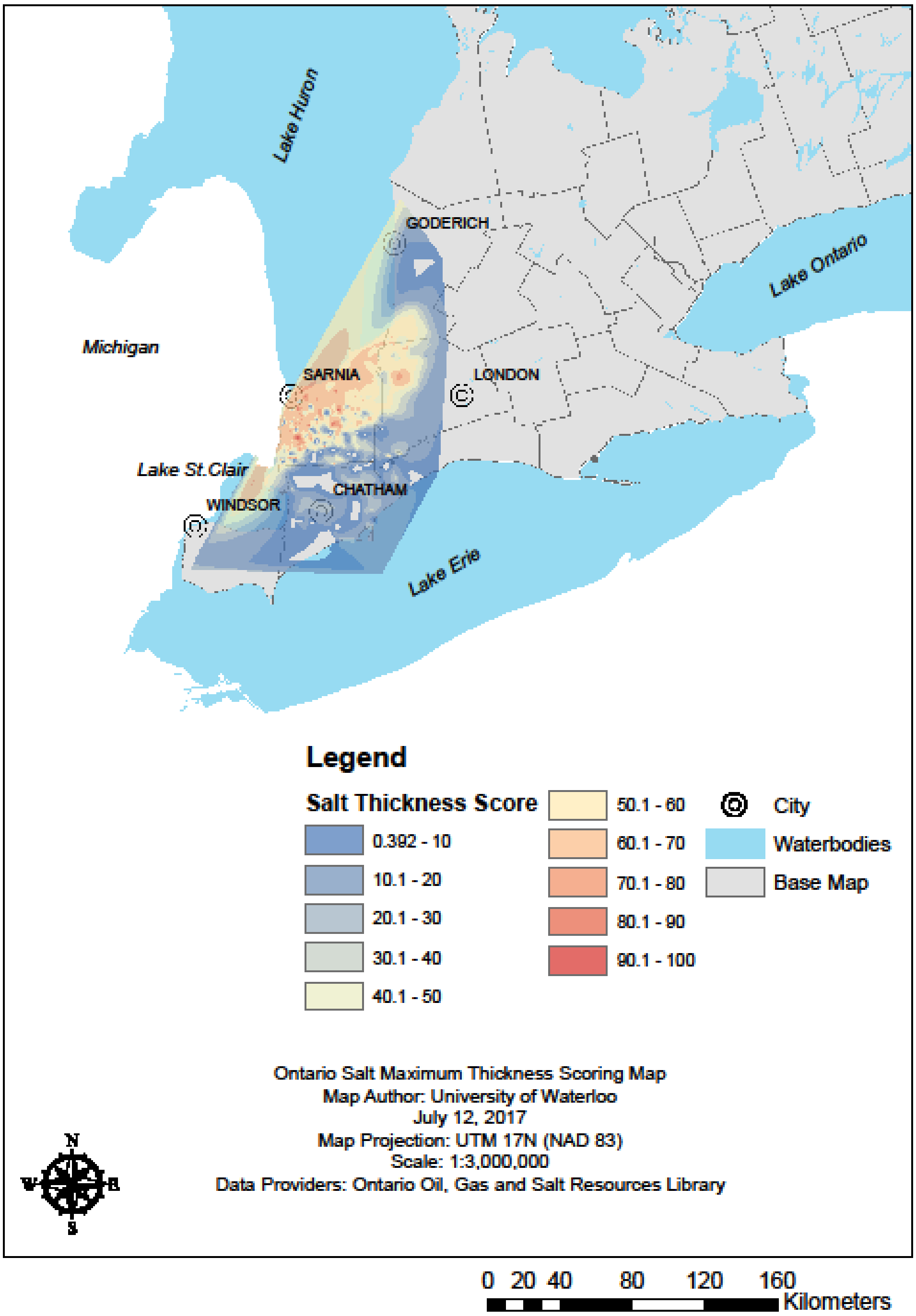


Appendix B: Scored Criteria Data Maps for Ontario, Western Canada, and Maritimes (CAES Siting Study)

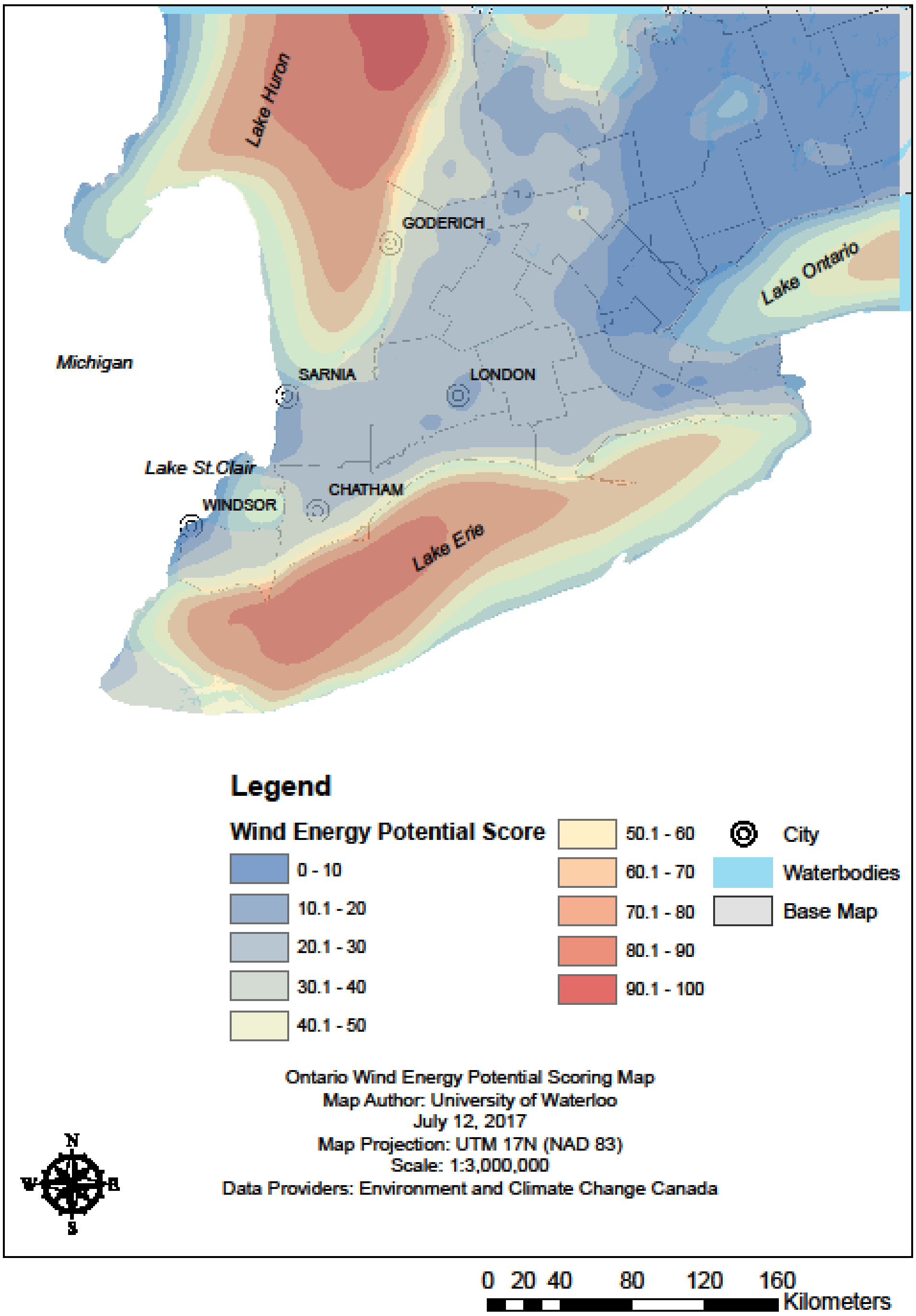
Ontario Salt Maximum Depth Scoring Map

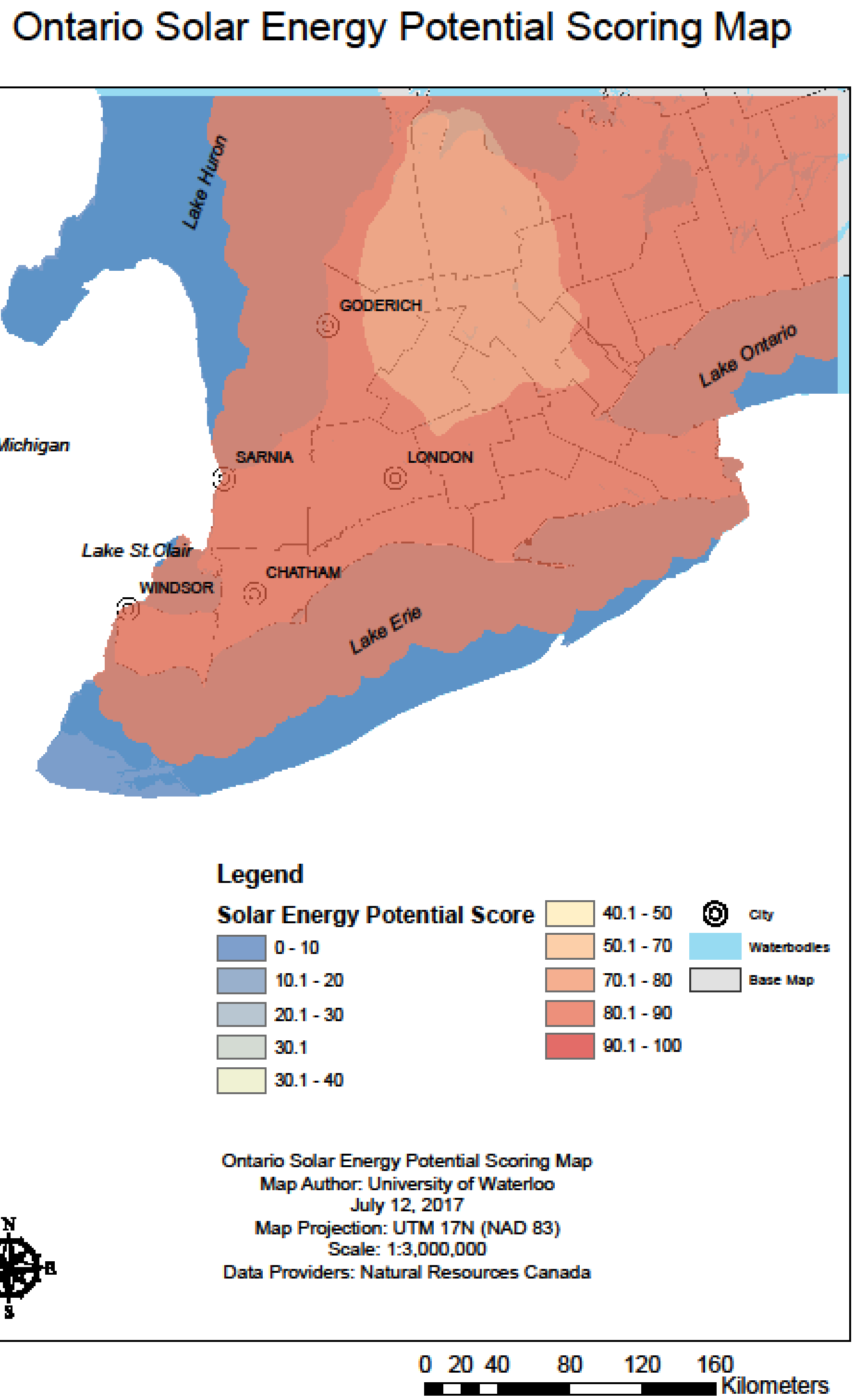


Ontario Salt Maximum Thickness Scoring Map



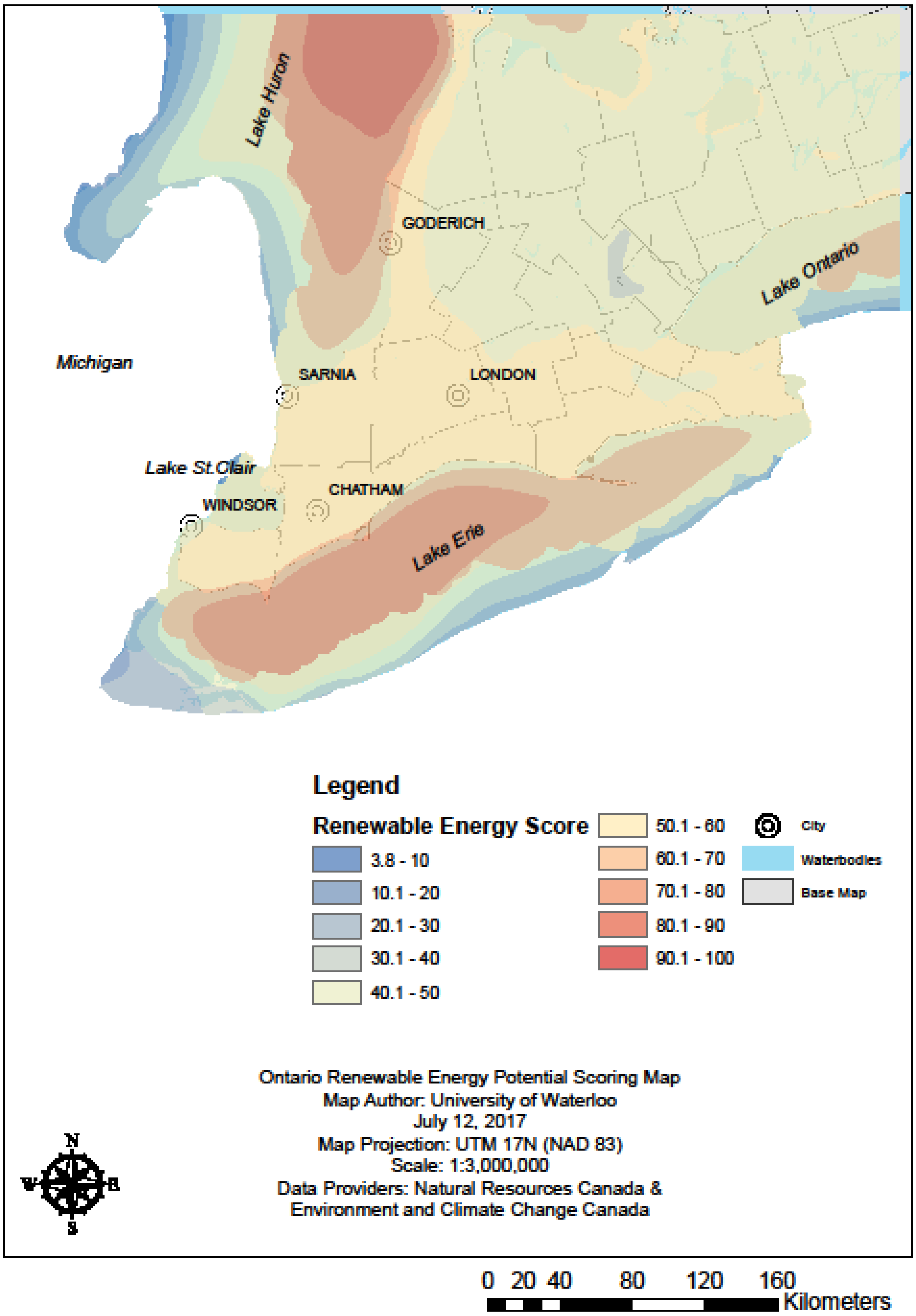
Ontario Wind Energy Potential Scoring Map



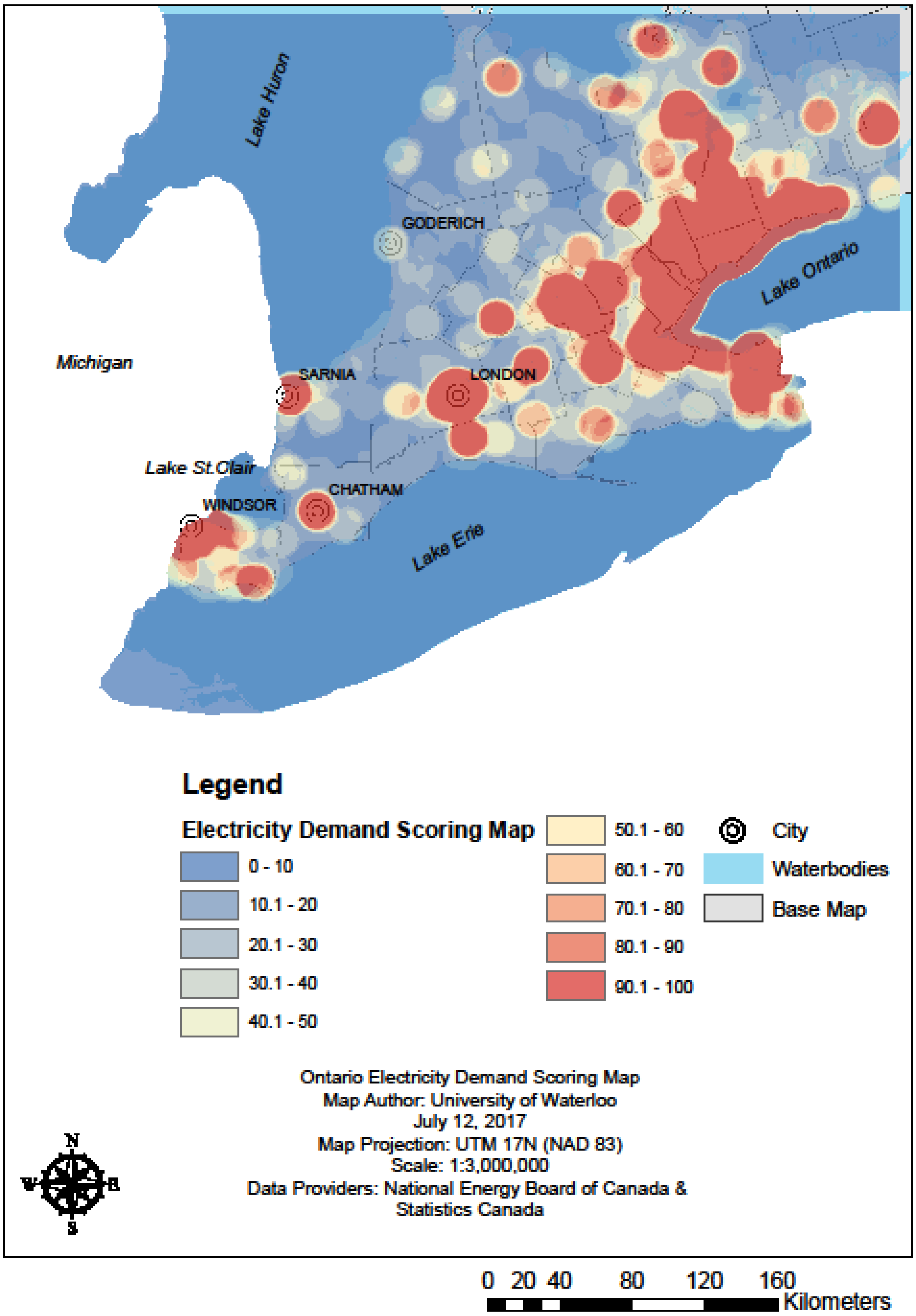


Ontario Solar Energy Potential Scoring Map
Lake Huron
GODERICH
Lake Ontario
Michigan
SARNIA
LONDON
Lake St.Clair
WINDSOR
CHATHAM
Lake Erie
Legend
Solar Energy Potential Score
0 - 10
10.1 - 20
20.1 - 30
30.1
30.1 - 40
40.1 - 50
50.1 - 70
70.1 - 80
80.1 - 90
90.1 - 100
City
Waterbodies
Base Map
Ontario Solar Energy Potential Scoring Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 17N (NAD 83)
Scale: 1:3,000,000
Data Providers: Natural Resources Canada
N
W
E
S
0 20 40 80 120 160
Kilometers

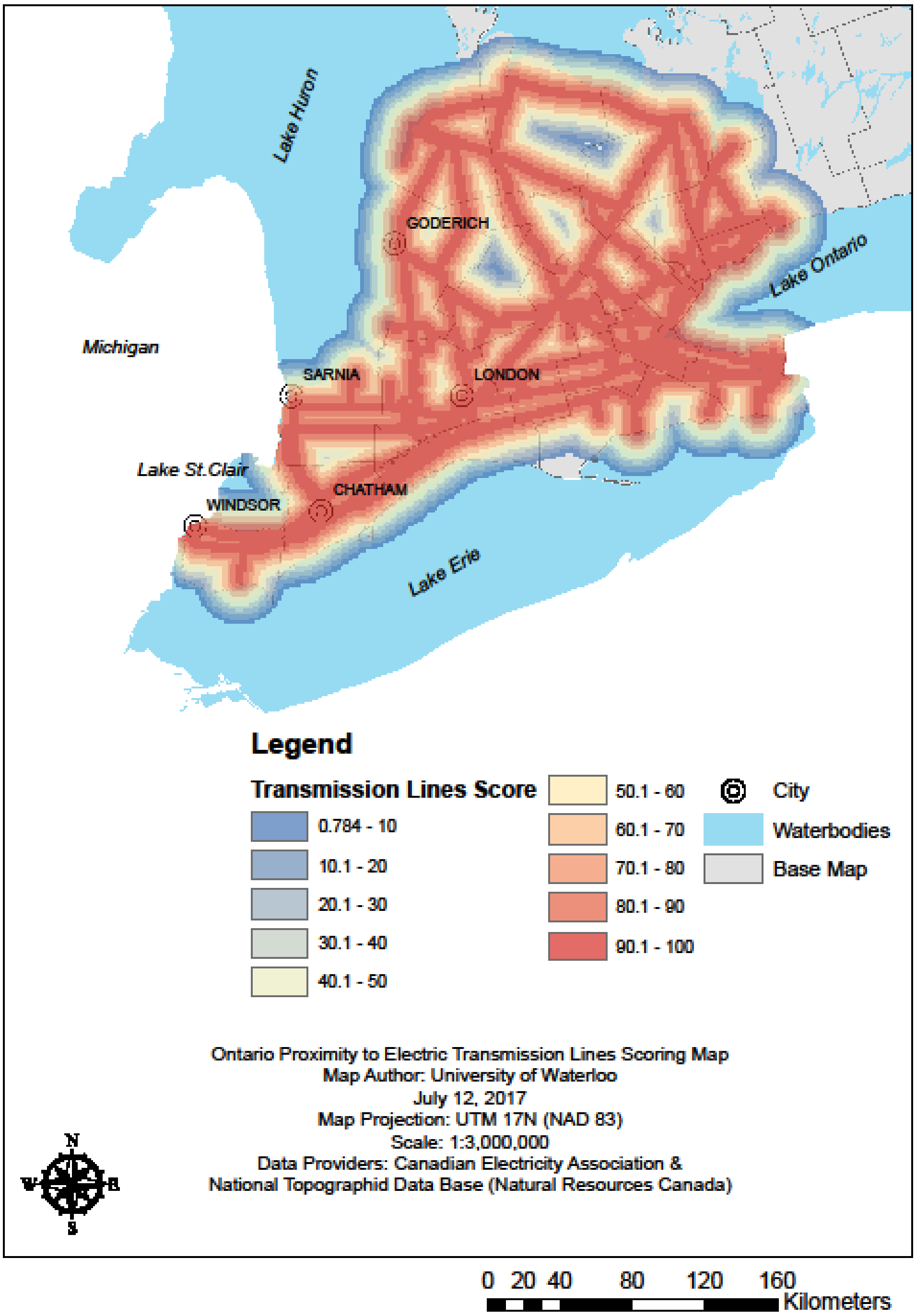
Ontario Renewable Energy Potential Scoring Map



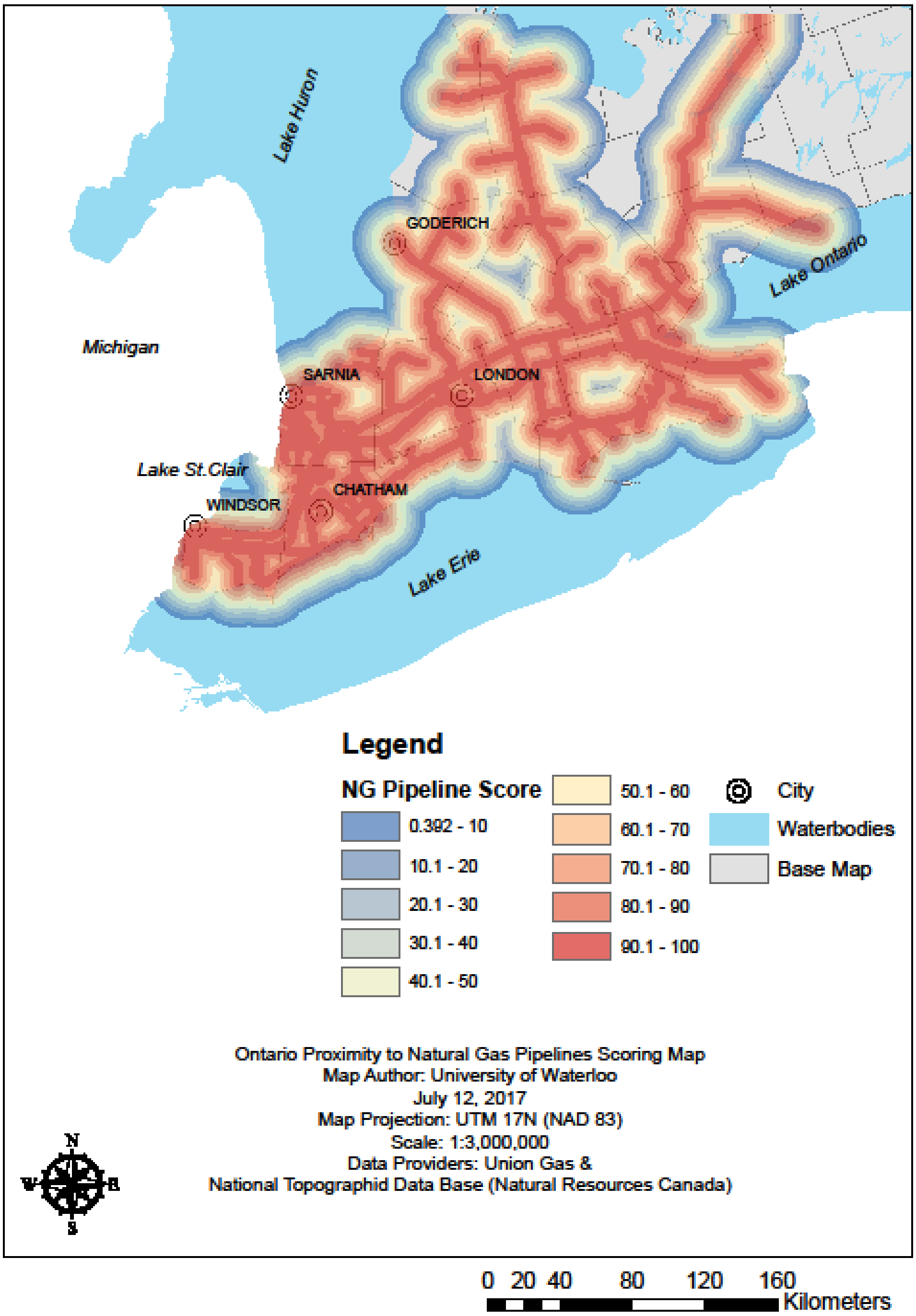
Ontario Electricity Demand Scoring Map



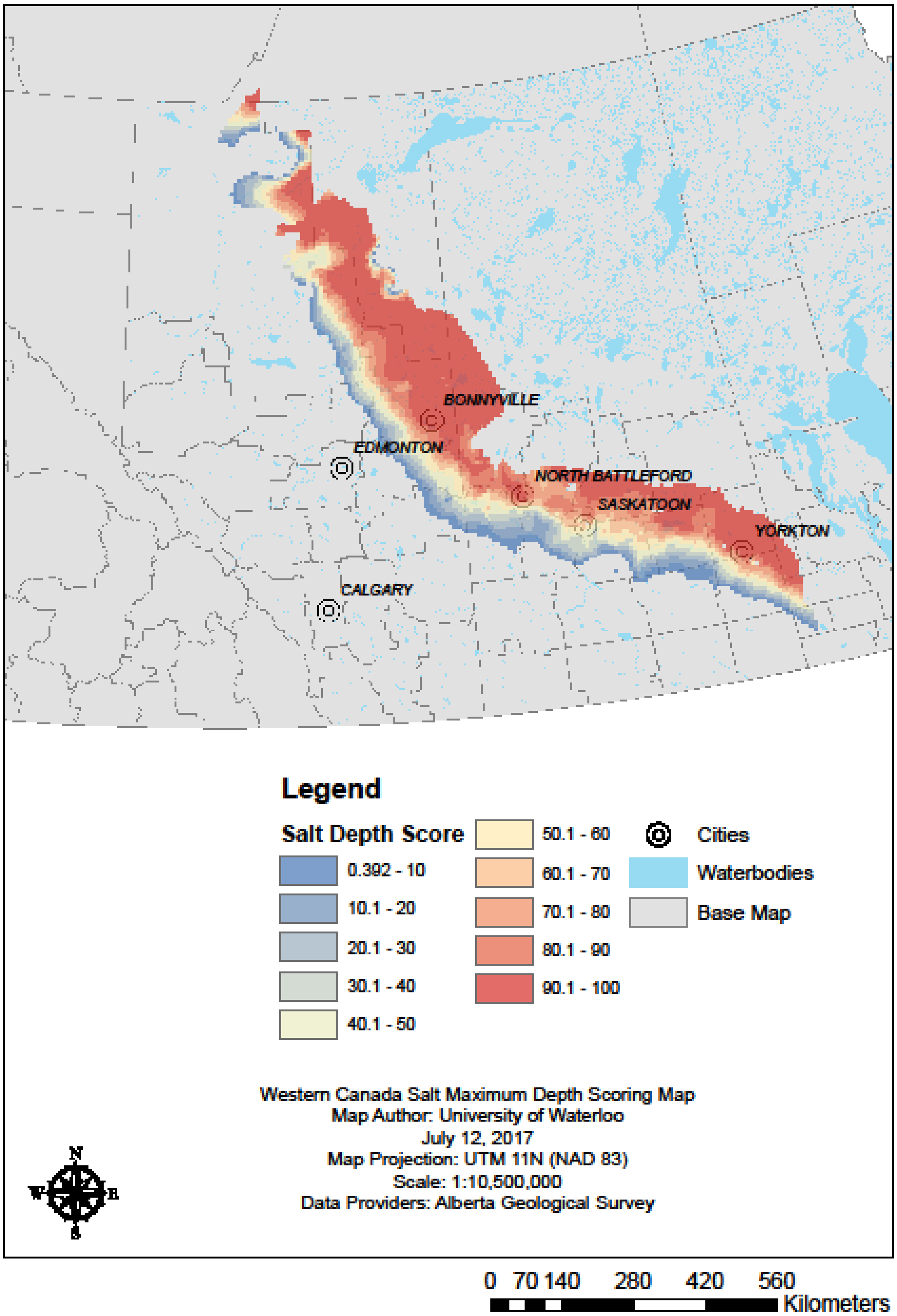
Ontario Proximity to Electric Transmission Lines Scoring Map



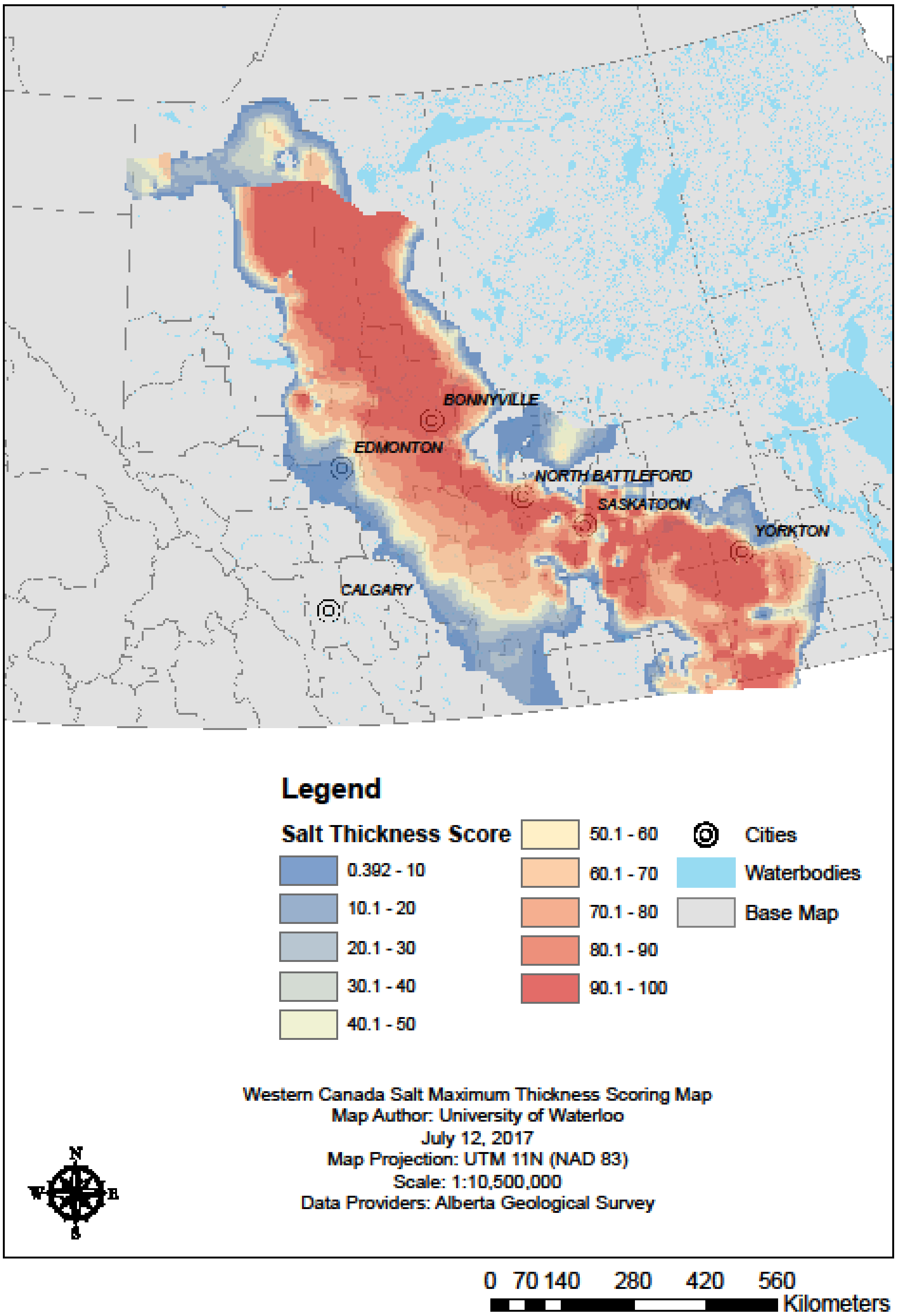
Ontario Proximity to Natural Gas Pipelines Scoring Map



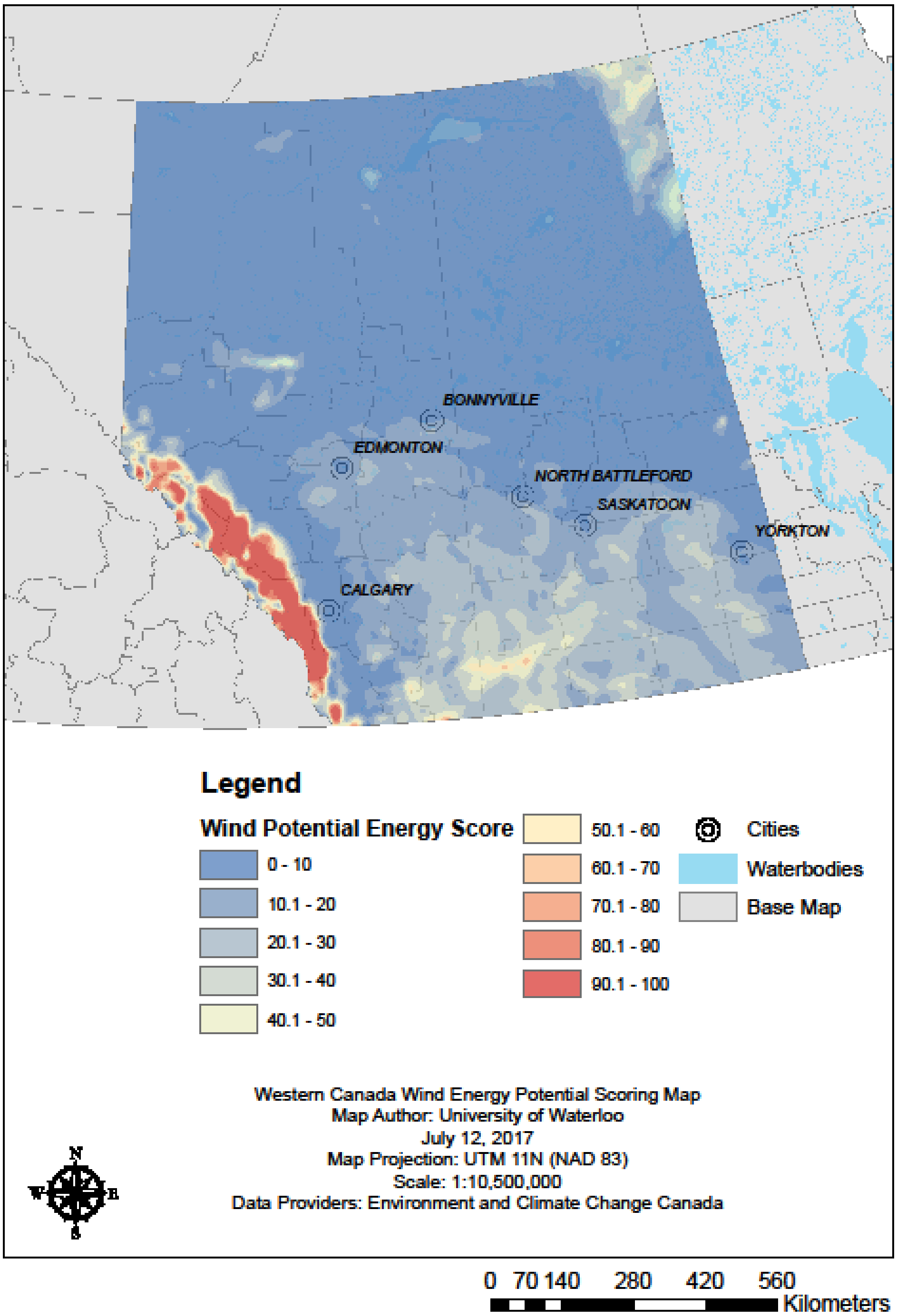
Western Canada Salt Maximum Depth Scoring Map



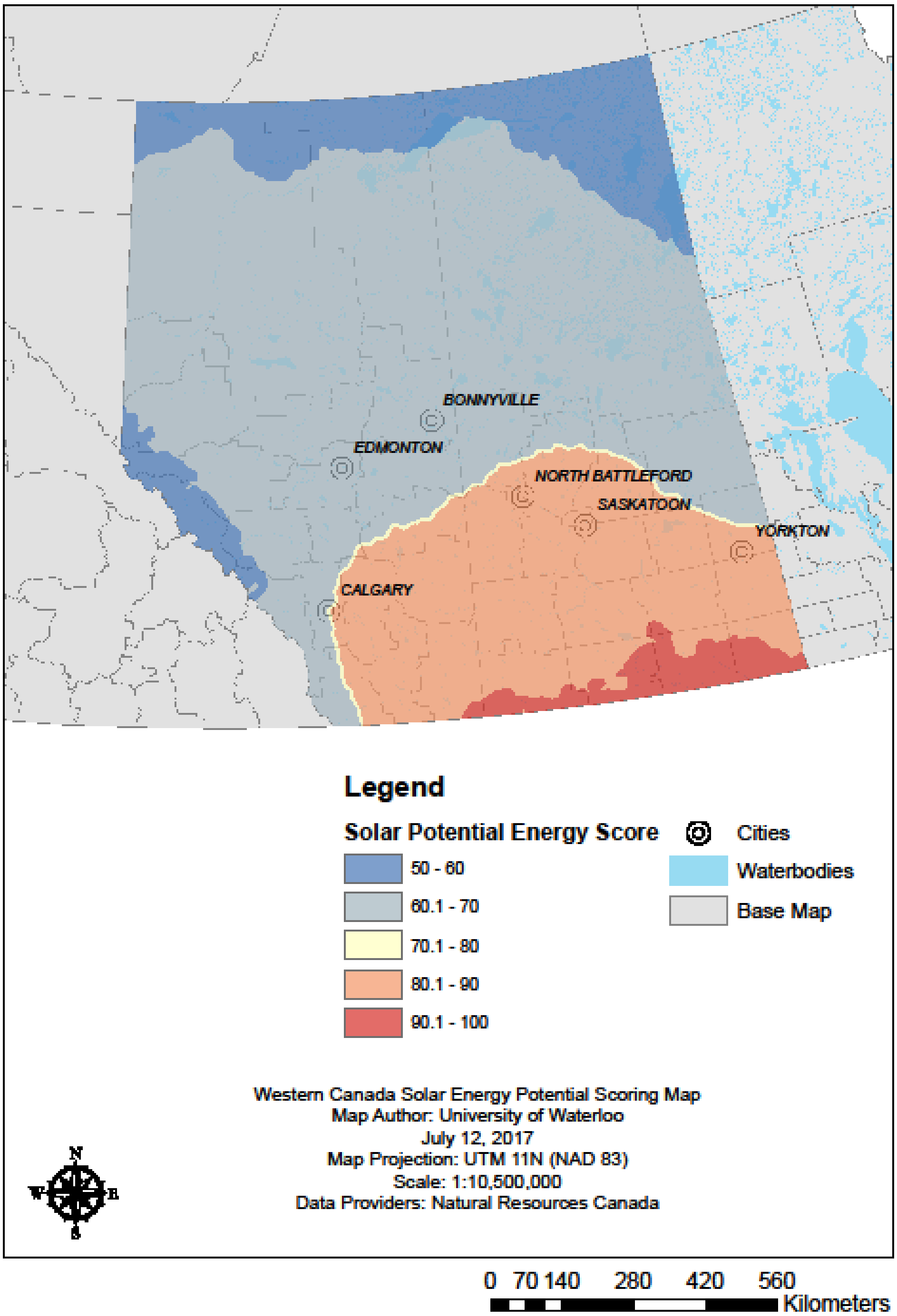
Western Canada Salt Maximum Thickness Scoring Map



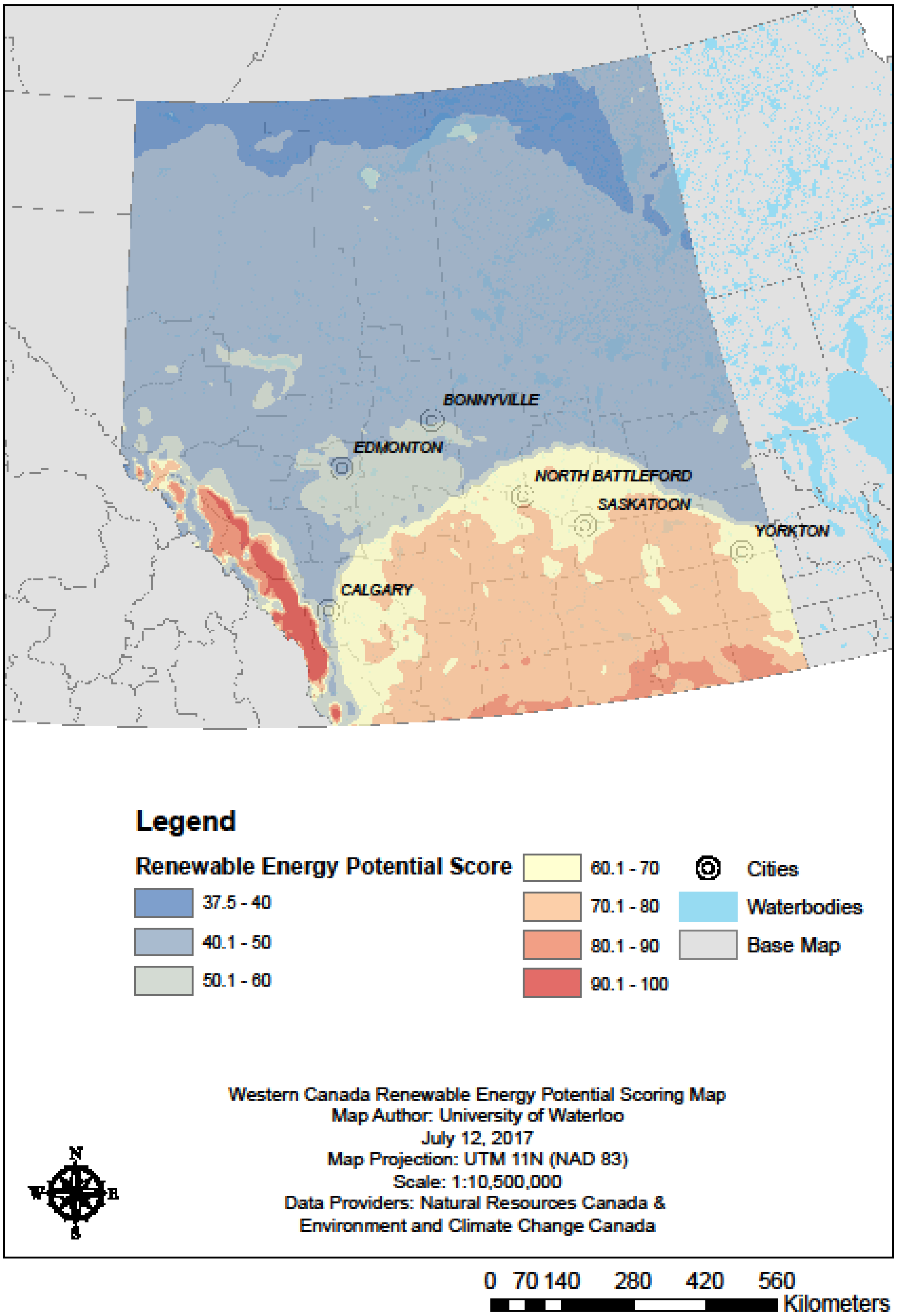
Western Canada Wind Energy Potential Scoring Map



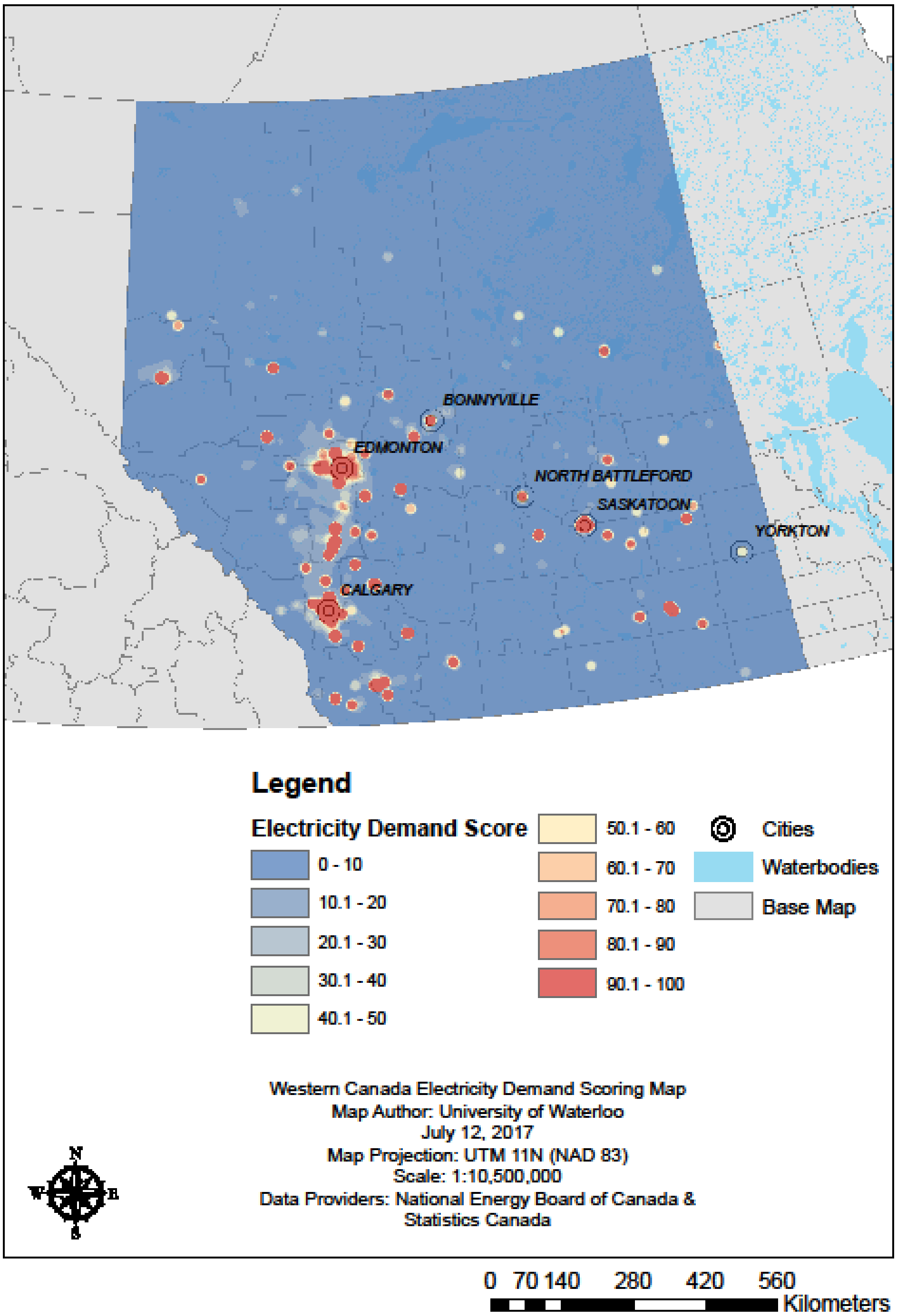
Western Canada Solar Energy Potential Scoring Map



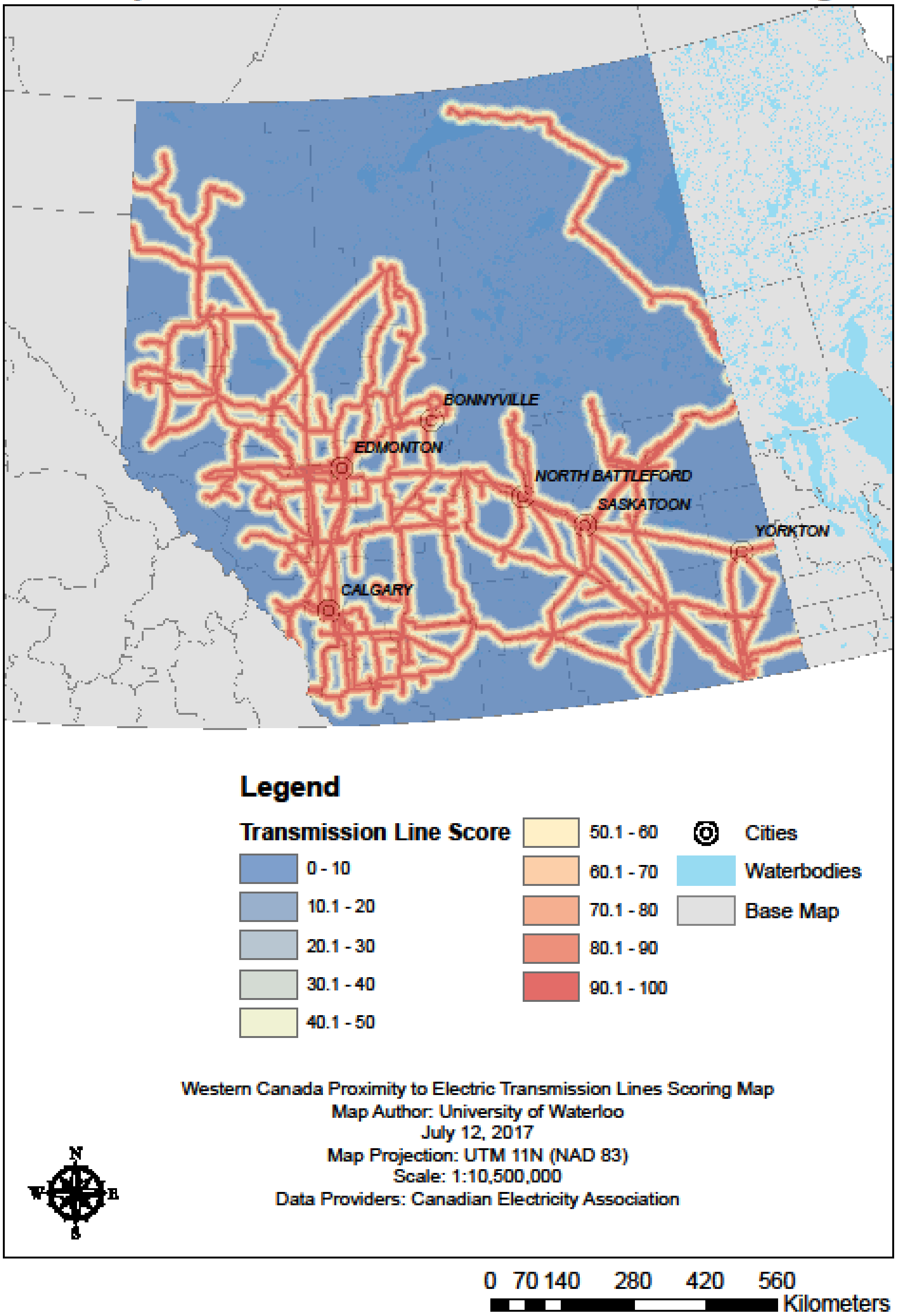
Western Canada Renewable Energy Potential Scoring Map

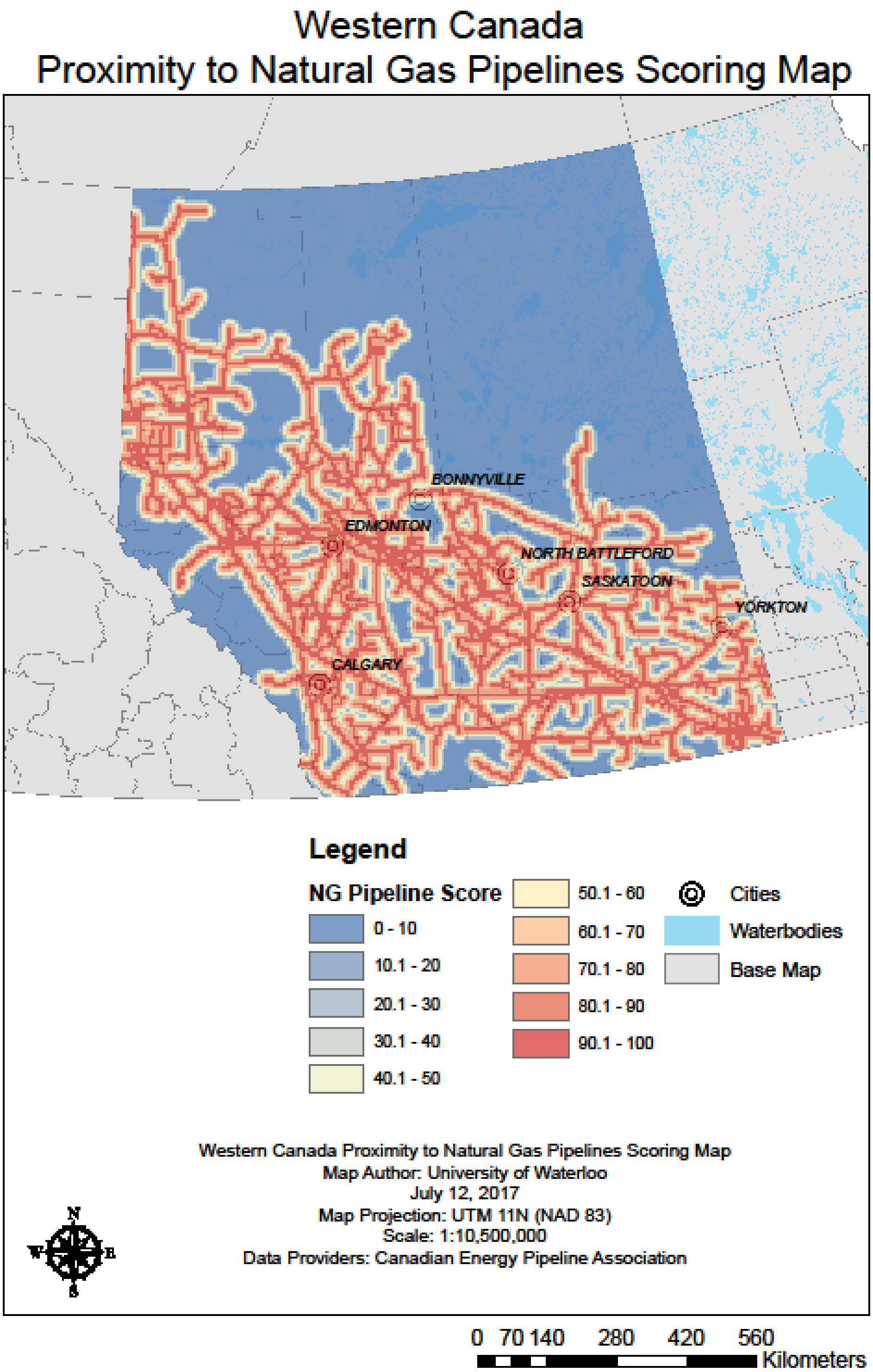


Western Canada Electricity Demand Scoring Map

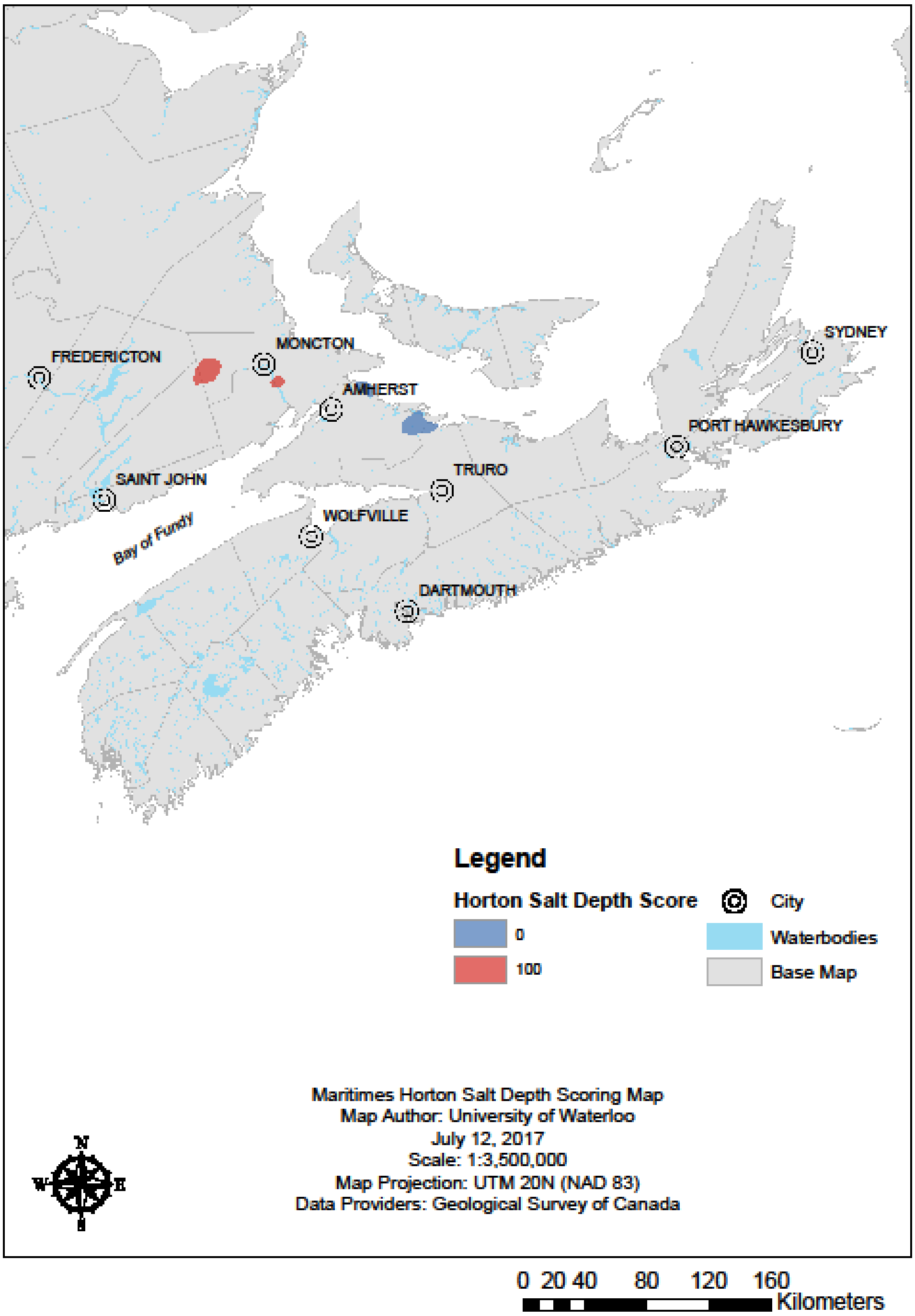


Western Canada
Proximity to Electric Transmission Lines Scoring Map

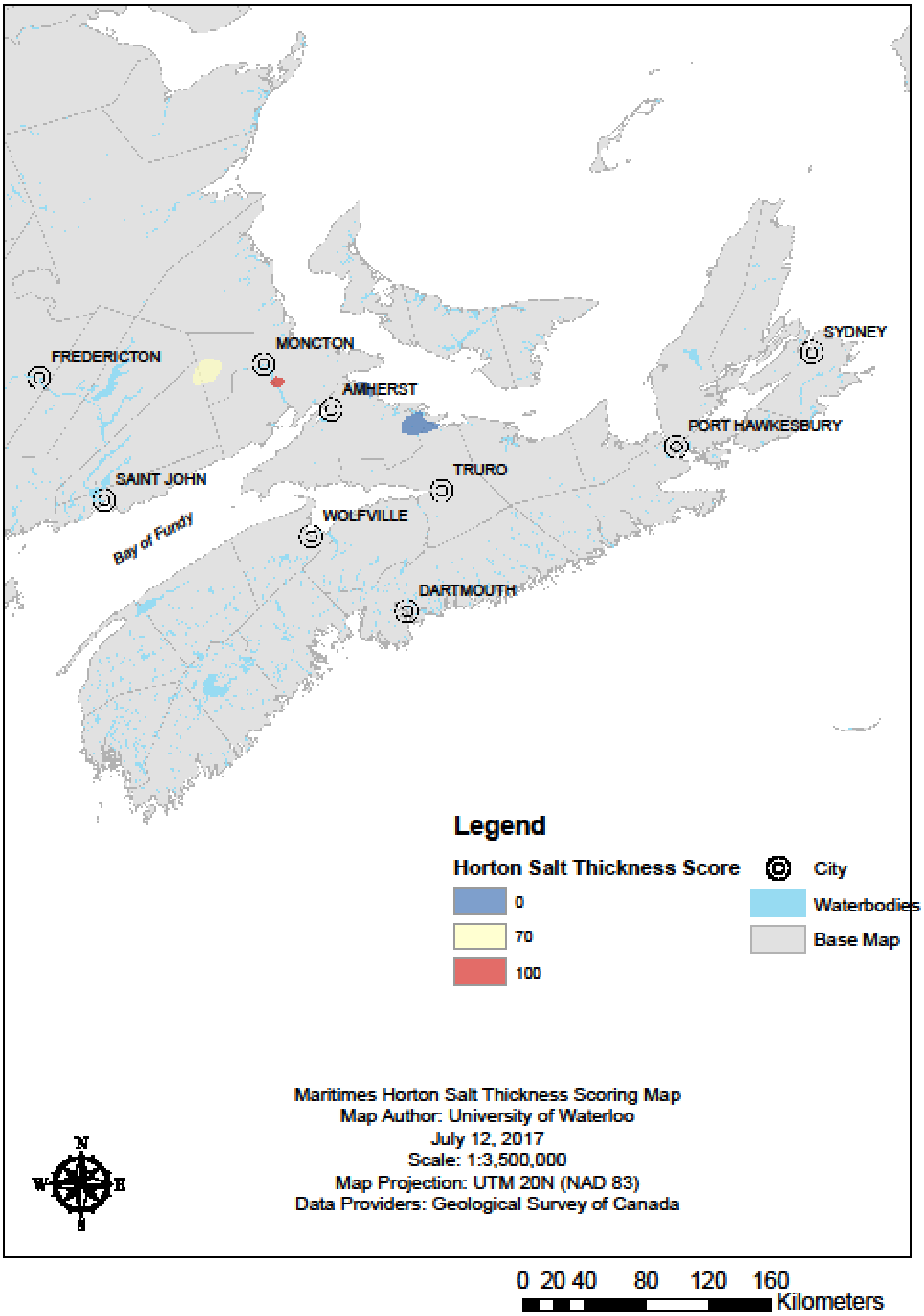



Western Canada
Proximity to Natural Gas Pipelines Scoring Map
BONNYVILLE
EDMONTON
NORTH BATTLEFORD
SASKATOON
YORKTON
CALGARY
Legend
NG Pipeline Score
0 - 10
10.1 - 20
20.1 - 30
30.1 - 40
40.1 - 50
50.1 - 60
60.1 - 70
70.1 - 80
80.1 - 90
90.1 - 100
Cities
Waterbodies
Base Map
Western Canada Proximity to Natural Gas Pipelines Scoring Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000
Data Providers: Canadian Energy Pipeline Association
N
W
E
S
0 70 140 280 420 560
Kilometers

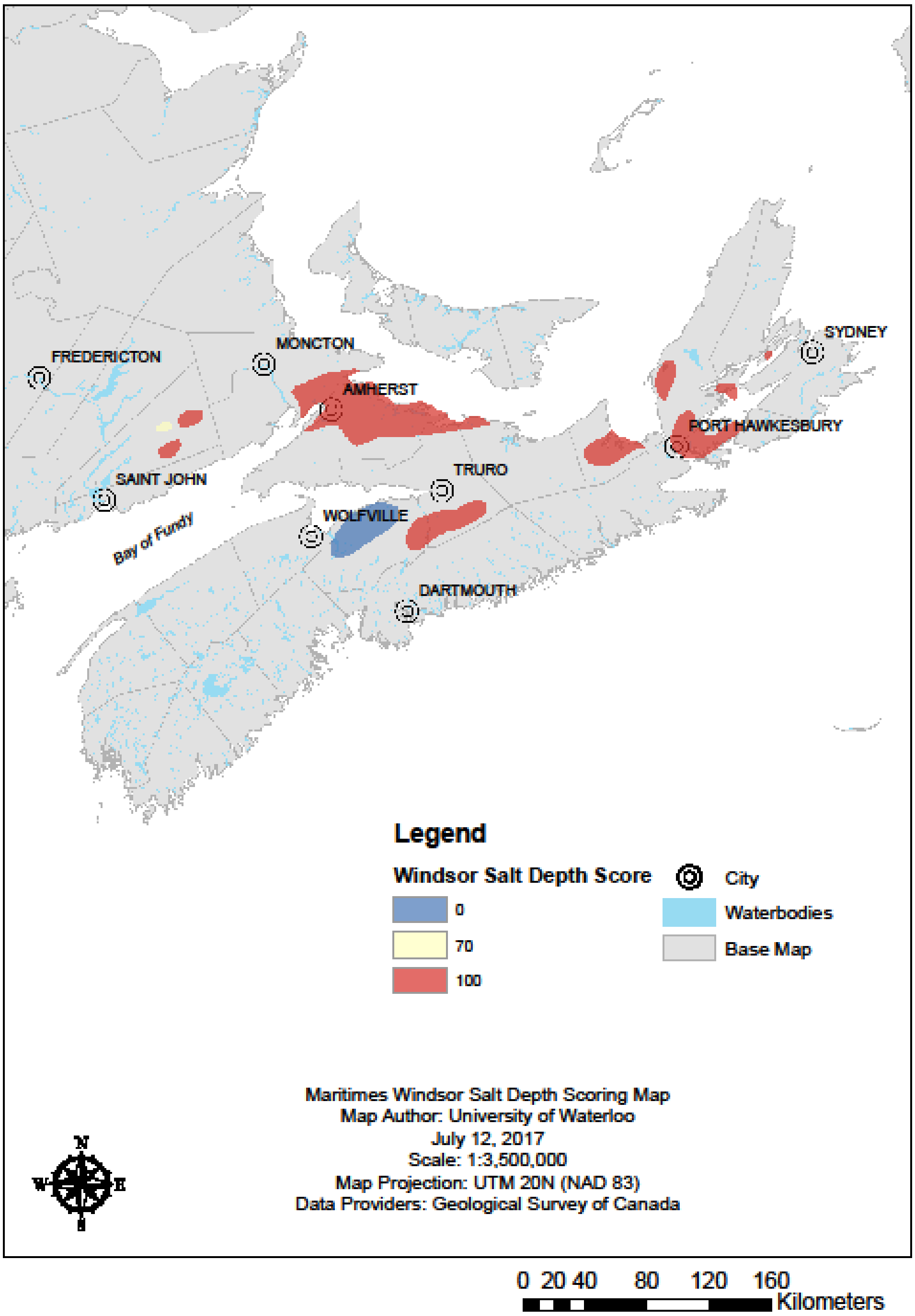
Maritimes Horton Salt Depth Scoring Map



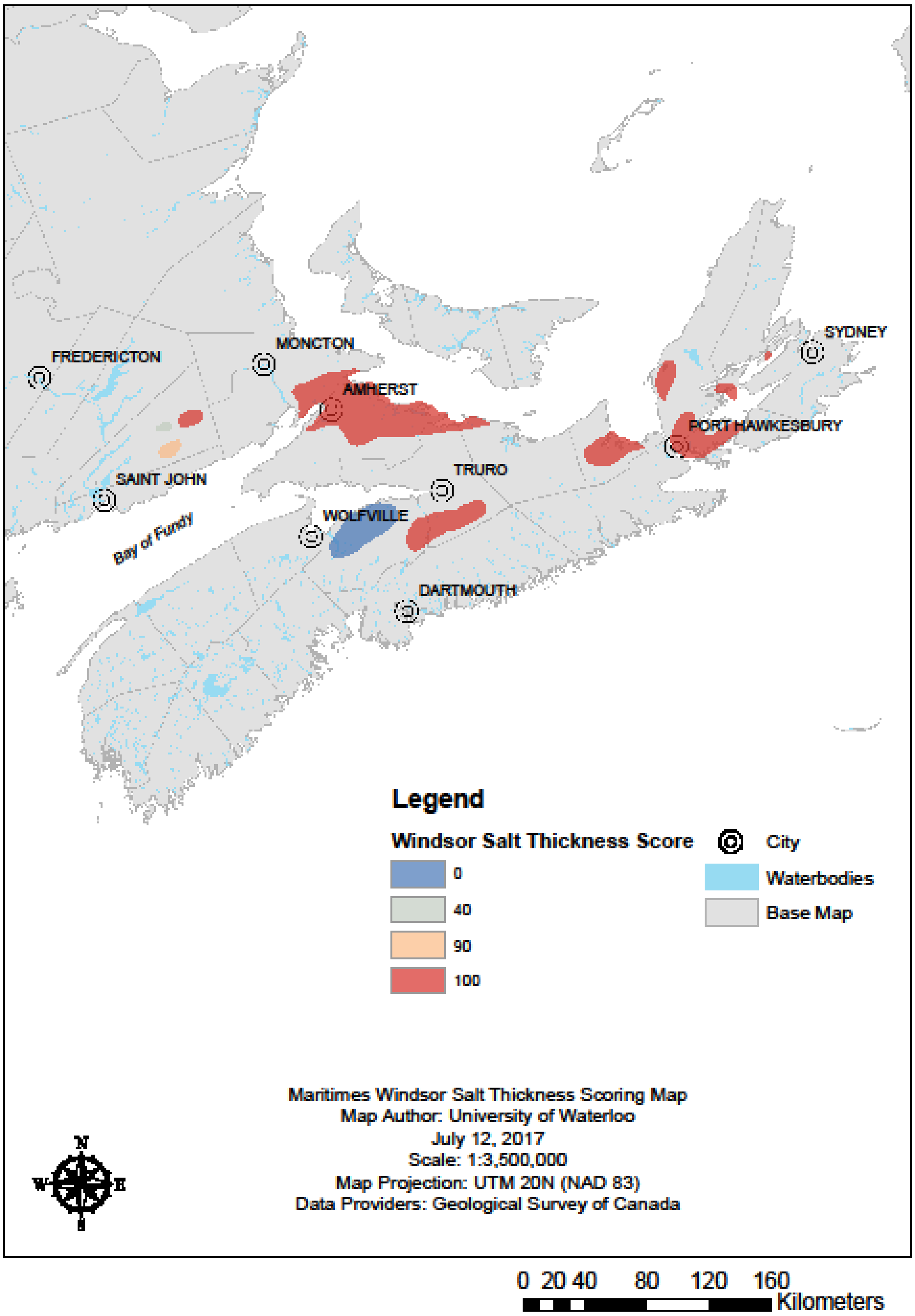
Maritimes Horton Salt Thickness Scoring Map



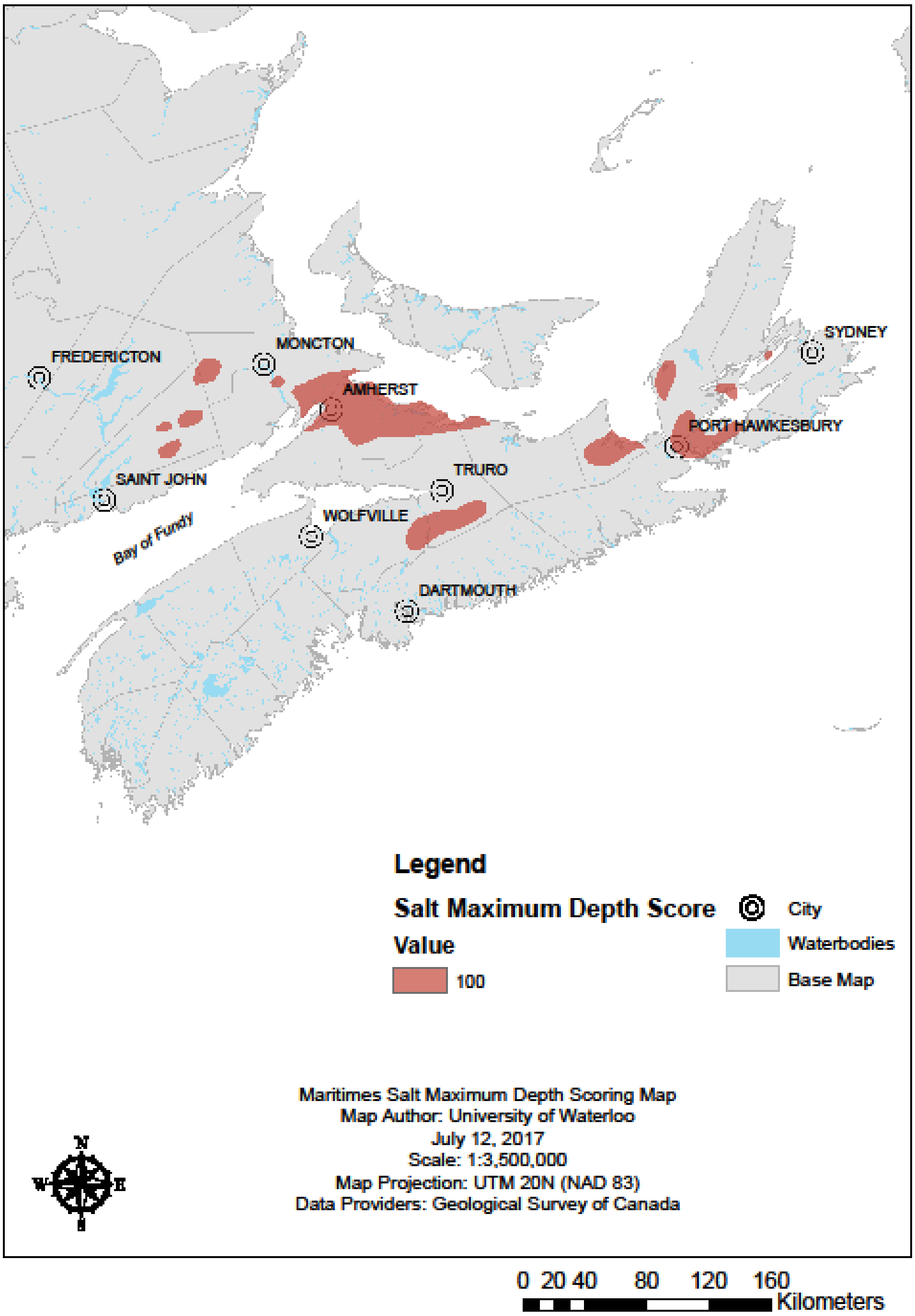
Maritimes Windsor Salt Depth Scoring Map



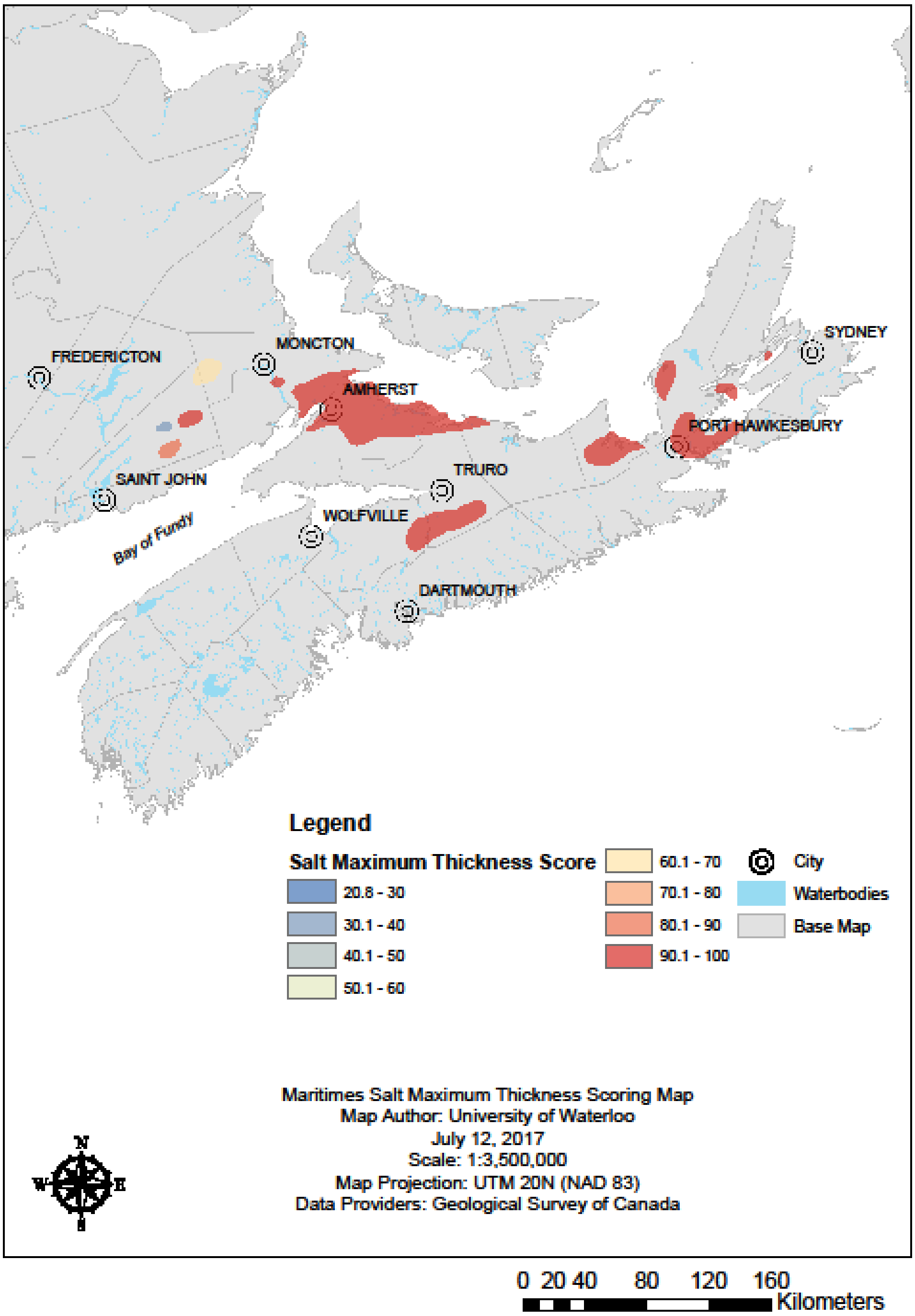
Maritimes Windsor Salt Thickness Scoring Map



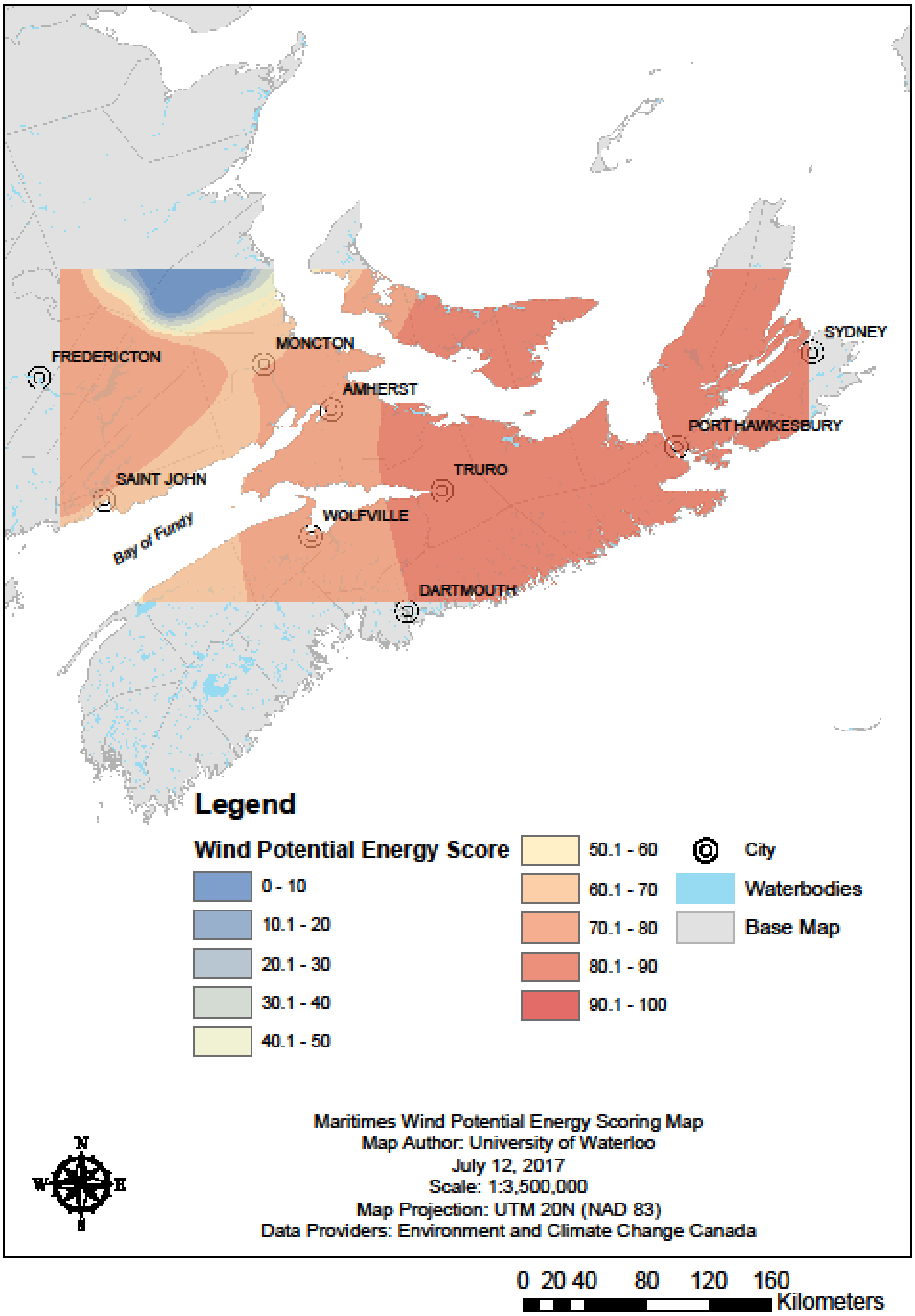
Maritimes Salt Maximum Depth Scoring Map



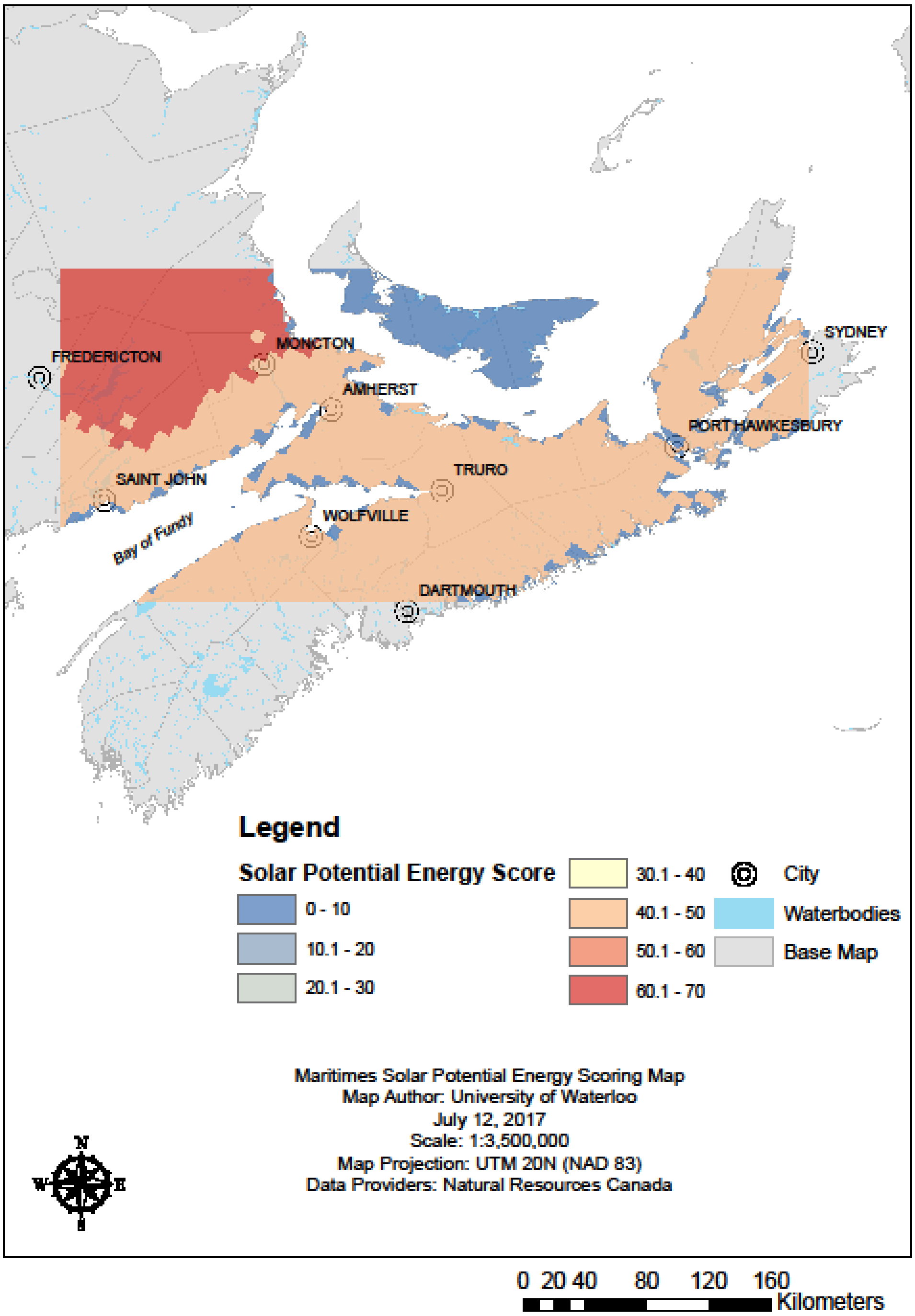
Maritimes Salt Maximum Thickness Scoring Map

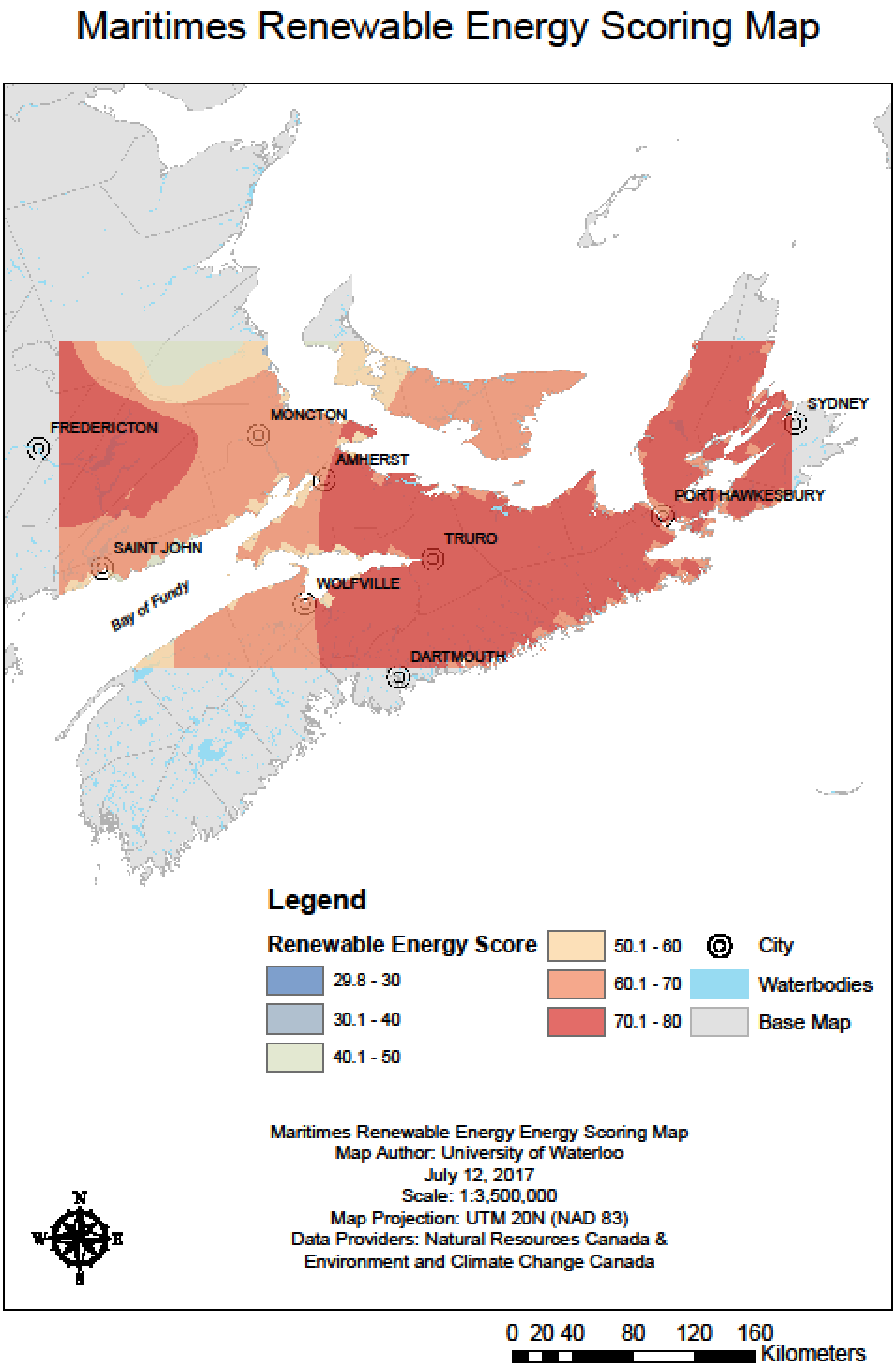


Maritimes Wind Potential Energy Scoring Map

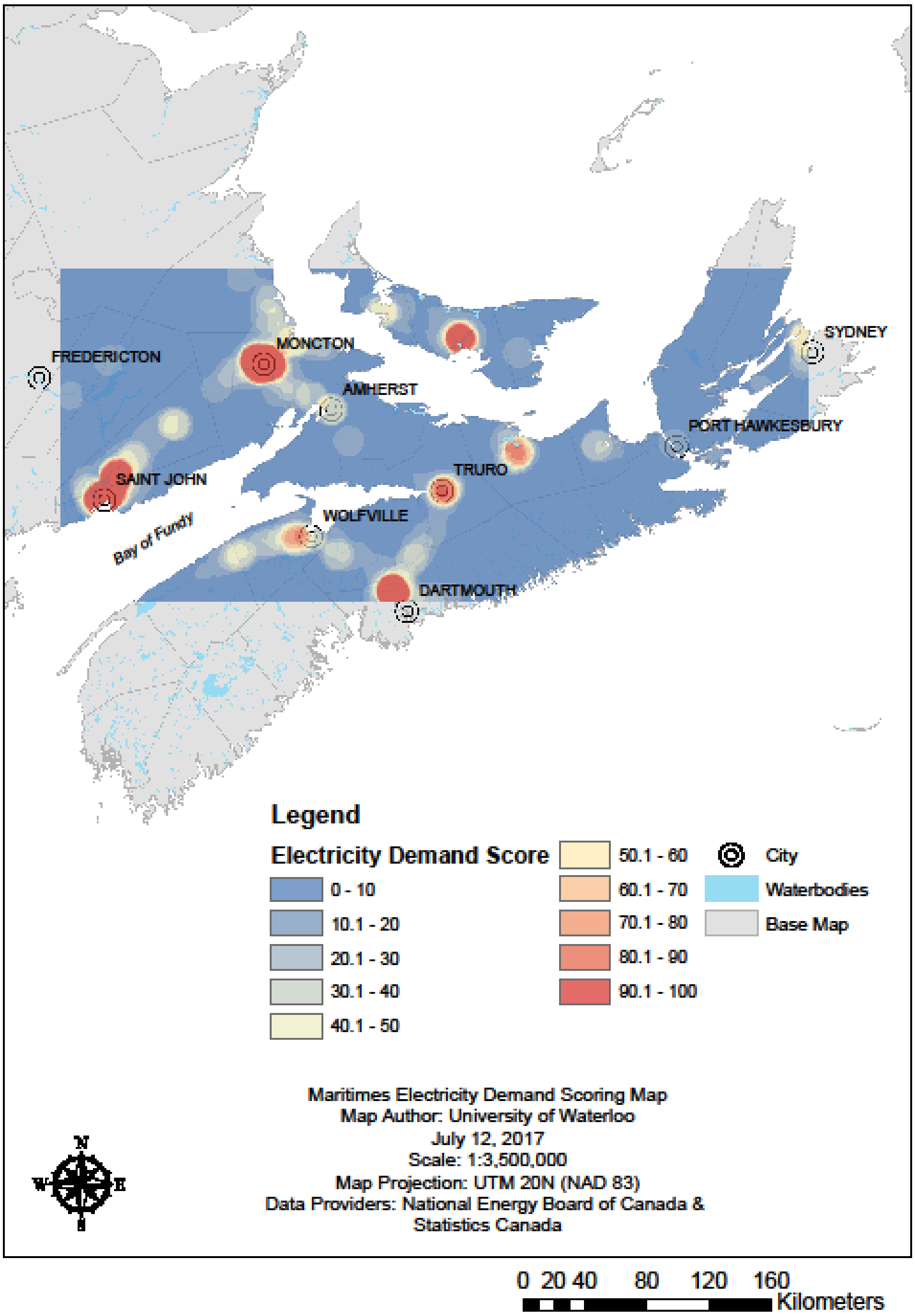


Maritimes Solar Potential Energy Scoring Map

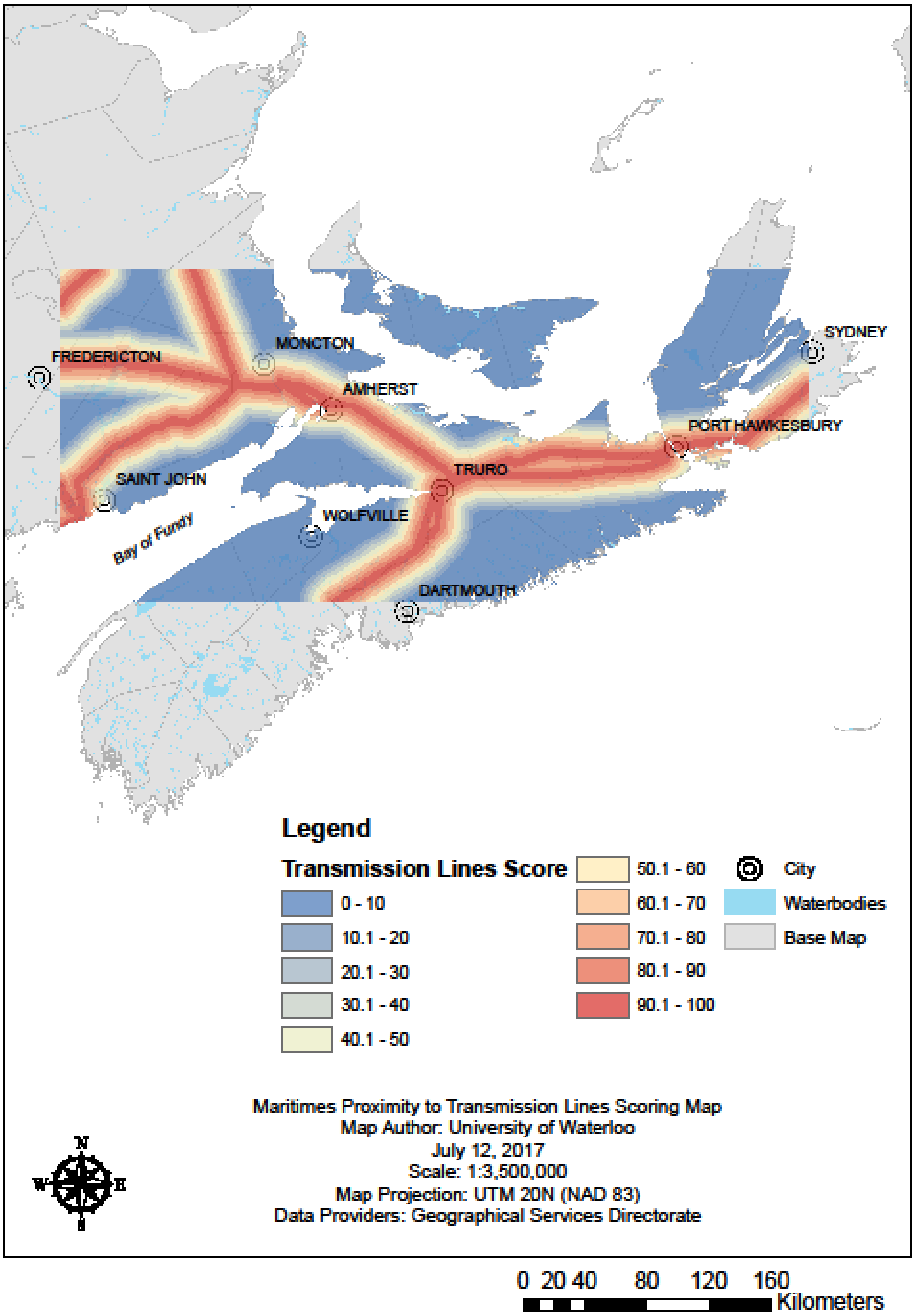



Maritimes Renewable Energy Scoring Map
FREDERICTON
MONCTON
AMHERST
SYDNEY
PORT HAWKESBURY
TRURO
SAINT JOHN
WOLFVILLE
Bay of Fundy
DARTMOUTH
Legend
Renewable Energy Score
29.8 - 30
30.1 - 40
40.1 - 50
50.1 - 60
60.1 - 70
70.1 - 80
City
Waterbodies
Base Map
Maritimes Renewable Energy Energy Scoring Map
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)
Data Providers: Natural Resources Canada &
Environment and Climate Change Canada
N
W
E
S
0 20 40 80 120 160
Kilometers

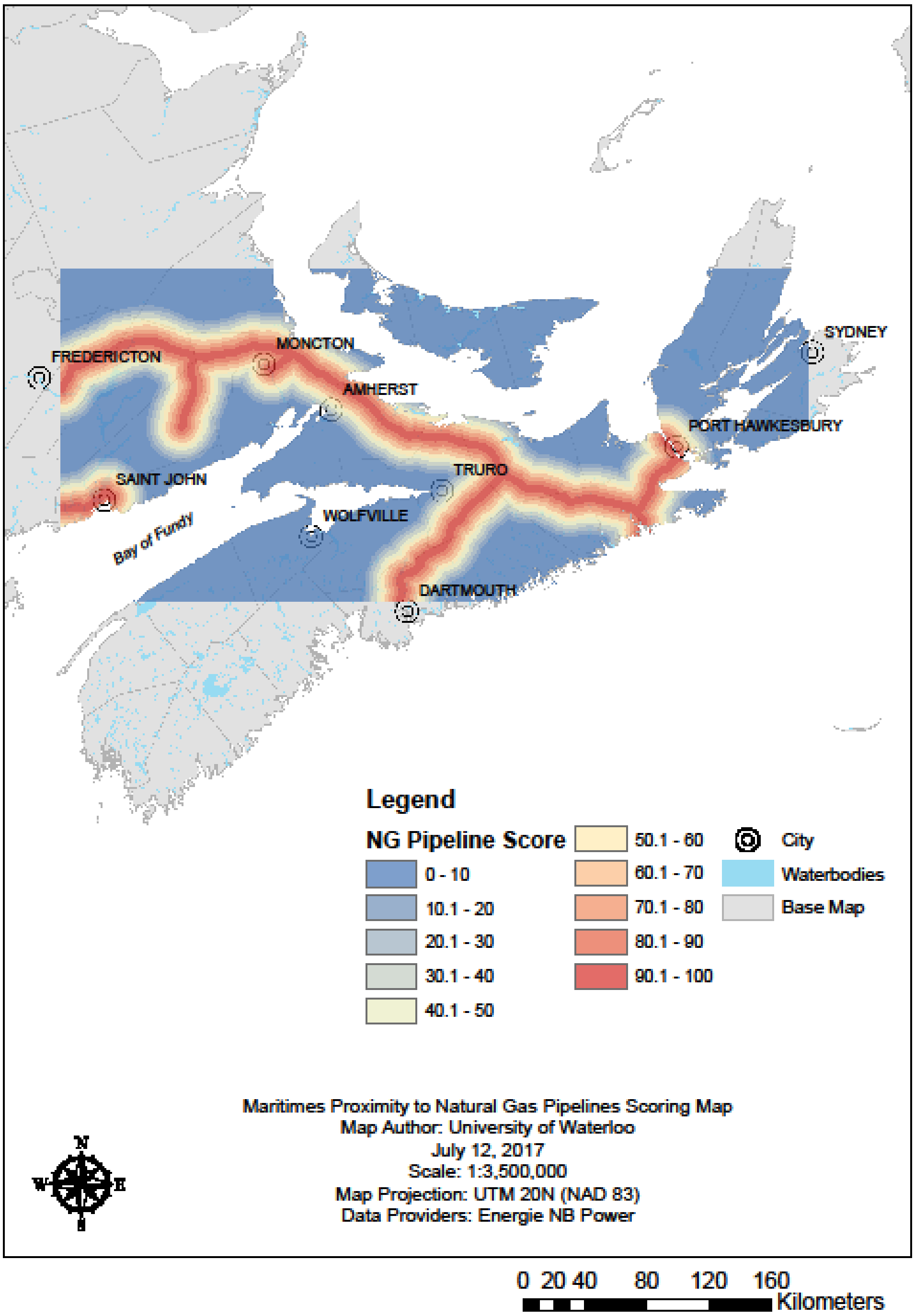
Maritimes Electricity Demand Scoring Map



Maritimes Proximity to Transmission Lines Scoring Map



Maritimes Proximity to Natural Gas Pipelines Scoring Map



Appendix C: MCA Evaluation Tables for Southwestern Ontario (Deep Brine Disposal Study)

County	Lambton			
Township	Sarnia			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1430	75	0.15	11.25
Thickness (m)	38	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				58

County	Essex			
Township	Mersea			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1004	92	0.15	13.8
Thickness (m)	45	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				61

County	Essex			
Township	Colchester South			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	883	97	0.15	14.55
Thickness (m)	75	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				71

County	Essex			
Township	Anderson			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	965	93	0.15	13.95
Thickness (m)	102	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				70

County	Essex			
Township	Maidstone			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1040	90	0.15	13.5
Thickness (m)	50	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				70

County	Kent			
Township	Howard			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1236	82.5	0.15	12.38
Thickness (m)	42	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				59

County	Kent			
Township	Tilbury East			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1109	87.5	0.15	13.13
Thickness (m)	20	75	0.15	11.25
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				56

County	Elgin			
Township	Malahide			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1080	89	0.15	13.35
Thickness (m)	82	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				60

County	Elgin			
Township	Aldborough			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1137	86	0.15	12.9
Thickness (m)	23	90	0.15	13.5
Permeability (mD)	10	4	0.25	1
Porosity (%)	12	48	0.2	9.6
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				54

County	Elgin			
Township	Southwold			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1082	89	0.15	13.35
Thickness (m)	18	65	0.15	9.75
Permeability (mD)	10	4	0.25	1
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				53

County	Norfolk			
Township	North Walsingham			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1095	88	0.15	13.2
Thickness (m)	60	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				60

County	Haldimand			
Township	Walpole			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	981	92.5	0.15	13.88
Thickness (m)	50	100	0.15	15
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				61

County	Haldimand			
Township	Canborough			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	863	97.5	0.15	14.63
Thickness (m)	60	100	0.15	15
Permeability (mD)	120	42	0.25	10.5
Porosity (%)	19	76	0.2	15.2
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				72

County	Oxford			
Township	Dereham			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1034	91	0.15	13.65
Thickness (m)	20	75	0.15	11.25
Permeability (mD)	10	4	0.25	1
Porosity (%)	12	48	0.2	9.6
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				53

County	Brant			
Township	Burford			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	900	96	0.15	14.4
Thickness (m)	15	50	0.15	7.5
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				54

County	Middlesex			
Township	Westminister			
Formation	Cambrian age strata			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	1079	89	0.15	13.35
Thickness (m)	15	50	0.15	7.5
Permeability (mD)	30	12	0.25	3
Porosity (%)	15	60	0.2	12
Reservoir Lithology	Coarse to medium grained quartzose sandstone	80	0.1	8
Caprock Lithology	Dolomitic shale of Shadow Lake, and fine grained limestone of the Gull River Formation	60	0.15	9
Karst Potential	No	If yes, add 10 to total score		0
Total Score (S)				53

County	Lambton			
Township	Enniskillen			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	123	2	0.15	0.3
Thickness (m)	80	100	0.15	15
Permeability (mD)	50	20	0.25	5
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				65

County	Lambton			
Township	Sarnia			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	137	12	0.15	1.8
Thickness (m)	95	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	20	80	0.2	16
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				73

County	Lambton			
Township	Moore			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	172	35	0.15	5.25
Thickness (m)	80	100	0.15	15
Permeability (mD)	25	10	0.25	2.5
Porosity (%)	17	67.5	0.2	13.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				66

County	Lambton			
Township	Sombra			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	177	38	0.15	5.7
Thickness (m)	70	100	0.15	15
Permeability (mD)	200	45	0.25	11.25
Porosity (%)	21	82	0.2	16.4
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				78

County	Lambton			
Township	Dawn			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	150	20	0.15	3
Thickness (m)	65	100	0.15	15
Permeability (mD)	50	20	0.25	5
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				68

County	Lambton			
Township	Euphemia			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	129	7	0.15	1.05
Thickness (m)	45	100	0.15	15
Permeability (mD)	25	10	0.25	2.5
Porosity (%)	17	67.5	0.2	13.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				62

County	Lambton			
Township	Enniskillen			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	123	2	0.15	0.3
Thickness (m)	80	100	0.15	15
Permeability (mD)	50	20	0.25	5
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				65

County	Lambton			
Township	Brooke			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	146	17.5	0.15	2.63
Thickness (m)	60	100	0.15	15
Permeability (mD)	25	10	0.25	2.5
Porosity (%)	17	67.5	0.2	13.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				64

County	Kent			
Township	Dover			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	133	8	0.15	1.2
Thickness (m)	50	100	0.15	15
Permeability (mD)	100	40	0.25	10
Porosity (%)	20	80	0.2	16
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				72

County	Kent			
Township	Zone			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	130	7	0.15	1.05
Thickness (m)	40	100	0.15	15
Permeability (mD)	25	10	0.25	2.5
Porosity (%)	17	67.5	0.2	13.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				62

County	Kent			
Township	Tilbury East			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	125	3	0.15	0.45
Thickness (m)	25	100	0.15	15
Permeability (mD)	50	20	0.25	5
Porosity (%)	18	72.5	0.2	14.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				65

County	Middlesex			
Township	Mosa			
Formation	Lucas			
	Parameter Value	Score (v)	Weight (w)	Si = v*w
Criteria:				
Depth (m)	137	11	0.15	1.65
Thickness (m)	55	100	0.15	15
Permeability (mD)	25	10	0.25	2.5
Porosity (%)	17	67.5	0.2	13.5
Reservoir Lithology	Limestone and Dolomite	80	0.1	8
Caprock Lithology	Shale and Limestone interbeds	80	0.15	12
Karst Potential	Yes	If yes, add 10 to total score		10
Total Score (S)				63

Appendix D: Well Cards (Deep Brine Disposal Study)

Appendix D displays a few well cards used in the MCA evaluation system. Well cards were obtained from the data repository of the Ontario's Oil, Gas and Salt Resources library. The well cards displayed represent the four sites:

- Well ID T012024 displays stratigraphy for the Cambrian age strata in Essex County. The Cambrian age strata in Essex County shows high disposal potential and received level 1 suitability rating.
- Well ID T008556 displays stratigraphy for the Cambrian age strata in Lambton County. The Cambrian age strata in Lambton County shows mediocre disposal potential and received level 2 suitability rating.
- Well ID F010189 displays stratigraphy for the Lucas Formation in Lambton County. The Lucas Formation in Lambton County shows high disposal potential and received level 1 suitability rating.
- Well ID T005119 displays stratigraphy for the Lucas Formation in Kent County. The Lucas Formation in Kent County shows mediocre disposal potential and received level 2 suitability rating.

CTY: Essex	TWP: Colchester South	TRACT: 8	LOT: 81	CON: FC
WELL NAME: Algonquin #23			WELL ID: T012024	CLASS: BD
OPERATOR: GEL Exploration Limited	Target: CAM		STATUS: BD - ACT	

DRILLING DATA	DATES	COORDINATES	SAMPLES
RIG TYPE: Rotary	LICENCE ISSUED: 2010-02-11	N/S BOUND: 2174.15 S	TRAY: 11721-22
GRND ELEV: 179.65	SPUD DATE:	E/W BOUND: 61.00 W	POOL
KB ELEV: 181.00	TD DATE: 2010-05-05	NAD 83	
TVD: 966.50 PBTD: 376.00	COMPLETE DATE:	SURF LAT: 42.00472250 SURF LONG: -82.96000250	
	WORKOVER DATE:	BOT LAT: 42.00472250 BOT LONG: -82.96000250	
	PLUG DATE:		

FORMATION	TOP	TVD	ELEV
Drift	1.35	1.35	179.65
Top of Bedrock	30.50	30.50	150.50
Bass Islands/Bertie	30.50	30.50	150.50
G Unit	112.00	112.00	69.00
F Unit	118.00	118.00	63.00
E Unit	150.00	150.00	31.00
C Unit	198.50	198.50	-17.50
B Unit	212.00	212.00	-31.00
B Anhydrite	230.00	230.00	-49.00
A-2 Carbonate	237.50	237.50	-56.50
A-2 Anhydrite	262.50	262.50	-81.50
A-1 Carbonate	265.00	265.00	-84.00
Guelph	276.50	276.50	-95.50
Goat Island	290.00	290.00	-109.00
Gasport	343.00	343.00	-162.00
Rochester	384.00	384.00	-203.00
Reynales/Fossil Hill	387.50	387.50	-206.50
Cabot Head	389.50	389.50	-208.50
Manitoulin	424.00	424.00	-243.00
Queenston	436.00	436.00	-255.00
Georgian Bay/Blue Mtn	499.00	499.00	-318.00
Collingwood	633.50	633.50	-452.50
Cobourg	640.50	640.50	-459.50
Sherman Fall	654.50	654.50	-473.50
Kirkfield	706.50	706.50	-525.50
Black River Group	735.50	735.50	-554.50
Shadow Lake	879.50	879.50	-698.50
Cambrian	883.00	883.00	-702.00
Precambrian	958.00	958.00	-777.00

Geology by Operator

LOCATION COMMENTS

DATE	ACCURACY	METHOD OBTAINED
2010-01-13	Within 1 metre	Survey Drawing (post 1997)

INITIAL GAS INTERVAL	FLOW 1000 m3/dM	SIP kPag
506.00 -	1.460	2896.00

INITIAL OIL INTERVAL	FLOW m3/d	SIP kPag

WATER RECORD INTERVAL	STATIC LEVEL	TYPE
110.00 - 126.00		Loss of circ.
345.00 - 384.00		Loss of circ.
905.00 - 958.00		Loss of circ.

LOGGING RECORD INTERVAL	TYPE	COMPANY
0.00 - 966.00	Resistivity	Weatherford
0.00 - 966.00	Sonic	Weatherford
0.00 - 966.00	Gamma Ray	Weatherford
0.00 - 966.00	Neutron	Weatherford
401.00 - 966.00	Formation Evaluation	Weatherford
401.00 - 966.00	Caliper	Weatherford
401.00 - 966.00	Density	Weatherford

Casing O.D. (mm)	Weight (kg/m)	Setting Depth (m)	How Set
298.00	62.50	46.60	CEM
219.00	35.70	400.62	CEM
60.00	6.80	894.00	HAN
114.00	15.60	905.90	CEM

CTY: Lambton	**TWP:** Sarnia	**TRACT:** 2	**LOT:** 11	**CON:** R4
WELL NAME: Imperial Brine Disposal #1			**WELL ID:** T008556	**CLASS:** BD
OPERATOR: Imperial Oil Ltd	**Target:** CAM		**STATUS:** BD - ABD	

DRILLING DATA	DATES	COORDINATES	SAMPLES
RIG TYPE:	**LICENCE ISSUED:** 1997-10-28	**N/S BOUND:** 110.30 S	**TRAY:** 10762-4
GRND ELEV: 184.90	**SPUD DATE:**	**E/W BOUND:** 274.70 W	**POOL**
KB ELEV: 189.30	**TD DATE:** 1997-11-17	**NAD 83**	
TVD: 1495.00 **PBTD:**	**COMPLETE DATE:**	**SURF LAT:** 42.95011111 **SURF LONG:** -82.39983333	
	WORKOVER DATE:		
	PLUG DATE: 1997-11-21	**BOT LAT:** 42.95011111 **BOT LONG:** -82.39983333	

FORMATION	TOP	TVD	ELEV
Drift	4.40	4.40	184.90
Top of Bedrock	36.00	36.00	153.30
Kettle Point	36.00	36.00	153.30
Hamilton Group	51.70	51.70	137.60
Dundee	146.40	146.40	42.90
Bois Blanc	287.20	287.20	-97.90
Bass Islands/Bertie	346.70	346.70	-157.40
G Unit	428.80	428.80	-239.50
F Unit	435.40	435.40	-246.10
F Salt	454.30	454.30	-265.00
E Unit	572.60	572.60	-383.30
D Unit	594.90	594.90	-405.60
C Unit	605.70	605.70	-416.40
B Unit	624.80	624.80	-435.50
B Salt	632.20	632.20	-442.90
A-2 Carbonate	725.00	725.00	-535.70
A-2 Shale	759.10	759.10	-569.80
A-2 Salt	775.90	775.90	-586.60
A-2 Anhydrite	807.70	807.70	-618.40
A-1 Carbonate	809.80	809.80	-620.50
A-1 Evaporite	845.50	845.50	-656.20
Guelph	850.50	850.50	-661.20
Goat Island	856.20	856.20	-666.90
Gasport	863.80	863.80	-674.50
Rochester	877.30	877.30	-688.00
Reynales/Fossil Hill	879.00	879.00	-689.70
Cabot Head	880.60	880.60	-691.30
Manitoulin	918.50	918.50	-729.20
Queenston	939.40	939.40	-750.10
Georgian Bay/Blue Mtn	1024.60	1024.60	-835.30
Cobourg	1128.60	1128.60	-939.30
Sherman Fall	1160.00	1160.00	-970.70
Kirkfield	1209.20	1209.20	-1019.90
Coboconk	1278.00	1278.00	-1088.70
Gull River	1315.50	1315.50	-1126.20
Shadow Lake	1428.00	1428.00	-1238.70
Cambrian	1431.20	1431.20	-1241.90
Precambrian	1469.00	1469.00	-1279.70
Geology by Operator			

LOCATION COMMENTS

DATE	ACCURACY	METHOD OBTAINED
	Within 5 metres	Survey Drawing (post 1997)

INITIAL GAS INTERVAL	FLOW 1000 m3/dM	SIP kPag

INITIAL OIL INTERVAL	FLOW m3/d	SIP kPag

WATER RECORD INTERVAL	STATIC LEVEL	TYPE
1438.00 - 1491.00		Salt

LOGGING RECORD INTERVAL	TYPE	COMPANY
1.00 - 452.50	Gamma Ray Neutron	Atlas
40.00 - 1491.00	Sonic	Atlas
50.00 - 450.00	Compensated Neutron Formation Density	Atlas
450.00 - 1490.00	Dual Laterolog Micro SFL	Atlas
450.00 - 1490.00	Lithodensity Tool	Atlas

CORE ID	TOP (m)	BOTTOM (m)	ANALYSIS
1074	1467.00	1471.50	Y

Casing O.D. (mm)	Weight (kg/m)	Setting Depth (m)	How Set
339.70	71.40	54.20	CEM
245.00	53.60	455.40	CEM

CTY: Lambton	**TWP:** Sarnia	**TRACT:** 2	**LOT:** 11	**CON:** R5
WELL NAME: Imperial Sarnia Refinery Disposal Well No. 1			**WELL ID:** F010189	**CLASS:** DEV
OPERATOR: Imperial Oil Ltd	**Target:** DEV		**STATUS:** BD - ABD	

DRILLING DATA	DATES	COORDINATES	SAMPLES
RIG TYPE:	**LICENCE ISSUED:**	**N/S BOUND:** 61.00 S	**TRAY:** 9710
GRND ELEV: 183.20	**SPUD DATE:**	**E/W BOUND:** 100.60 E	**POOL**
KB ELEV: 185.60	**TD DATE:** 1958-08-11	**NAD 83**	
TVD: 243.84 **PBTD:**	**COMPLETE DATE:**	**SURF LAT:** 42.95030556 **SURF LONG:** -82.41208333	
	WORKOVER DATE:	**BOT LAT:** 42.95030556 **BOT LONG:** -82.41208333	
	PLUG DATE: 1974-05-01		

FORMATION	TOP	TVD	ELEV
Drift	2.40	2.40	183.20
Top of Bedrock	36.00	36.00	149.60
Kettle Point	36.00	36.00	149.60
Hamilton Group	48.80	48.80	136.80
Dundee	146.90	146.90	38.70
Lucas	184.40	184.40	1.20
Geology by Operator			

LOCATION COMMENTS

DATE	ACCURACY	METHOD OBTAINED
	Within 20 metres	Well Records (1954 to 1997)

INITIAL GAS INTERVAL	FLOW 1000 m3/dM	SIP kPag

INITIAL OIL INTERVAL	FLOW m3/d	SIP kPag

WATER RECORD INTERVAL	STATIC LEVEL	TYPE

LOGGING RECORD INTERVAL	TYPE	COMPANY

Casing O.D. (mm)	Weight (kg/m)	Setting Depth (m)	How Set
273.05	61.00	45.10	CEM
178.05	34.20	196.30	CEM
59.94	9.81	200.90	

CTY: Kent	**TWP:** Lake Erie	**TRACT:**	**LOT:** 221	**CON:** T-2
WELL NAME: Consumers' 13624			**WELL ID:** T005119	**CLASS:** DEV
OPERATOR: Dundee Oil and Gas Limited	**Target:** SAL		**STATUS:** GP - SUS	

DRILLING DATA	DATES	COORDINATES	SAMPLES
RIG TYPE: Rotary	**LICENCE ISSUED:** 1979-07-16	**N/S BOUND:** X	**TRAY:** 2320
GRND ELEV: 174.70	**SPUD DATE:**	**E/W BOUND:** X	**POOL**
KB ELEV: 181.30	**TD DATE:** 1979-08-05	**NAD 83**	Lake Erie-Morpeth Pool
TVD: 534.00 **PBTD:** 530.00	**COMPLETE DATE:**	**SURF LAT:** 42.19491000 **SURF LONG:** -81.42841444	
	WORKOVER DATE:	**BOT LAT:** 42.19491000 **BOT LONG:** -81.42841444	
	PLUG DATE:		

FORMATION	TOP	TVD	ELEV
Drift	30.50	30.50	150.80
Top of Bedrock	79.30	79.30	102.00
Kettle Point	79.30	79.30	102.00
Hamilton Group	140.60	140.60	40.70
Dundee	219.00	219.00	-37.70
Lucas	254.00	254.00	-72.70
Amherstburg	270.00	270.00	-88.70
Bois Blanc	309.10	309.10	-127.80
Bass Islands/Bertie	340.00	340.00	-158.70
G Unit	372.60	372.60	-191.30
F Unit	380.20	380.20	-198.90
E Unit	405.30	405.30	-224.00
C Unit	443.70	443.70	-262.40
B Unit	461.70	461.70	-280.40
B Anhydrite	476.20	476.20	-294.90
A-2 Carbonate	484.30	484.30	-303.00
A-2 Anhydrite	497.00	497.00	-315.70
A-1 Carbonate	499.00	499.00	-317.70
Guelph	507.00	507.00	-325.70
Geology by Operator			

LOCATION COMMENTS

DATE	ACCURACY	METHOD OBTAINED
	Within 100 metres	Well Records (1954 to 1997)

INITIAL GAS INTERVAL	FLOW 1000 m3/dM	SIP kPag
496.50 - 528.80	26.937	5723.00

INITIAL OIL INTERVAL	FLOW m3/d	SIP kPag

WATER RECORD INTERVAL	STATIC LEVEL	TYPE

LOGGING RECORD INTERVAL	TYPE	COMPANY
34.70 - 528.00	Gamma Ray Neutron	Schlumberger
34.70 - 528.00	Caliper	Schlumberger
271.40 - 528.30	Density	Schlumberger
280.00 - 524.30	Dual Laterolog	Schlumberger
450.00 - 530.00	Completion/Perforation	Schlumberger

CORE ID	TOP (m)	BOTTOM (m)	ANALYSIS
747	510.60	528.80	Y

Casing O.D. (mm)	Weight (kg/m)	Setting Depth (m)	How Set
273.05	75.90	30.50	HAN
244.09	53.60	79.60	CEM
178.05	29.79	271.50	CEM
59.94	6.99	502.87	HAN
41.91	3.57	513.94	HAN
114.05	14.41	532.70	CEM