Identification and Estimation of Greenhouse Gas Reduction Opportunities through the Implementation of CAES in Canada

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 multi-criteria analysis (MCA) work was commissioned by Natural Resources Canada and was a group project which I directed and lead. The contributions of all authors on the report were as follows:

- Fraser Lord (primary author): developed and lead the implementation of the study methodology. Responsible for the quality and interpretation of the results, and meeting the overall project scope and timeline. Intimitly involved in all work completed for the study to allow for an accurate and seamless report to be written. Also responsible for incorporating all revisions and comments from reviewers. Created and implemented the informal expert elicitation survey for criteria weights.
- Jai Duhan: lead the collection of geologic data and interpretation, and drafted the geologic criteria and geologic discussion sections of the MCA work. Developed the geologic criteria scoring systems.
- Mina Lee: primary GIS handler, implemented and executed MCA in the GIS environment using ArcGIS and Terrset.
- Logan Miller: helped with GIS data collection, formatting, and input into the MCA. Developed the electricity demand criterion.
- Dipanjan Basu: reviewed and edited the report.
- Maurice Dusseault: offered advice on study methodology and criteria scoring systems. Aided in the creation of the informal survey.
- Arjun Tharumalingam: helped with Maritimes geology data collection and interpretation.

The life cycle assessment work, discussed towards the end of this document, will be published in the proceedings of the GeoOttawa2017 conference. This work was carried out solely by myself but the contents of the publication, much of which are present in this document, was reviewed by Maurice Dusseault.

Abstract

To reduce greenhouse gas emissions, federal and provincial initiatives have pushed for increased renewable energy penetration on Canadian electric grids. However, renewable power sources such as wind and solar power require "balancing" to provide reliable and affordable energy. Within the context of renewable energy and the electric grid, balancing refers to services and activities which help match instantaneous electrical supply and demand. This balancing is necessary at different power and time scales to be able to meet demand from second to second and from day to day. Furthermore, the economics of renewable energy relies on these power sources not being curtailed frequently. Grid-scale (100+ MW) energy storage is an ideal low-carbon solution for balancing renewable energies, and compressed air energy storage (CAES) is a preferred option for this because it is a low-cost, low-impact, low-risk and mature technology. CAES uses conventional air turbine technology in tandem with underground caverns to compress and store air during periods of low electric demand. The stored air is then heated and used to generate electricity during periods of high demand. The air is typically heated by burning natural gas but at much more efficient rates than natural gas turbine power. Alternatively, a newer thermal energy storage technology can be used to store the heat of compression and then use it to heat the expanding air. Several CAES projects are in different stages of planning and development around the world, including a demonstration-scale CAES facility in Goderich, Ontario. However, CAES deployment in Canada faces a number of barriers, including a lack of awareness about the technology, its potential, and facility siting requirements.

To support the development of low-carbon energy, through removing barriers to energy storage deplyoment, two supporting studies were conducted: a CAES siting study and a life cycle assessment (LCA) of CAES. The siting study examined the first-order technical feasibility and potential application of CAES as a bulk energy management system for balancing renewable energy with electricity demand across Canada. This evaluation required a new methodology to be developed which could identify potential opportunities for CAES in Canada. To determine these opportunities, a multi-criteria analysis (MCA) framework was established and implemented in a geographical information systems (GIS) software. The LCA study compares the global warming potential (GWP) impacts of balancing renewable energy with CAES to a single-cycle combustion turbine (SCGT) fulfilling the same role. The LCA only considers the operational phase of these facilities and examines the impacts of realistic operating conditions on the carbon intensity of energy produced from these technologies.

The MCA uses a robust linear weighted additive model with simple linear piece-wise scoring systems for the criteria. This study used six criteria, salt formation (i) depth and (ii) thickness, (iii) renewable energy potential, (iv) energy demand, (v) proximity to existing natural gas infrastructure, and (vi) proximity to existing electrical infrastructure, grouped into three categories, namely, geology, energy potential, and existing infrastructure. Studies with a more focused area of interest are encouraged to include additional criteria and detail, such as caprock considerations, proximity to environmentally and socially sensitive areas, and economic assessment. The weighting for the criteria in this analysis was determined by an informal survey of experts on CAES from industry and academia.

There are three major geologic basins in Canada which contain salt strata for storage: the Western Canadian Sedimentary Basin which underlies much of the prairies, the Michigan basin which underlies part of southwestern Ontario, and the Maritimes Basin complex which underlies a section of the Gulf of St. Lawrence and extends under New Brunswick and Nova Scotia. Generally speaking, all three of these formations are suitable for salt cavern storage but with unique challenges. The salt beds in Ontario are not very thick and could require multiple caverns and careful consideration of non-salt roof rocks

for cavern stability and tightness. In Saskatchewan and Alberta, the salt layers are quite deep, and some are impure enough to create extra challenges. The Maritimes Basin has been subjected to high tectonic stresses, and folding and faulting have resulted. These structural complexities make mapping and use of the rock salt more challenging. This issue is worsened by the lack of information available on the basin's salt formations.

The availability of existing natural gas and electrical infrastructure were not determined to be a significant limiting factor in this first-order analysis. However, further investigation into capacity-constrained transmission lines will be an important determining factor in regional CAES siting.

Municipalities such as Sarnia and Windsor in southwestern Ontario are ideal for their salt presence, nearby wind and solar energy potentials, available infrastructure, and high energy demand stemming from a large industrial sector. Saskatchewan and Alberta rely on coal and fossil fuels for a significant portion of their energy demand, but they both have access to large salt formations and strong solar energy potential. The salt formations in western Canada also happen to underlie many areas of heavy industrial development which uses huge amounts of energy. Areas of interest for Western Canada include Yorkton, Saskatoon, North Battleford, Bonnyville, and, potentially, Edmonton and Fort McMurray. Nova Scotia and New Brunswick are also dependent on coal power for much of their energy; however, these provinces have access to thick salt domes and strong coastal winds. Wind energy supported by CAES may be able to replace coal power in the Canadian Maritimes. Furthermore, the east coast has access to exceptional tidal power which will require support from energy storage once it has been developed. Areas of opportunity for CAES in Nova Scotia and New Brunswick include Moncton, Amherst, Port Hawkesbury, and Dartmouth.

Location score is highly dependent on the depth and thickness of available salt formations. This emphasises the need for high-quality geologic data, a more comprehensive list of geologic criteria, and the need for further studies into alternative storage mediums such as porous aquifers. According to survey respondents, the proximity of a site to existing electrical transmission infrastructure is also an important consideration. This accentuates the need to address the assumptions made in the evaluation of this criterion, namely that a CAES facility could connect to the electric grid at any point and that transmission congestion is not an issue.

Although there is elements of uncertainty in the MCA conducted in this study, spatially distributed multi-criteria analysis proves to be a viable but data intensive methodology. A discrete analysis, in which only a few key alternatives are selected and compared, is likely to be a simpler and less resource-intensive investigation in most cases. This can be particularly true at different scales where a higher quality of data is needed to produce reliable results. The MCA results determined in this study illustrate the key areas that should be considered for a more in-depth discrete analysis. Such a study could focus on including a more comprehensive list of criteria and their scoring systems.

Given that CAES has been demonstrated to be technically feasible across Canada, it is important to evaluate the environmental and economic differences between CAES and gas turbines for renewable energy integration. Standard LCA modelling methodology evaluates energy generation technologies function at optimal efficiency, referred to as design point operation or design load. Results from this study are in close agreement with other studies regarding CAES and SCGT design point impacts. Under these ideal conditions, SCGT energy has greater impacts than CAES by a factor of 2.2. However, these technologies have different partial loading efficiencies and minimum operating loads which play an important role during highly variable operation characteristic of balancing intermittent power sources.

To evaluate the impact of these operating differences between CAES and SCGTs, an operations model was created using scaled down 2016 data from Ontario's electricity grid. Both technologies are operated to try to provide the power required to meet a net flexible energy demand which represents the difference between Ontario's demand and the summation of all of the inflexible power produced in Ontario, including hydro, nuclear, and renewables. This demand reflects the role typically filled by gas turbines on Ontario's grid. This modelling found that SCGTs' minimum load of 40% results in a significant portion of wasted energy from excess power production.

The realistic operating scenario created and the partial loading efficiency curves are integrated into the LCA which evaluates the average impact per unit of energy for these technologies under these conditions. It was found that the GWP impact per kWh increases by 19% for SCGTs and 3% for fuel-fired CAES. These operating considerations increase the ratio of impacts from SCGTs and CAES to 2.5.

These differences in GWP impacts are important when considering which technology should be used for balancing renewable energy. However, this modelling is also important to predict the impact that carbon pricing will have on the economics of these technologies. Two recent studies indicate that CAES and SCGTs are relatively cost competitive today. However, given that the Canadian federal government is mandating 10 \$/tonne CO_2e carbon pricing by 2018 and is generally expected to increase over time. Based on the GHG emissions calculated in this study, at 50 \$/tonne CO_2e the levelised cost of energy for SCGTs will increase by 4.0 ₵/kWh compared to just 1.6 ₵/kWh for CAES. This indicates that SCGTs are sensitive to carbon pricing and should not be installed for renewable energy integration. Instead, CAES is an ideal form of energy storage for large-scale renewables integration.

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1.0 Introduction

This chapter will introduce why there is a need for low-carbon energy storage in Canada, why compressed air energy storage (CAES) is worth considering, and how CAES works. The chapter concludes with the goal and scope of the studies described in this document.

1.1 Decarbonising the Electric Grid

In 2014 the Intergovernmental Panel on Climate Change (IPCC) issued a synthesis report (IPCC, 2014) which discussed historical and projected anthropogenic global warming emissions and pointed out how the different emission scenarios would likely result in temperature and water level increases and the risks associated with these climate changes. The IPCC's report laid out the scope and potential impacts of the global challenge that is climate change. Recognition of the consequences of human-made global warming spurred leaders of countries from around the world to meet and agree to the terms of an international plan to curb greenhouse gas (GHG) emissions, known as the Paris Agreement. Canada was among the countries that ratified the agreement to attempt to keep global warming levels below 2°C. As a result, federal and provincial governments in Canada have been producing legislations, such as the Green Energy Act in Ontario, to reduce the GHG emissions from every sector of the economy.

Canada's path towards carbon neutrality is uncertain, but it is clear that more rapid and targeted GHG reduction initiatives will be necessary. For example, public production of electricity in Canada generated 78.2 megatonnes of carbon dioxide equivalent ($MtCO_2e$) in 2014, about 11% of the total 732.5 $MtCO_2e$ produced across all sectors in Canada as illustrated in Figure 1 (Environment and Climate Change Canada, 2016a, 2016b). For Canada to meet its GHG emissions reduction target of 30% by 2030, the electricity sector will need to reduce its emissions. This is particularly true when considering the likelihood that other sectors of the economy will become increasingly reliant on electricity in an attempt to reduce their GHG emissions. For the energy sector to be low carbon, it will need to continue to shift reliance from fossil fuels to renewable energy sources such as wind, solar, hydro, tidal, and biofuels. In fact, this transition is already evident in Figure 2 (National Energy Board, 2016) which illustrates the anticipated electricity generating station capacity additions and retirements

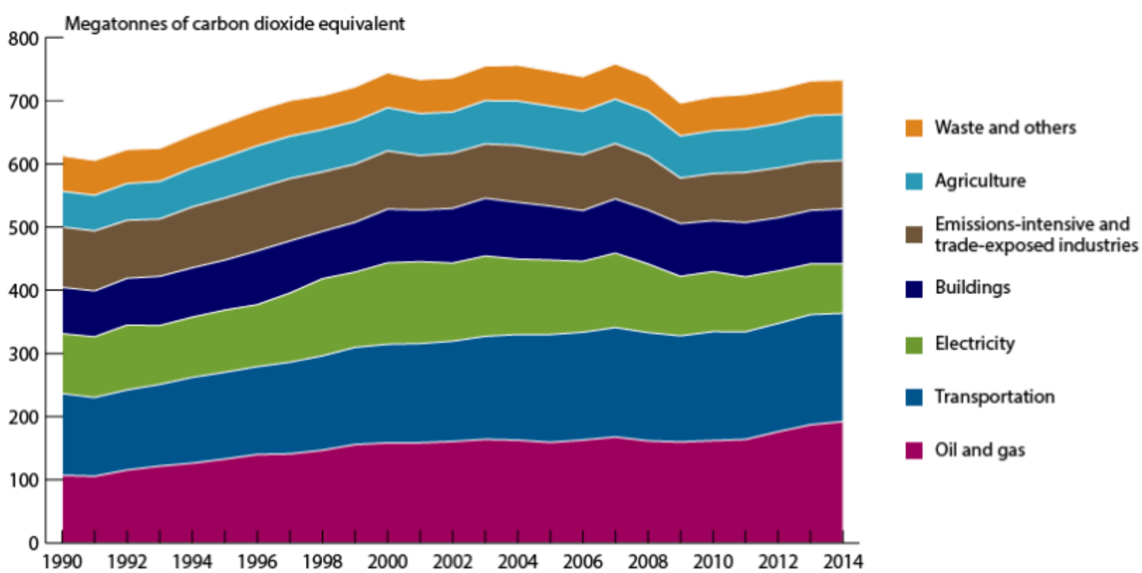

Figure 1 Greenhouse Gas Production in Canada by Sector (Environment and Climate Change Canada, 2016b)

in Canada by 2040. While nuclear energy is also a promising and proven form of low-carbon power generation, it comes with certain risks and is not a substitute for flexible on-demand energy.

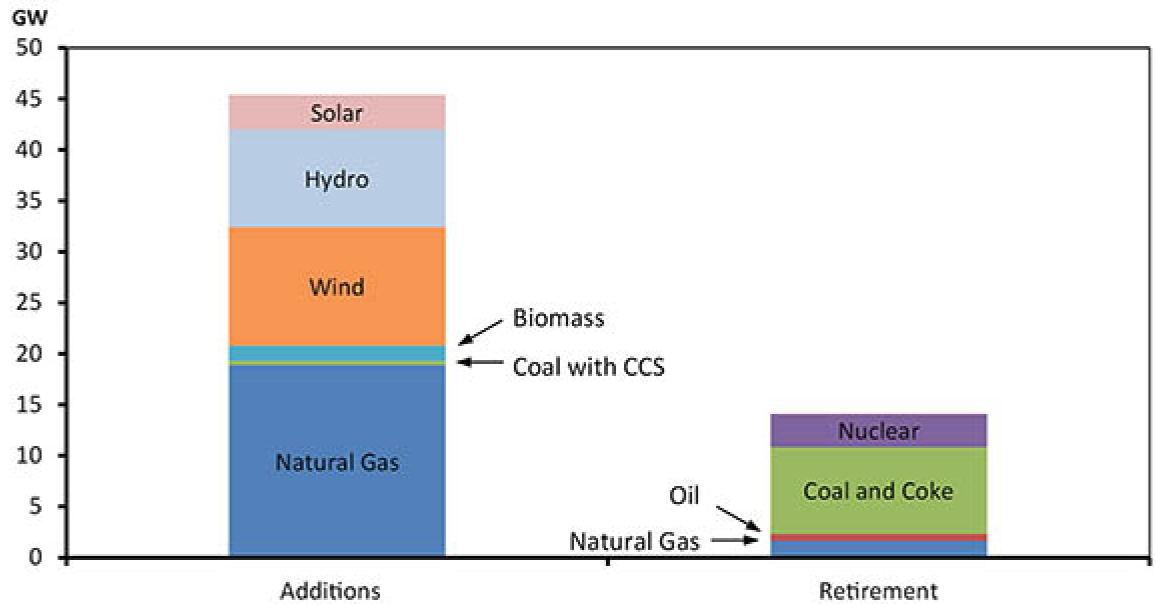

Figure 2 Generating capacity additions and retirement forecasts for Canada by 2040 (National Energy Board, 2016)

Distributed renewable energy sources such as wind and solar power are, by most measures, low impact forms of power generation (Hertwich et al., 2015; Pehnt, 2006). However, these energy sources come with many engineering challenges such as low energy density (wide spatial distribution), intermittent and variable production, and difficulties in predicting and planning for use. The intermittent and uncertain production cannot provide the consistency and reliability necessary to operate the electric grid while maintaining current standards. To balance the variable nature of renewable energy sources, Canada's electric grids will need larger portions of flexible energy generating capacity which can respond to these weather-dependent fluctuations. Historically, this flexible energy has been provided by hydropower and natural gas turbines; however, grid-scale (100 MW+), sustainable, and reliable energy storage is considered an ideal candidate for meeting flexible power needs. For the electric grid to maintain its performance and reliability through weekly and seasonal fluctuations, the system will need these grid-scale energy storage facilities to be able to store days or weeks-worth of energy that CAES can provide (A. Cavallo, 2007; A. J. Cavallo & Keck, 1995). However, the efficient integration of renewable energy is also important to maintaining the affordability of electricity in Canada; the relatively low levelized cost of wind and solar energy is highly susceptible to curtailment (OSPE-PEO Energy Task Force, 2013). As an example, Ontario consumers paid generators $339 million from 2009-2014 for the curtailment of power generation, and Ontario regularly sells electricity to the US at a loss (Adams & Luft, 2016). Electricity prices have clearly been impacted by poor renewable energy integration. Proponents of maintaining natural gas for renewable energy integration will point out that newer combined-cycle gas turbine (CCGT) power plants have achieved an overall efficiency of 50-55% and can produce power at roughly half of the amount of carbon dioxide (CO_2) produced per kWh when compared to a coal power plant. However, the ramp rate for CCGT plants is too slow to balance variable energy sources effectively. Therefore single-cycle gas turbines (SCGT) would need to be employed for this purpose if conventional means were used. Alternatively, energy storage such as CAES can be used to balance energy variations with demand effectively.

1.2 Managing Intermittent Energy

A wide variety of energy storage technology is available today. These technologies vary, for example, in maturity, price, energy storage form, potential size, response time, and facility lifetime. Because of the varying principles regarding how these different energy storage technologies work and the resulting differences in how these technologies operate, different technologies are suitable for different roles. Figure 3 illustrates how different technologies vary in power output and how much energy, expressed in terms of duration of discharge at rated power output, these technologies can store. It is worth noting that the limits defined by the boxes in this figure are soft limits and technologies may be applicable or practical outside of the ranges given; however, the limits are roughly defined by what the technology naturally offers. Ultimately, not all energy storage technologies are suitable for bulk energy management.

Successful implementation of high levels of renewable energy onto an electric grid will require services from all three categories given in Figure 3: response services or frequency regulation, transmission and distribution network support, and bulk energy and power management. Bulk energy management on the scales that will be needed is an especially challenging hurdle because these services will be responsible for keeping the electric grid running reliably, even when renewable power sources are idle. The energy storage technologies available today which are 100 MW or greater in scale are limited to pumped hydro storage (PHS) and CAES. Canada generates a significant amount of electricity from PHS already, and it has a proven track record around the world. Unfortunately, most of the best locations for PHS have already been developed, and the construction of new dams is highly contentious and involves flooding large areas. Further, PHS stores massive volumes of water which, if released in an uncontrolled fashion,

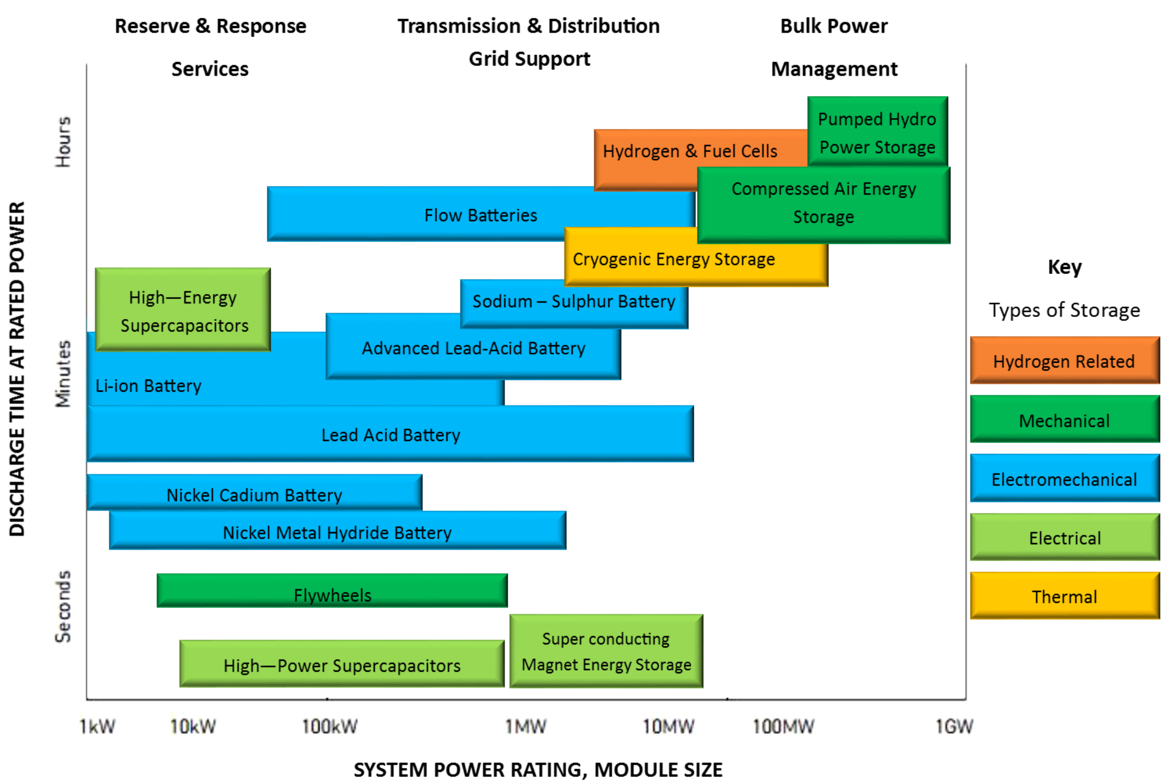

Figure 3 System power versus duration of storage for different energy storage technologies (After University of Birmingham Energy Storage Centre Report)

can result in significant property damage and loss of life. PHS reservoirs also increase silt deposition which either reduces the available storage or requires costly maintenance to clean out. It is worth noting here that battery energy storage projects around the world are becoming larger by the month and are starting to move into the territory of bulk energy management. While these projects can be located and constructed much more conveniently and rapidly, the material demands necessary for global battery deployment are far in excess of what is produced today, and the environmental impact of the end-of-life of these facilities is still a concern largely left unaddressed (Ashby & Polybank, 2012). Batteries often use highly potent toxic substances and can be a fire hazard. In contrast, CAES is a very low-risk, environment-friendly facility which stores its energy deep underground and in a medium that is stable and non-toxic. The underground storage of air in CAES also means that the facility has a small surface footprint and does not usually require displacing homes or businesses. Economically speaking, CAES is an ideal choice because of its unique operating advantages, lowest capital cost per unit of power or energy stored, and its low operation and maintenance costs (Ashby & Polybank, 2012; Daim, Li, Kim, & Simms, 2012; Kondoh et al., 2000). Note that energy-to-fuel storage options are not considered here because round-trip efficiencies back to electricity are low. Comparing these technologies is complicated, and a function of many variables, but interested readers can learn more about the differences between these technologies from existing literature (Aneke & Wang, 2016; Ashby & Polybank, 2012; Daim et al., 2012).

CAES is a mechanical form of energy storage which operates similarly to combustion turbines but with the ability to store air between the compression and expansion stages. A graphic representation of the typical layout and components of fuel-fired CAES is illustrated in Figure 4, note that the illustration shows two pipes going underground for ease of understanding but in practice one pipe, referred to as a well, is used for both injection and extraction. The storage component of CAES allows for the elimination or reduction of renewable and baseload power curtailment during periods of low demand. The spinning reserve functionality of CAES, combined with curtailment reduction, makes this energy storage technology ideal for intermittent energy integration. However, CAES is adaptable and can be dispatched for a variety of purposes: arbitrage, black-start capabilities, emergency power, load-following, and transmission and distribution deferral, for example. Unlike batteries, CAES is also well-suited for frequent deep discharge cycles without significant negative impact on the facility's useful service life.

The design, construction, and operation of CAES technology have benefitted greatly from years of experience from two other industries: hydrocarbon storage and combustion turbines. Additionally, there are two conventional fuel-fired CAES facilities that have been operating for decades and have demonstrated the reliability of this technology. These two facilities are located in Huntorf, Germany and McIntosh, USA, and a summary of their technical operating characteristics can be found in Table 1. The maturity of this technology is important because it makes an investment in the technology less risky and it means that it is deployment-ready. These factors are essential to implement energy storage quickly to keep pace with intermittent renewables growth. There is a number of modern CAES projects in different stages of planning and development around the world, some prominent examples are: Apex's Bethel Energy Center fuel-fired CAES project in Texas, RWE Power's ADELE adiabatic CAES project in Germany, Gaelectric's Larne CAES project in Northern Ireland, Pacific Gas and Electric's CAES project in San Joaquin County, California, and a demonstration-scale adiabatic CAES project being developed by NRStor in Goderich, Ontario. Experience with CAES to-date and the continuing research and development set CAES apart as a promising, mature technology that can be used, amongst many other utilities, to match intermittent renewable energy with daily and, possibly, even seasonal load cycles. Further, the potential of CAES to be combined with thermal energy storage

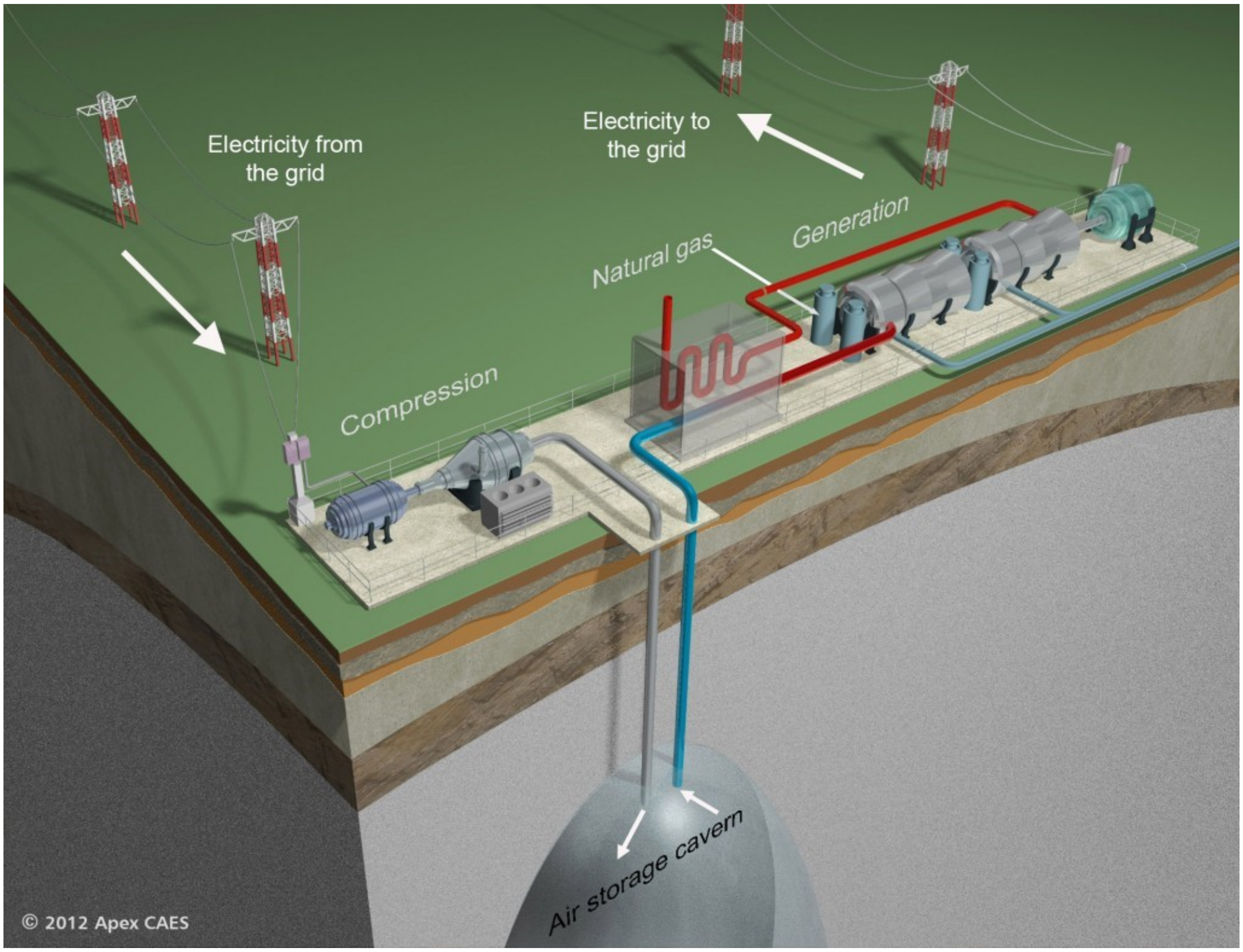

Figure 4 Typical layout and components of fuel-fired CAES (Image from http://www.apexcaes.com/caes accessed 23/05/17).

and other heat sources to become fuel-free is a rapidly developing field and holds much potential for synergy with industrial processes.

1.3 Barriers to CAES Implementation

Despite the maturity of CAES technology, these facilities are complicated and multi-faceted and require specific geologic conditions to allow for the economic storage of large masses of air underground. Above ground compressed air storage is possible but it is higher risk and costly for large-scale facilities. Therefore, to allow CAES implementation in Canada to proceed, opportunities for CAES development need to be identified. To identify these opportunities a methodology for comparing potential CAES sites is needed. The development of a method for site comparison and the subsequent identification of development opportunities for CAES is addressed in part one of this research.

Furthermore, the argument of whether CAES or SCGT should be utilised for balancing intermittent renewable energy is ongoing and has received little attention in Canadian specific contexts. Based on the estimated installation of 18 GW of natural gas generating power in Canada by 2040, as seen in Figure 2, it appears that there is a preference in the industry for sticking with conventional means of generation. The comparative environmental and economic impacts of these technologies need to be closely examined to determine which is preferable.

Table 1 Operating characteristics of existing diabatic CAES facilities

	Huntorf	McIntosh
Plant		
Operating utility	E.ON Kraftwerke	PowerSouth
Cycle efficiency[a]	0.42	0.54
Energy input for 1 kW h_{el} energy output	0.8 kW h_{el}/ 1.6 kW h_{gas}	0.69 kW h_{el}/ 1.17 kW h_{gas}
Energy content (related to power output)	642 MW h	2640 MW h
Planning – construction – commissioning	1969–1978	1988–1991
Compression		
Compressor manufacturer	Sulzer (today MAN Turbo)	Dresser-Rand
Max. el. input power	60 MW	50 MW
Max. air mass flow rate	108 kg/s	Approx. 90 kg/s
Compressor units	2	4
Charging time (at full load)	Approx. 8 h	Approx. 38 h
Storage		
Cavern construction company	KBB	PB-KBB
Cavern pressure range	46–72 bar	46–75 bar
Cavern volume	310,000 m^3	538,000 m^3
Expansion		
Turbine manufacturer	BBC (today Alstom)	Dresser-Rand
Max. el. output power	321 MW	110 MW
Control range (output)	100–321 MW	10–110 MW
Discharging time (at full load)	Approx. 2 h	Approx. 24 h
Start-up time (normal/ emergency)	14/8 min	12/7 min
Max. mass flow rate	455 kg/s	154 kg/s
HP turbine inlet	41.3 bar/490 °C	42 bar/538 °C
ND turbine inlet	12.8 bar/945 °C	15 bar/871 °C
Exhaust gas temperature	480 °C	370 °C (before recuperator)

Adapted from "A review on compressed air energy storage: Basic principles, past milestones and recent developments," M. Budt, D. Wolf, R. Span, & J. Yan, 2016, *Applied Energy*, *170*, p. 250-268. Copyright 2016 by Elsevier.

1.4 Objectives

In order to address the barriers to CAES implementation discussed in the previous section, this document discusses a two-part research program. Part one of the research, Sections 2-7, addresses the need for CAES siting by producing the following products:

- A suitable method for evaluating and comparing potential sites for CAES, and
- A first-order assessment of the technical feasibility and potential application of CAES as a bulk energy management system for balancing renewable energy with electricity demand across Canada.

The site evaluation process is setup as a simple, but robust, multi-criteria analysis (MCA) that will allow for easy replication of the study. The analysis framework and data collected are valuable as a starting point for more comprehensive or focused studies with a similar application of evaluating CAES or other energy storage technologies. The analysis is set up to assess the continuous geospatial potential of CAES using an integration of MCA and geospatial information systems (GIS). The software chosen for integrating these two analytic systems was Clark Labs'© Terrset software, which is easily and economically available from clarklabs.org. ArcGIS was also used for GIS data manipulation.

The second part of the research, Sections 8-10, examines the comparative performance of CAES and SCGT by answering the following questions:

- What are the global warming potential (GWP) impacts of using CAES and SCGT for balancing intermittent renewable energy under realistic operating conditions, and
- How does carbon pricing affect the economics of these technologies?

To address these questions, the author investigated how big of an impact partial loading inefficiency has on the GWP of these technologies. The GWP impacts were assessed using life cycle assessment (LCA) techniques and methodology. An SCGT is utilised for the comparison instead of a CCGT because, as noted earlier, CCGTs do not have a sufficiently quick ramp rate and startup time to effectively balance fluctuations in wind power production.

2.0 Multi-Criteria Analysis

This study makes use of the robust and flexible platform the multi-criteria analysis (MCA) methodology offers. MCA is a field of study dedicated to comparing and evaluating alternatives, usually used for making informed decisions about complex subjects that can involve a wide variety of inputs and considerations. This field of analysis is very versatile and is often used as an alternative to monetary comparisons when important considerations to an objective are difficult to or cannot be monetised. MCA has methods of incorporating qualitative data which can be invaluable when attempting to incorporate criteria such as public perception or opinion into engineering and policy decision making (Dodgson, Spackman, Pearman, & Phillips, 2004).

Within the field of MCA, there are many different methods or frameworks which can be used to compare alternatives. This study utilised a method which uses scoring and weights because non-scoring methods, such as the dominance method, are not practical for or capable of assessing a very large number of alternatives. The continuous spatial nature of this study, which makes for a nearly infinite number of possible options, meant that a scoring and weighting method was necessary. The first order nature of the study and the mutual independence of the criteria meant that a simple additive model is well suited for the analysis. This also makes the methodology considerably simpler, making it more practical for other groups or organisations to replicate the method for their own study. This methodology is known as a weighted-linear-additive model, and it is also categorised as a 'compensatory' method. In compensatory methods, a good score on one criterion can compensate for a bad score on another, resulting in a balanced impact on the site score. This may seem intuitive, but some MCA forms do not allow for this compensation, and a poor score on one criterion may result in a poor overall evaluation despite all around good performance.

2.1 MCA Approach

The weighted-linear-additive MCA methodology involves five basic steps:

1. Identification of objectives,
2. Identification of options to achieve objectives,
3. Identification and scoring of criteria to compare alternatives,
4. Analysis and suitability of scoring,
5. Interpretation of results.

The objective of this study was discussed in Section 0 and is limited by the scope of the study set out in Section 2.2. Any location in Canada is technically an option for CAES siting; however, most of the country is not underlain by salt rock formations. Therefore, the study is limited to geologic formations where salt is present. The constraints on CAES siting and criteria used to evaluate potential sites are introduced briefly in Section 2.3.

The criteria scoring systems use a combination of global and local scoring on a scale from 0-100, and each criterion has a unique system. A local scoring system in MCA means that the scoring system is designed to accommodate the range of values expected to be found in the scope of the study. Conversely, a global scoring system is designed to accommodate the full range of values possible for any region or scope. Criteria scoring is based on reviewed literature, input from academic and industry experts, and the author' professional judgement. The scoring functions are piecewise linear functions created to evaluate the suitability of a range of criteria values for CAES. The details on the development and justification of each scoring system for each criterion are given in the relevant sub-sections of

Section 3.0. A standardised, dimensionless scoring system of 0-100 allows for the addition of scores between different criteria that would otherwise be incompatible. For example, the criteria of depth to salt layer and proximity to the electric grid can both be measured in distance units; however, the addition of these two numbers is meaningless because these numbers are relevant on different scales. A similar problem is encountered with criteria that have different units and even between criteria with the same unit under the same category; for this reason, it is advantageous to evaluate all of the criteria on a common, unit-less scale. Criteria are scored based on metrics, which refers to the input data which is evaluated to determine a criteria score. In contrast to the criteria's unitless scores which are only meaningful within the context of the MCA, metrics have units with physical meaning, such as distance or energy.

After determining a score for every criterion for a site, an overall score must be assigned to that site which represents the suitability of the location for CAES development. Individual criteria scores are multiplied by their corresponding weight ranging over 0-1 and then added together to determine an overall site score from 0-100. The purpose of these weighting factors is to account for the fact that different criteria will vary in how influential they are on a site's suitability. The determination of weighting factors is discussed further in Section 4.0. A summary of the MCA process is shown in Figure 5; this process is used to evaluate every possible site within the scope of the study, beginning with the metric values for the location as inputs to the analysis.

2.2 Scope and Limitations of MCA

The scope of the MCA is a first-order assessment of the potential of CAES across Canada. To complete a study of such a broad scope required a large number of assumptions and simplifications. One of the major limitations of multi-criteria analysis is that a similar quality of information is needed for all of the sites, for each criterion. What this means is that if detailed stratigraphic information for one site with all of the associated mechanical parameters is available, but for another site only an estimation of some of the same information is available, then an equivalent level of information must be used. Reaching an equivalent level of information between sites may be done by extrapolating the less detailed site information; however, more commonly the detailed site information has to be simplified or ignored for analysis alongside the less detailed site information.

The size of the facility being considered implicitly impacts the scoring of criteria and their weighting. This study assumes a 160 MW facility with 1200 MWh of storage, which is estimated to require approximately 165,000 m^3 of storage volume. Furthermore, the cavern storage is assumed to be operated in a constant volume scheme. This is an important consideration because hydraulic pressure compensation of the compressed air can be used for constant pressure operation, which opens up gaseous salt cavern storage to new opportunities and different challenges.

It is important to note that CAES can use a variety of geologic formations for underground compressed air storage. However, this study only considers salt cavern storage for CAES and not porous aquifers, hard rock cavities, or abandoned mines as potential air storage. Salt cavern storage is typically the most economical form of underground storage and was used for both of the existing large-scale CAES operations. In fact, salt cavern storage has technical advantages over storage in alternative geologic formations. Porous aquifer storage can suffer from larger storage losses and usually requires multiple wells to meet the required air mass flow rates needed to drive the expanders. McGrail et al. (2013) and Succar & Williams (2008) discuss CAES design and operation within porous aquifer formations. Hard rock cavities are expensive to create, and abandoned mines are highly site-specific and can also suffer from higher storage losses. As no large-scale CAES projects have yet been proposed in Canada, it is

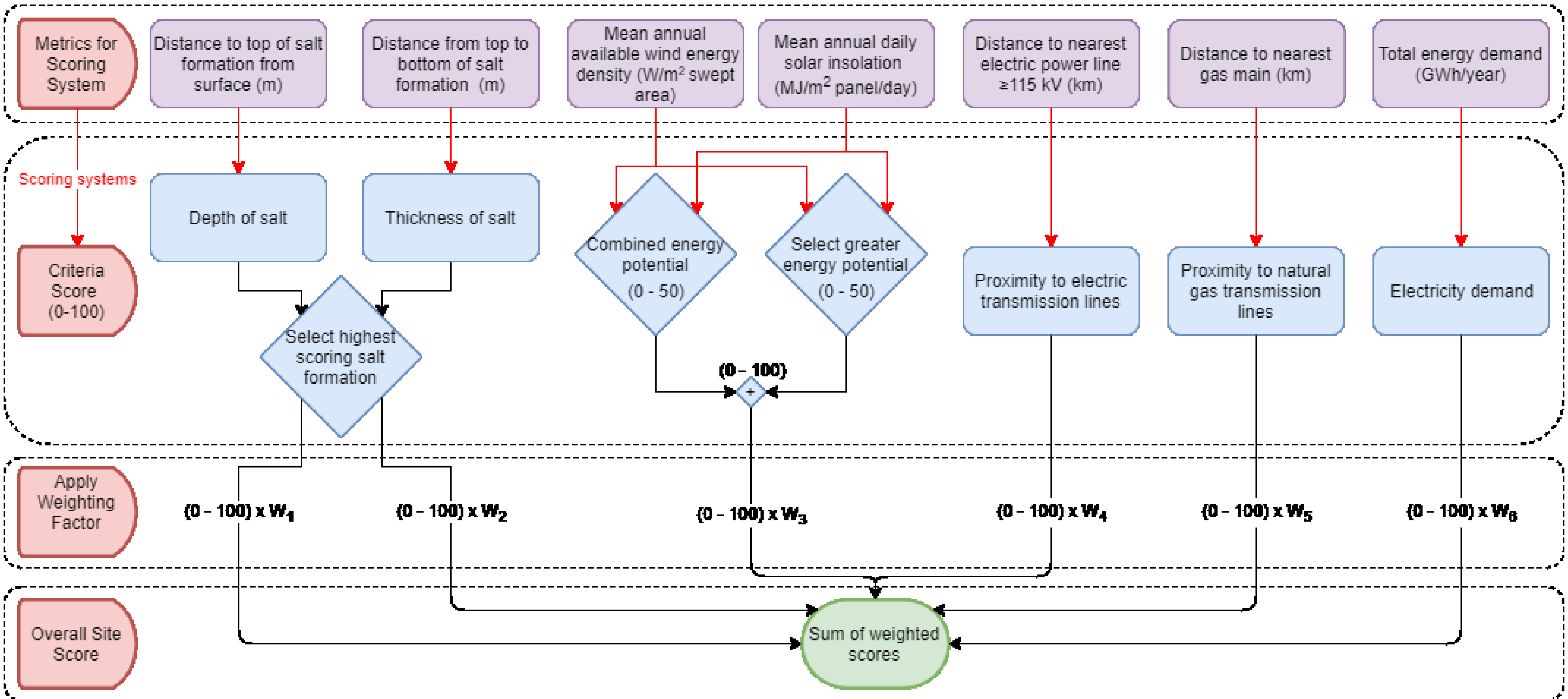

Figure 5 Process diagram of the weighted-linear-additive multi-criteria analysis used for site evaluation and comparison

reasonable to focus on salt cavern storage with the initial assumption that these storage options represent the most economical sites for CAES development.

As discussed earlier, large-scale energy storage will play a critical role in future energy grids with high levels of renewable energy penetration. As a result, this report will focus on the potential for CAES to aid in increasing renewable power penetration and integration into electricity grids.

The GIS data used in this study was acquired primarily from online government portals or advocacy groups and data repositories such as the Oil, Gas and Salt Library of Ontario and the Alberta Geological Survey. The data acquired is considered to be reasonably reliable, but not all of the information has been verified; some of the information presented on the GIS maps may be inaccurate or out-of-date. Where possible, data were compared across different sources to ensure completeness.

A monetary assessment of CAES is beyond the scope of this research and was not performed. Such an assessment involving, for example, a cost-benefit analysis could be incorporated into a multi-criteria study in a variety of ways and would likely be dependent on the availability of proprietary data that was not available for this study. It is recommended that other individuals or organisations undertaking more in-depth siting studies for CAES integrate a monetary evaluation process as a criterion.

2.3 Facility Siting Constraints and Criteria

2.3.1 Constraints

One potential problem with weighted-linear-additive (WLA) MCA is that there is no built-in method for dealing with constraints. No matter how poorly a site performs on any individual criteria, WLA MCA does not exclude that site from being scored and potentially even being an attractive option even though it may be impossible or impractical. The following list of constraints outlines the technical limitations to the deployment of CAES in salt:

1. Geologic Constraints
   i. Maximum practical cavern depth in salt – 2000 m
   ii. Minimum practical cavern depth in salt – 200 m
   iii. Minimum thickness of salt – 20 m
   iv. Minimum caprock quality – variable, should have low porosity and little natural fracturing, and should comprise stiff and competent strata
2. Electric Grid Constraint
   i. Need for increased clean, flexible energy on the electric grid to support increased renewable energy penetration – specifically where hydropower is not the dominant form of energy generation
3. Environmental Constraints
   i. Cannot be sited on designated parkland
   ii. Cannot be sited on indigenous people lands/treaty lands

The above list of criteria is included here for the readers understanding and potential inclusion in future studies aiming at eliminating heuristics; however, these constraints were not strictly implemented in the methodology for this study. Generally, a site that meets this list of constraints is considered eligible for CAES deployment, but the implementation of these constraints varies. The geologic constraints were not used to limit the analysis, but they did influence the scoring systems for the geologic criteria. Opinions on what the maximum and minimum geologic limitations should be differ; the values given in the above list are based on the experience and views of the author. The environmental constraints were not considered to be a first-order issue but may be influential for provincial or regional scale studies. The electric grid constraint was utilised to narrow the scope of the MCA to only provinces where CAES deployment would be beneficial for achieving increased renewable energy penetration and reduced GHG emissions. In practice, this took the form of ignoring provinces where hydropower is the dominant form of energy generation since it is both low-carbon and flexible enough to support intermittent renewables integration. Electricity generation by fuel type is given for each province and territory in Canada in Figure 6. The largest source of electricity in British Columbia, Manitoba, Quebec, and Newfoundland and Labrador is hydropower, and these provinces are therefore not a focus for CAES investigations, per the electrical grid constraint given above. Enforcement of this limitation does not have a significant impact on the analysis because these provinces also have limited access to salt formations. Further, studies on CAES using alternative geologic storage mediums, and on the usefulness of CAES in a hydropower-dominant grid are useful next steps for considering CAES in these provinces.

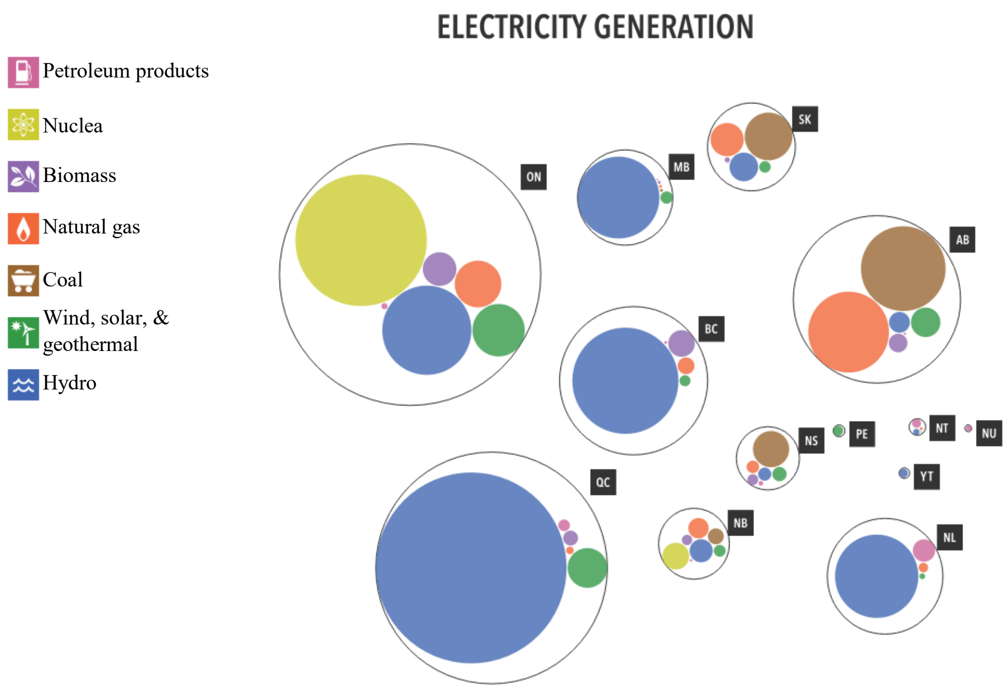

Figure 6 Electricity generation in Canada by region and fuel type for 2016 (Image from the National Energy Board's 'Canada's Energy Future' tool accessed 02/06/2017)

2.3.2 Criteria

The potential of CAES for a site that meets all the constraints is measured using a weighted MCA. First-order criteria for CAES were established through a process of professional judgement and open discussion amongst academics at the University of Waterloo with some input from industry experts.

Through a detailed look at the design framework, considerations that are important to the technical feasibility of establishing a CAES facility were identified. After being identified, these considerations were given one or more metrics for geospatial evaluation. To aid the readers in understanding and discussing the different criteria, these criteria were grouped into four main categories, and described below:

1. Geology
   a. Depth to salt formation
   b. Salt formation thickness
   c. Caprock
2. Energy supply and demand
   a. Renewable energy potential
      i. Wind energy potential
      ii. Solar energy potential
      iii. Tidal energy potential
   b. Electrical energy demand
3. Existing infrastructure
   a. Proximity to electrical transmission lines
   b. Proximity to natural gas transmission lines
4. Environmental, Social and Economic Site Suitability
   a. Proximity to indigenous lands
   b. Proximity to parks and environmentally sensitive areas
   c. Electricity market type and size

While this list represents an excellent cross-section of the considerations that go into siting a CAES facility, the broad scope of this study and limited data availability made implementation of the full list into the MCA challenging. Section 3.0 discusses the complete list of criteria and which ones were included in the MCA.

3.0 Considerations for CAES Site Selection

In the previous section, a list of potential CAES siting criteria was identified. In this section, why the selected criteria are important, how they affect the suitability of a potential CAES site, and which ones were included in the MCA is discussed. The discussion on the influence of each parameter will lead to the reasoning behind the construction of the piecewise linear scoring system for each criterion. The criteria are grouped and discussed according to the four main categories set out in Section 2.3.2. The scoring systems were created through experience, discussion, review, and iteration, and are not universally relevant. Experts in the field may choose to revise the scoring systems to reflect their experience, opinions, and interests.

3.1 Geologic Criteria for Salt Cavern Storage

The depth and thickness of salt formations for underground compressed air storage are the only two geologic criteria included in the MCA. These criteria are followed by a discussion on the importance of the caprock for salt cavern storage; however, it was not included as a criterion. Characterising the caprock can lead to numerous criteria, and it was decided that evaluating caprock suitability in terms of a single preference-independent criterion would be too impractical for a study of this breadth and scope. In fact, there are many mechanical and structural properties of salt which are important in the design of a cavity, such as stiffness, strength, purity, moisture content, etc., and should strictly be considered as geologic criteria. Unfortunately, data of this detailed nature is too sparse to characterise the full extent of the salt formations of interest in this study, and they were therefore neglected. Regardless, the two criteria included are sufficient to identify areas that hold the most promise for salt cavern storage. It is common to have multiple viable salt strata underlying the same region, especially with bedded salts. Where there are multiple salt strata, the GIS analysis scores these strata separately based on both the geologic criteria and then these scoring maps are superimposed, and the highest score for a given location is used. Therefore, the MCA results do not distinguish which strata were best for any particular location, and the reader should refer to the geologic criteria scoring maps to identify strata selection.

3.1.1 Depth of Salt

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 report, 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, Wolf, Span, & Yan, 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 upper range of the depth is controlled by the minimum air pressure in the cavern. Low air pressure can increase the creep rate 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 (Equation 1):

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

where:

- $\dot{\varepsilon}_{ss}$ = steady-state strain rate (s^{-1})
- $\sigma_1 - \sigma_3$ = deviatoric stress (the difference between the major and minor principal stresses) (MPa)
- T = temperature (°K)
- A = material-dependent parameter (includes texture, moisture content mineralogy, and impurity content) (s^{-1})
- n = parameter based on different mechanisms or creep regime and determined from the slope of $\ln(\dot{\varepsilon}_{ss})$ versus $\ln(\sigma_1 - \sigma_3)$ plot (dimensionless)
- σ_o = normalising stress at which a particular mechanism is initiated (MPa)
- R = universal gas constant (8.314 J/(mol·°K))
- Q = activation energy of a given mechanism (J/mol)

From the above equation it can be observed that the creep rate is a function of the normalised deviatoric stress to the power of 'n', which is typically about 3 (Rothenburg & Dusseault, 2002). At similar cavern pressures, the deviatoric stress is greater in deeper caverns as compared to shallower caverns. The equation also demonstrates that creep rate increases exponentially with temperature as part of the -Q/RT term. In the subsurface, the temperature of rocks typically 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 mid-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, as a rule of thumb (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 creep 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 7.

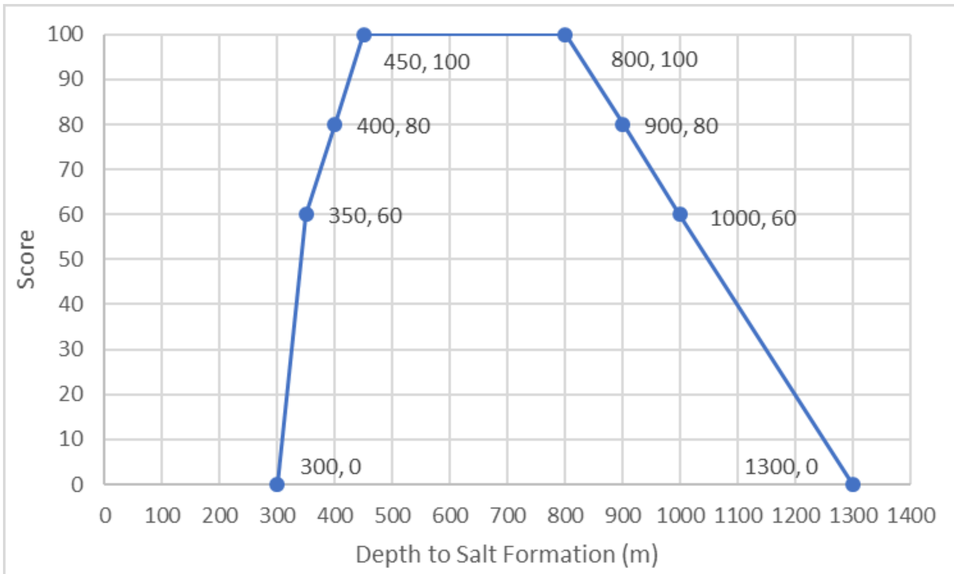

Figure 7 Scoring system for depth to salt criterion

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.

3.1.2 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 8. 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, geomechanical analysis is advised to assess the long-term stability of the roof. Bruno (2005) conducted a parametric analysis of salt cavern design in thin bedded salts and the report is a good reference for understanding the influence of geomechanical factors, such as the height/diamter ratio, on cavern stability and closure. 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 report 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.

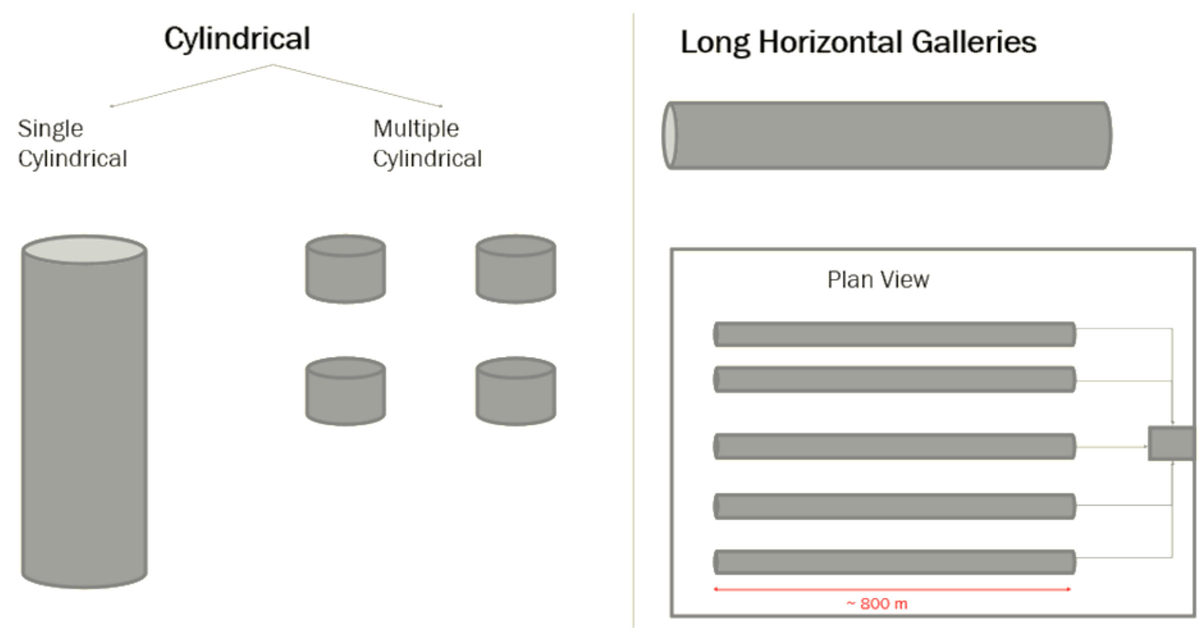

Figure 8 Salt cavern configuration alternatives for achieving large volumes

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. However, above 90 m the slope of the graph is reduced to reflect that additional salt thickness will have less influence over cavern design as space becomes less of a limiting factor. Figure 9 shows the global scoring system used to evaluate the salt formation thickness criterion.

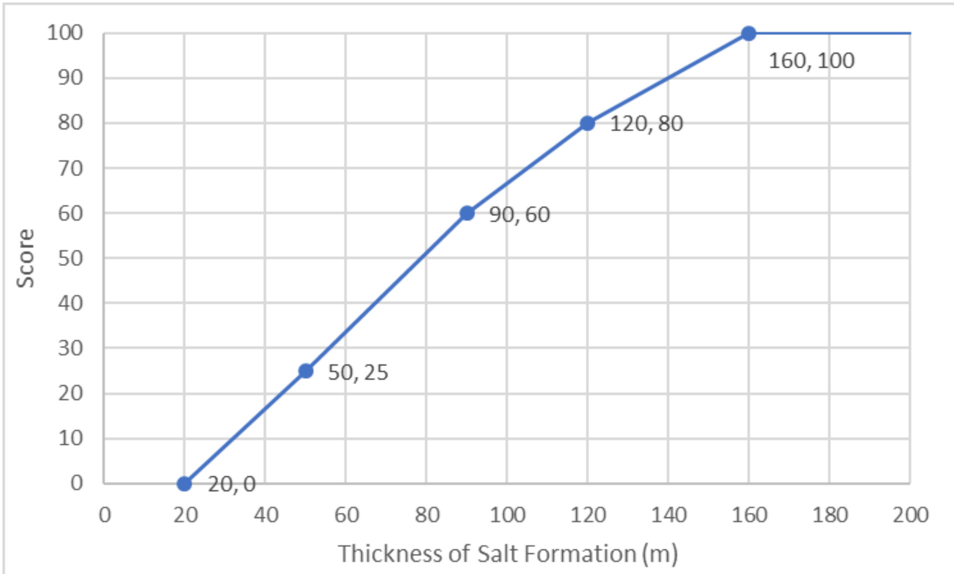

Figure 9 Scoring system for salt formation thickness criterion

3.1.3 Caprock

The caprock for a cavern refers to the material overlying the cavity which includes the geologic layer that comprises the cavity ceiling and the layers above which influence the stability and integrity of the cavern. This is a difficult limit to define as the stress field around the cavern, and the potential pathways for material to escape from the cavern are site specific. Consideration of the caprock is vital in analysis and design because it acts as a load-bearing structure which bears the weight of the overburden and distributes it away from the salt cavern. Caprocks with large elastic moduli benefit cavern operation by reducing strain rates, subsidence, and cavern volume loss (Ehgartner & Park, 2009). In addition to stabilising the cavern, the caprock layers must be impermeable enough to trap the high-pressure air and prevent its migration upwards.

The caprock can consist of a combination of salt and non-salt layers. Salt domes have the vertical extent to allow for thick salt layers between the cavern and the first non-salt overburden layer. However, because of limited thickness, caverns in bedded salt deposits may not always have a salt roof; therefore, the thin salt layer and the non-salt layer have to fulfil the requirements of the roof of the cavern. In the bedded salt deposits, an operator should try to leave a thick salt roof to maintain tightness and prevent interface slip between the non-salt roof and the salt roof. (Bruno & Dusseault, 2002) showed that interface slip between the ceiling salt and the non-salt roof decrease with larger salt roof thickness.

In the cases where a non-salt layer is required to act as a roof layer, such as in thinly bedded salt deposits, the layer should contain the following roof rock characteristics: moderate to high elastic modulus, moderate to high strata thickness, no major faults/joints, and very low permeability.

3.2 Energy Potential for Renewable Power Integration

Modern electricity grids have been called the most complicated machine that man has ever created. Adding a piece to this complex machine is not as simple as plugging into an electrical outlet in a building, and this is the reason why connecting to the electric grid usually requires several electrical and power related studies before receiving approval. It is, however, impossible to incorporate many of these highly complicated issues into a broad scoped study which looks at an area that covers numerous different jurisdictions, each of which has their unique electric infrastructure and regulations. On the other hand, attempting to site a facility without considering the larger system with which it will become a part of may lead to misleading results which are not practical or useful. The following criteria attempt to capture some of the core considerations related to supply and demand electricity markets with renewable energy.

3.2.1 Integration with Renewable Energy Sources

Situating CAES near renewable energy power plants can be highly advantageous. Since renewable energy is often at its greatest potential in isolated areas, this energy must be transported by electrical transmission lines. Building enough transmission capacity to support the fleet of renewable power at its peak generation (which it may rarely produce) is not efficient or cost effective. Renewable power supported by CAES allows for a reduction in the needed capacity of the transmission line while maintaining higher transmitted capacity factors for the renewable power. Transmitted capacity factors for a wind farm that is transmission constrained can improve by as much as 39% to 80% when CAES is added (Greenblatt, Succar, Denkenberger, Williams, & Socolow, 2007).

To be forward thinking, this study uses publicly available energy potential maps. Energy potential maps offer greater insights into how the country's power generation may develop rather than focussing on currently operating renewable power plants. 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. Note that the swept area for a wind turbine is the circular area that the blades of the turbine cover, and that the mean daily global insolation is for a south facing fixed panel at a tilt equal to the latitude of the installation. The tilt angle that the map was created for is not evident from the website it was obtained from but was determined by comparing the map to values given for Calgary in the original paper that produced the maps (Pelland et al., 2006). The renewable energy potential score for a given site is a composite score calculated according to:

$$Renewable\ energy\ potential\ score = 0.5 * average(ws, ss) + 0.5 * max(\mathrm{ws}, \mathrm{ss}) \quad (2)$$

where: *ws* = wind energy potential score
ss = solar energy potential score

Therefore, the renewable energy potential score is 50% average available resource and 50% best available resource. The scoring system was setup in this way to create a comprehensive evaluation which addresses two main concerns. First, a site only needs to be strong in one source of energy for it to be viable to ideal for power generation and second, a site that is strong in both resources has greater potential for power generation. A potential site is evaluated for this criterion based on the average potential of renewables within a 10 km radius.

Note that this report focusses on wind and solar energy resources only. However, tidal energy projects are being demonstrated or developed on both the Canadian coasts, and this energy resource potential represents a possible opportunity for energy storage to aid in its integration. Additional common sources of renewable energy which are not considered in this study are hydropower and biofuels because they are not intermittent sources of energy and therefore do not rely on balancing from flexible power sources.

The scoring systems for solar and wind powers were based on a simple idea that a score of 100 should represent some of the best potentials available for that resource across Canada. Conversely, a score of 0 represents the worst potential for that resource across Canada. These potentials are assumed to be linearly related to the energy density of the resource. The resulting scoring systems for wind and solar energy potentials are shown in Figure 10 and Figure 11, respectively. Note that these scoring charts do not share a common metric, as is clear from the units on the *x* axis. The author investigated the possibility of using a common metric but the effort revealed that this is a complicated exercise that is not practical for the scale of this study. In an ideal scenario, a common metric could be the levelised cost of energy, although this does not necessarily capture concerns relating to land use or social considerations. However, attempting to calculate energy production based solely on the metric of energy density is challenging and requires a multitude of assumptions including topography, technology, statistical variability, efficiency, and more. Considering all the assumptions necessary it was determined that a simpler approach is likely to provide more transparent results without significantly impacting the accuracy of the results. Further studies on this topic, especially those focused on a narrower range of sites, may require a more objective comparison between renewable energy potentials.

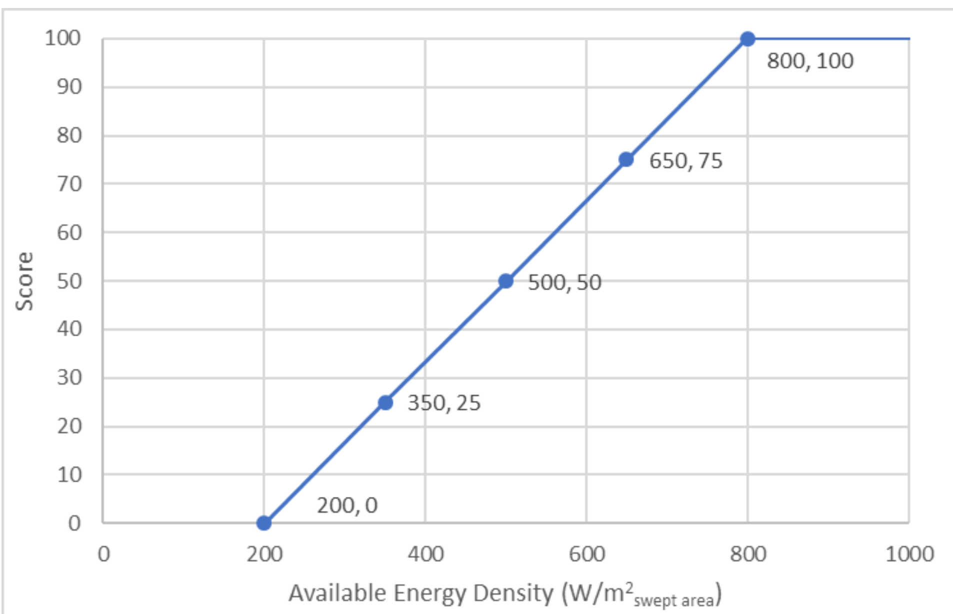

Figure 10 Scoring system for wind energy potential criterion

Wind and solar energy potentials were scored based on a local scale for Canada. The best wind potential that is accessible for market use will vary from province to province and country to country; studies using the methodology established in this report will need to change the scoring to reflect the resources available within the area under consideration.

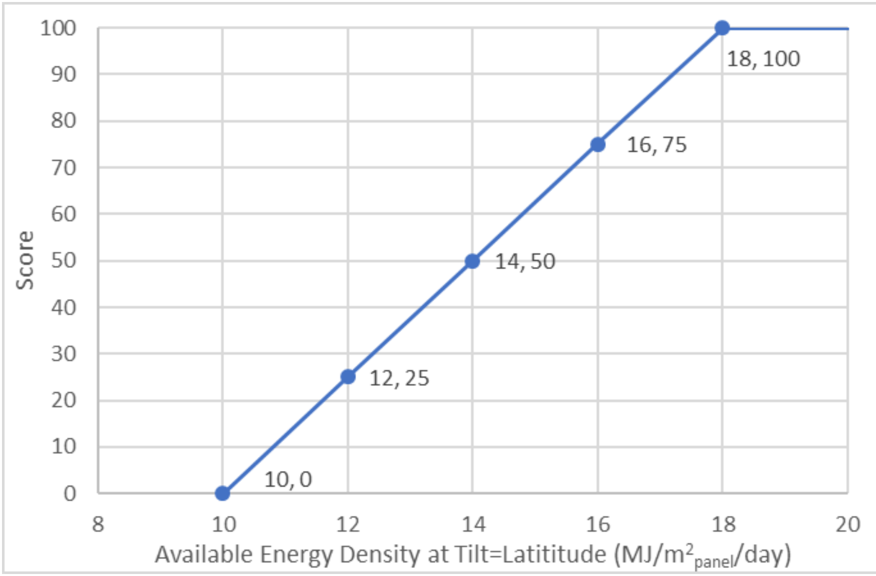

Figure 11 Scoring system for solar energy potential criterion

3.2.1 Electrical Demand

The less distance energy has to be transmitted, the more efficient the overall production and consumption cycle is. Therefore, just as it is desirable to site storage where energy is generated it is also beneficial to site storage where the energy is consumed. Ideally, the full production and consumption phase of electricity would all occur near each other. Unfortunately, renewable energy potential is often situated far away from highly developed areas, making this criterion at odds with the renewable energy potential criterion. It is still important to include this criterion because energy storage can also be useful for renewable power integration when sited near load centres. At load centres, energy storage is better able to help match supply and demand or offer auxiliary services such as spinning reserves. Spinning reserves are a valuable service where a facility is online and ready to rapidly provide or consume electrical power to or from the grid to help match supply and demand over relatively short durations. Spinning reserves compensate for supply and demand fluctuations and give slower responding generators time to adjust to meet the market needs.

For this study, population density by federal electoral districts is used as a proxy for electricity demand. The population of each district is multiplied by the average energy consumption per capita for the respective province. The average energy use per capita includes all energy consumed in the province, including residential, industrial, and commercial sectors. Although areas of heavy industrial energy consumption will vary somewhat from population density, this proxy is assumed to be adequately close for a first-order assessment. In Canada, a significant amount of heat and industrial process energy needs are supplied by the combustion of fossil fuels instead of electricity. While no distinction is made between energy sources for this criterion, the growing trend towards electrification means that energy demand is assumed to be a good proxy for future electricity demand.

The electricity demand scoring system is a simple local linear setup where proximity to the higher energy consuming electoral districts results in a high site score. For this criterion, the electricity demand score for a site is determined by summing the energy demand within a 10 km radius and scoring the site based on that value. 10 km was used because it is a reasonable distance for transmitting electricity without high voltage transmission lines and was found to be ideal for smoothing energy demand across the study area. The summation of the local energy demand for a site is calculated according to:

$$Electricity\ demand = \sum_{i=1}^{n} \frac{A_i}{A_{t,i}} P_i * ED_{capita} \quad (3)$$

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

Note that energy demand within electoral districts is assumed to be equally distributed across the area. The scoring system for electricity demand is shown in Figure 12.

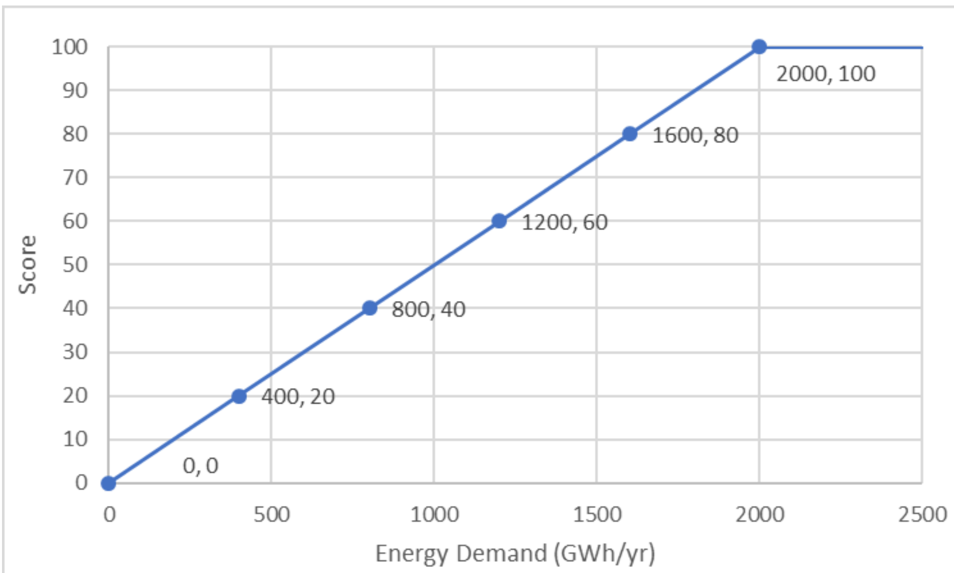

Figure 12 Scoring systems for electrical demand criterion

3.2.2 Existing Infrastructure

Access to sufficiently sized infrastructure is always a challenge and a major consideration when siting a large power generation project. Without good access to transmission, the services offered by a potential facility become less valuable and can significantly impact the attractiveness of a potential site. Building new infrastructure for a facility is always required to some degree, but new electrical and natural gas transmission lines face rigorous permitting requirements, land acquisition hurdles, and a price tag of hundreds of thousands to millions of dollars per kilometre. If these upgrades are necessary, they can delay the project or make it economically unfeasible. For these reasons, it is desirable to locate the facility where the needed infrastructure is already in place.

A conventional CAES facility needs access to both moderate to high voltage electrical transmission lines and moderate to high capacity natural gas transmission pipes. Higher voltage transmission line access is desirable because it allows the facility more direct access to support the larger electric grid without the high losses associated with connecting through low voltage lines. Although a CAES facility uses considerably less natural gas than a conventional natural gas power generation facility, the

McIntosh CAES plant still burns approximately 1.17 kWh of natural gas per kWh of electricity produced or 4000 British Thermal Units (BTU) of gas (Budt et al., 2016; Nakhamkin et al., 1992). Without a reliable supply of gas, a conventional CAES facility's operations can be impacted. On-site natural gas storage can be used to help manage gas supply and demand for the facility, but access to at least a moderately sized natural gas pipe with spare capacity is still necessary. Alternatively, an adiabatic CAES facility can be operated without the use of natural gas, eliminating the need to connect to any gas infrastructure. Adiabatic CAES siting is explored separately in an alternate criteria scenario described in Section 4.0.

Connections to the electric transmission lines require a substation. Furthermore, many transmission lines in Canada are at capacity during periods of peak transmission; this is known to be an issue in southwestern Ontario, around the London area. However, transmission constraints are not considered in this study for several reasons. First, transmission congestion is complicated to include in a MCA analysis and would require data collection across the country which is beyond the scope of this study. Second, transmission congestion will change over time with the addition of new generating capacity and the retirement of older facilities. Finally, and perhaps most importantly, CAES can help alleviate congestion depending on how it is operated. Thus, an area of transmission congestion may be a poor location for CAES or possibly an ideal location; this must be assessed using site-specific modelling to assess the potential impacts. In summary, this study assumes that no transmission connection issues will arise and that potential projects can connect to the transmission grid at any point.

The scoring systems for proximity to electric and natural gas transmission infrastructure are both on a scale of distance, measured in kilometres, and are assumed to be linear. Proximity to either of these connections are assumed to be equally desirable, and the scoring systems are influenced by other similar studies in the US and Iran (McGrail et al., 2013; Satkin, Noorollahi, Abbaspour, & Yousefi, 2014). The scoring systems for these criteria are shown in Figure 13.

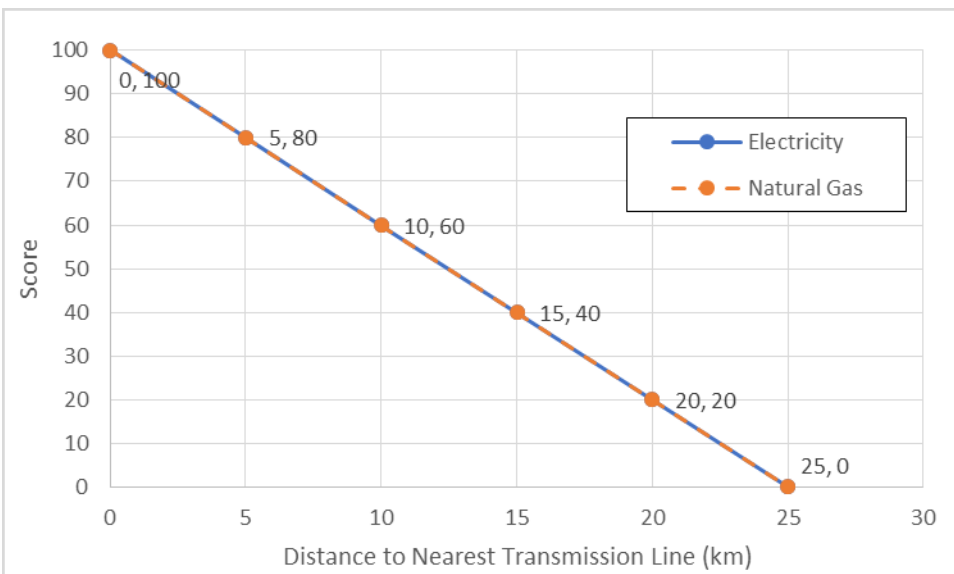

Figure 13 Scoring systems for electrical and natural gas transmission line proximity criterion

3.3 Environmental, Social, and Economic Considerations

Considerations in this category will be influential in a detailed site study. However, the first-order impacts of these considerations are difficult to relate to the technical feasibility or site potential.

Further, data on the geospatial variability of social acceptance of new large-scale power generation projects, for example, is generally not available. Typically, most people are opposed to the creation of any large-scale industrial facilities near their residence and CAES or other energy storage projects are likely to meet less public resistance if sited away from highly developed areas. It is also fair to say that large industrial facilities such as CAES should not be located on or near First Nations lands, unless the project has their approval and, preferably, positively engages their community. Additionally, it should be noted that the creation of underground cavities does pose a small, but real, risk to objects at ground level. Depending on the depth and size of the cavern(s), cavern collapse or shrinkage may result in sinkhole formation or ground surface subsidence. For the range of depths ideal for CAES, the risk of cavern collapse causing sinkhole formation is quite low and surface subsidence, if any, is likely to be spread over a large area. The most likely mechanism for damage to objects/facilities on the surface is from tilting or cracking resulting from uneven subsidence across the foundations of buildings and structures. Developers looking to construct underground storage caverns will need to investigate and address the risk of damaging structures at ground level.

As previously mentioned, no cost assessments were performed as part of this study. However, the inclusion of a metric such as capital costs would be highly valuable but difficult to incorporate. Estimating capital costs for CAES installations can be done by using the existing literature and case studies (McGrail et al., 2013; Zakeri & Syri, 2015), but making this estimate to accurately reflect how cost changes with spatial location would be a challenge. Some costs such as electrical and natural gas infrastructure connections can be reasonably estimated, but varying construction costs geospatially is not as simple. A study looking to incorporate capital costs as a criterion in a geospatially continuous study would need to be conducted over a relatively small area. Alternatively, discrete locations can be compared to allow for more tangible cost estimate changes.

Economic criteria that could easily be included in future studies are market size and type. A larger energy market is better for CAES so that the economy of scale can be capitalised on; CAES makes the most economic sense when it is a large (100+ MW) scale facility. The market type will be important to a developer considering a CAES project. In an open market system, CAES may be free to operate according to market demands and incentives to maximise the value of the project. This is especially true in areas where renewable power generators are continuing to drive off-peak electricity prices lower. Where government subsidies support renewable power, the price of electricity can sometimes drop below zero, making energy storage even more attractive. Monopoly markets where a single power generator has been designated can be difficult for a developer to work within. It may be possible to secure a project under contract to the designated power generator, but these contracts are likely to be fixed rate contracts with little operational flexibility. However, a siting study is also applicable to government run power generators such as SaskPower which may wish to add energy storage to their network.

From an environmental perspective, the location of the facility is influential in two ways: (1) proximity to environmentally sensitive areas and (2) transportation and transmission distances. To minimise the environmental impact of a CAES facility, it should be located away from environmentally sensitive areas and close to energy production and consumption centres. Proximity to sensitive areas is not considered a first-order consideration and will be important for studies at the regional scale. The second consideration is effectively captured in the list of criteria used in this study.

4.0 Criteria Weighting Selection

Two base case sets of criteria weights were used in the MCA analysis. The first set of weights were estimated based on the experience of the author and were used to obtain preliminary results and iterate upon the criteria scoring systems. The second set of criteria weights were established through an informal survey of CAES experts in Canada. The survey was completed by thirteen respondents, seven from industry and six from academia, who are experts from different fields of study relating to CAES, including geomechanics, power engineering, electricity markets, project development, and mechanical and thermal systems. Weights were calculated from the survey by averaging and normalising the scores given by the respondents. In addition to providing criteria weights, survey respondents were asked to evaluate how confident they were in the weights they provided. Both sets of weights and the average uncertainty associated with the survey results are given in Table 2. A blank copy of the survey used to obtain criteria weight data can be found in Appendix D.

Table 2 Estimated and informal survey results for multi-criteria analysis weights

Criterion	**Estimated MCA Weight**	**Survey MCA Weight**	**Uncertainty in Survey**	**Difference**
Depth of salt	0.20	0.173	29%	-0.027
Thickness of salt	0.20	0.192	26%	-0.008
Renewable energy potential	0.15	0.153	24%	0.003
Proximity to electric transmission lines	0.15	0.204	13%	0.054
Proximity to natural gas transmission lines	0.15	0.145	25%	-0.005
Electricity demand	0.15	0.133	24%	-0.017
Total	1.0	1.0		

The initial criteria weight estimates are all within the range of uncertainty for the survey weights except for the proximity to electrical lines criteria, which is 26% less in the initial estimates. Three weights differed by more than 10%: depth to salt, proximity to electric transmission lines, and electricity demand. The weight of the depth criterion dropped by 0.027, but the difference is still well within the average uncertainty in the survey responses. The depth criterion was also rated the most uncertain of the criteria at 29% of the survey weight. This is not surprising since it is difficult to define the ideal depth for a cavern, which is both site-specific and flexible depending on the cavern's function. Further, there is very little literature available on optimising storage cavern depth in salt. These factors create a lot of uncertainty around the criterion. The importance of the proximity to electric transmission lines criterion was undervalued in the estimates. This is evident from both the dramatic increase in its weight after the survey and the minimal uncertainty associated with it. The respondents were confident that the most important consideration when siting CAES is that it should be constructed near existing power lines. Conversely, the survey responses indicate that the local energy demand around a CAES site is the least important criterion for CAES siting. This result is consistent with the conventional centralised power generation and distribution model that Canada's electricity grid was built around. The premise of the centralised power generation model is that large-scale facilities can be constructed to capitalise on economies of scale and the power can then be transmitted and distributed by wire to where it will be consumed. Given the average uncertainty of 23% in the experts' weightings, and the discrepancies between weighting sets, both sets were used in the MCA, and the results were contrasted. However, no uncertainty was directly built into the analysis.

Two additional weighting sets were used in the analysis, making for a total of four, to address different scenarios. Adiabatic CAES does not use natural gas when producing electricity; therefore, another weighting set was created for this type of facility by removing the natural gas connection criterion from the survey results and uniformly scaling up the rest of the weights to maintain a sum of one. The second scenario uses the same process but eliminates three criteria: natural gas connection, depth of salt, and thickness of salt. The resulting weighting set is geology and technology neutral and can be used to evaluate where future studies should focus their efforts when looking for non-salt geologic storage for CAES.

5.0 Data Sources and Discussion

Data collected for this study came from a number of sources, mostly open accesses government funded organisations. This section will discuss what data was obtained, where it was obtained from, and how it was modified, if at all. The following discussions will comment on where each criterion or resource is particularly strong. Maps of the basic input, or metric, data collected for the analysis can be found in Appendix A; maps of the criteria produced from processing the metrics through their respective scoring systems can be found in Appendix B. A summary of all of the data collected for this study and their sources are presented in Table 3.

Table 3 GIS data sources summary

Data/Information	Coverage	Source
Wind Potential	Canada	*Environment and Climate Change Canada* http://www.windatlas.ca/maps-en.php
Solar Potential	Canada	*Natural Resources Canada* http://geoappext.nrcan.gc.ca/arcgis/rest/services/Energy
Energy Demand	Canada	*National Energy Board of Canada* https://www.neb-one.gc.ca/nrg/ntgrtd/ftr/2016pt/pblctn-nfrmtn-dwnlds-eng.html
Natural Gas Pipelines	Alberta/Saskatchewan	*Canadian Energy Pipeline Association* http://aboutpipelinesmap.com
	Ontario	*Union Gas* https://www.uniongas.com/storage-and-transportation/resources/maps
	Nova Scotia/New Brunswick	*National Energy Board of Canada* https://www.neb-one.gc.ca/nrg/ntgrtd/mrkt/archive/mrkt/dnmc/2013/index-eng.html
Transmission Lines ≥115kV	Alberta/Saskatchewan/ Ontario	*Canadian Electricity Association* http://powerforthefuture.ca/electricity-411/electricity-map/
	Nova Scotia	*New Scotia Power* https://www.nrcan.gc.ca/earth-sciences/geography/atlas-canada/selected-thematic-maps/16872
	New Brunswick	*New Brunswick Power* https://www.nbpower.com/en/about-us/our-energy/system-map
Salt Formation Depths	Alberta/Saskatchewan	*Alberta Geological Survey* http://www.ags.gov.ab.ca/
	Ontario	*Ontario Oil, Gas and Salt Resource Library* http://www.ogsrlibrary.com/
	Nova Scotia/New Brunswick	Howie, R. D. (1988). Upper Paleozoic evaporites of southeastern Canada. Ottawa, Canada: Energy, Mines and Resources Canada.

Data/Information	Coverage	Source
Salt Formation Thicknesses	Alberta/Saskatchewan	*Alberta Geological Survey* http://www.ags.gov.ab.ca/
	Ontario	*Ontario Oil, Gas and Salt Resource Library* http://www.ogsrlibrary.com/
	Nova Scotia/New Brunswick	Howie, R. D. (1988). Upper Paleozoic evaporites of southeastern Canada. Ottawa, Canada: Energy, Mines and Resources Canada.

5.1 Geology

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 Complex which underlies a section of the Gulf of St. Lawrence and extends under New Brunswick and Nova Scotia. The locations and approximate extent of these major salt formations are shown in Figure 14.

Figure 14 Major salt formations in the Canadian provinces (Adapted from the http://www.saltinstitute.org/salt-101/production-industry/ accessed 29/05/2017)

5.1.1 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 15 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).

Salt is contained in units F, D, B, and A2; Table 4 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.

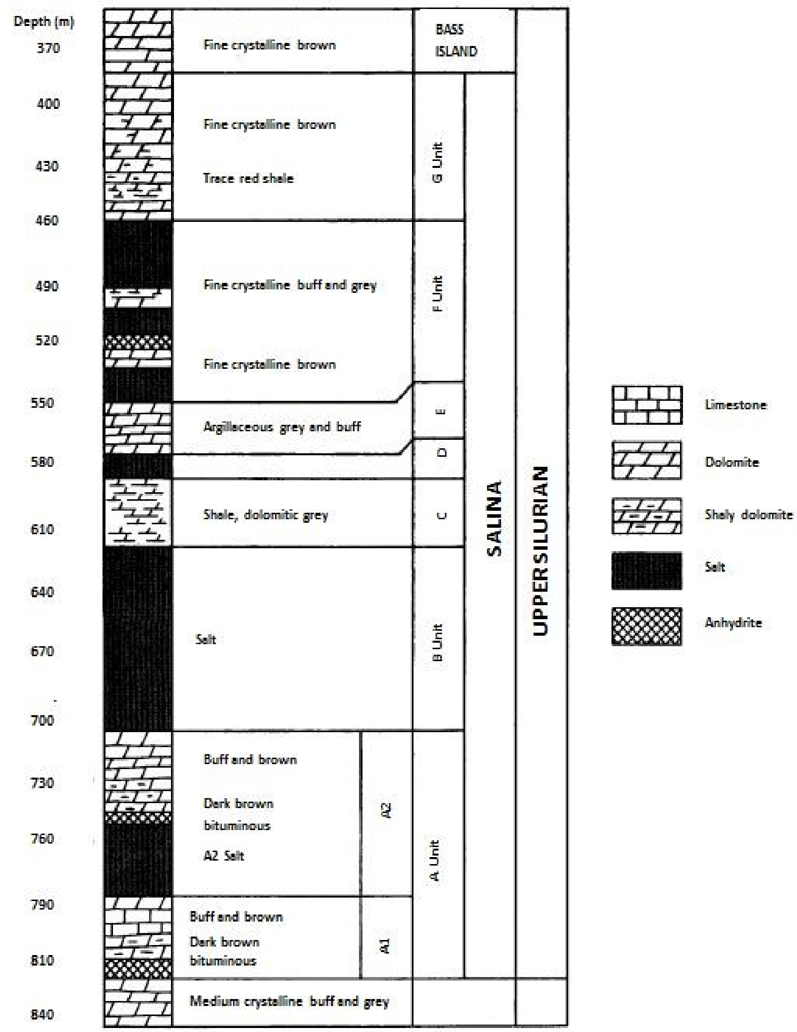

Figure 15 General stratigraphic section of southwestern Ontario (Hewitt 1962)

Table 4 Lithological information of the Salina Group Units (Hewitt 1962)

Formation	Unit		Description
Upper Salina			Top of Salina Formation.
	Upper Salt Beds	G	Fine crystalline brown dolomite, shaly dolomite, some anhydrite, and red shale.
		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 in thick 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 with some bituminous shale; Salt up to 140 ft (43 m) thick; where salt is absent the base of A2 is marked by anhydrite.
	A1		Fine to medium-grained, buff to brown dolomite; Fine to dense, brown-grey and dark-grey dolomite with dark-grey

Formation	Unit	Description
		bituminous shale; Anhydrite at base.

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.

5.1.2 Western Canadian Sedimentary Basin

Salt strata in Alberta are thicker and located at larger depths compared with those of salt strata in Ontario. Thus, 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 16 illustrates the location of these salt units. Isopach and depth maps of the salt units are given in Appendix A.

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

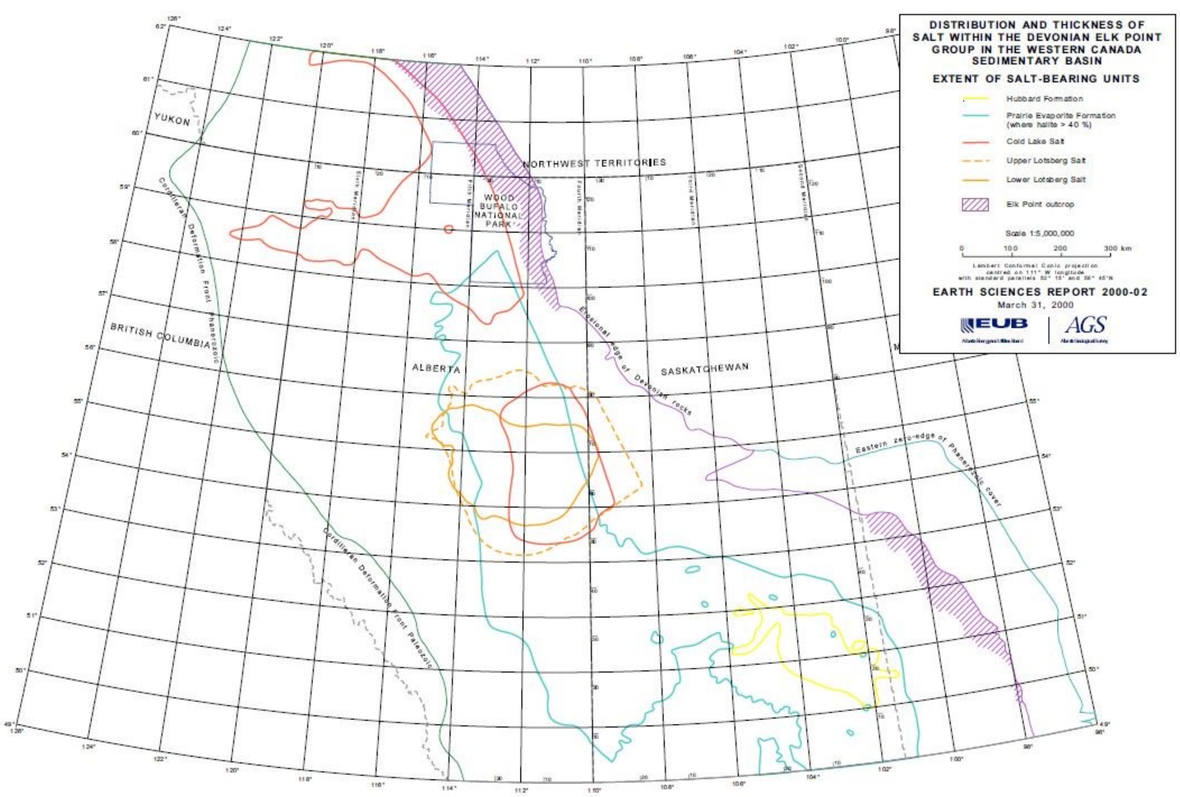

Figure 16 Extent of salt beds in western Canada (Grobe 2000)

Lotsberg salts ranges from greater than 2100 m in the west to 1050 m in the east. The thickness of the Lower Lotsberg salt varies from 0 m at the depositional edge to 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 thickness of the Upper Lotsberg salt varies from 0 m at the depositional edge to 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% extends 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.

5.1.3 Maritimes Basin Complex

Salt strata in Nova Scotia (NS) and New Brunswick (NB) are part of the two Upper Paleozoic groups: (1) the Horton Group and (2) the Windsor Group. The Horton Group is deposited in at least 2 locations in NB and one location in NS (Howie, 1988). The Windsor Group evaporites are underlain by the Horton Group rocks. The Windsor Group is widely distributed in the Maritimes and is comprised of more than 50% evaporites including halite (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 salt cavern storage.

The strata in the Maritimes Basin Complex 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 difficult 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 was 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 17. 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).

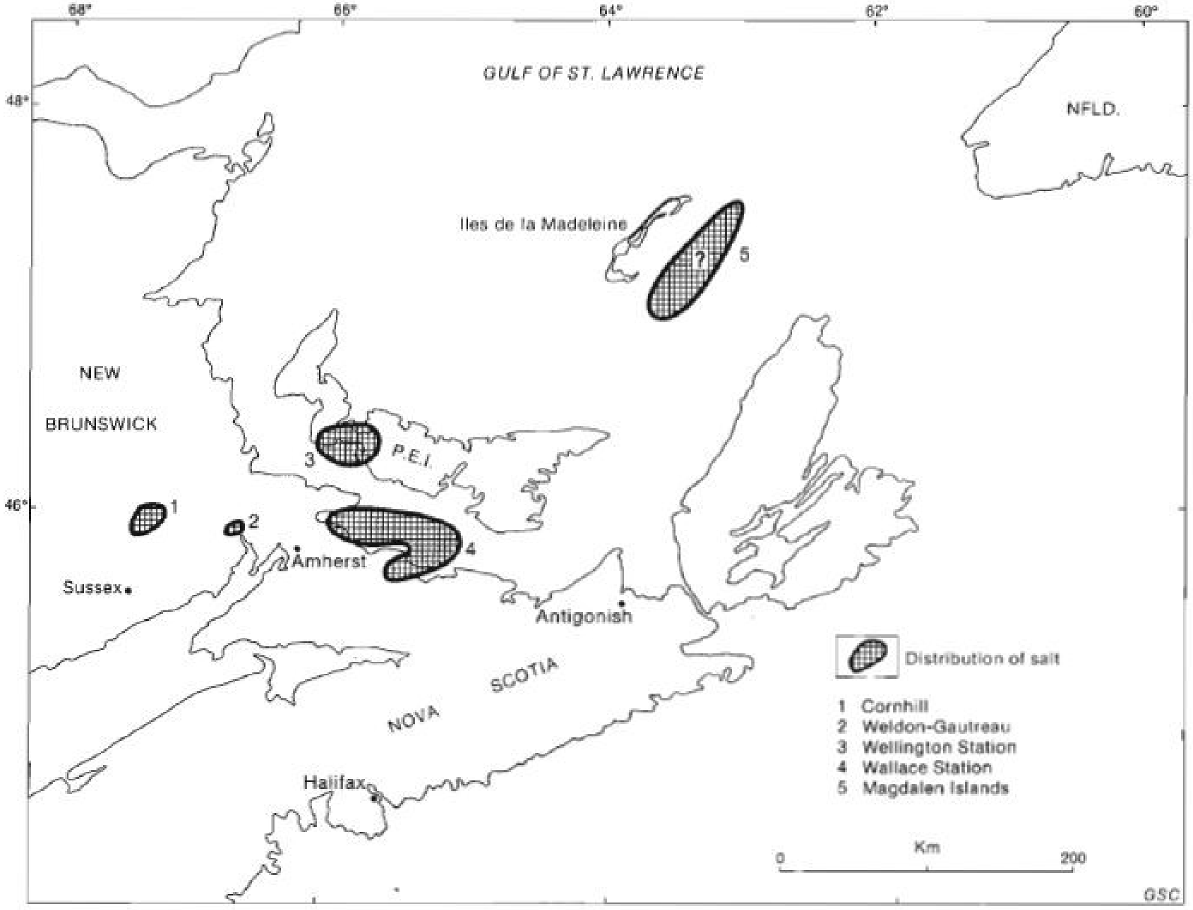

Figure 17 Distribution of the Horton Group salt in Atlantic Canada (Image from Howie 1988)

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 18 illustrates and numbers areas underlain by the Windsor Group salt deposits. Table 5 summarises depth, thickness, and salt complexity information available for the deposits numbered 1 through 18 in Figure 18. 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.

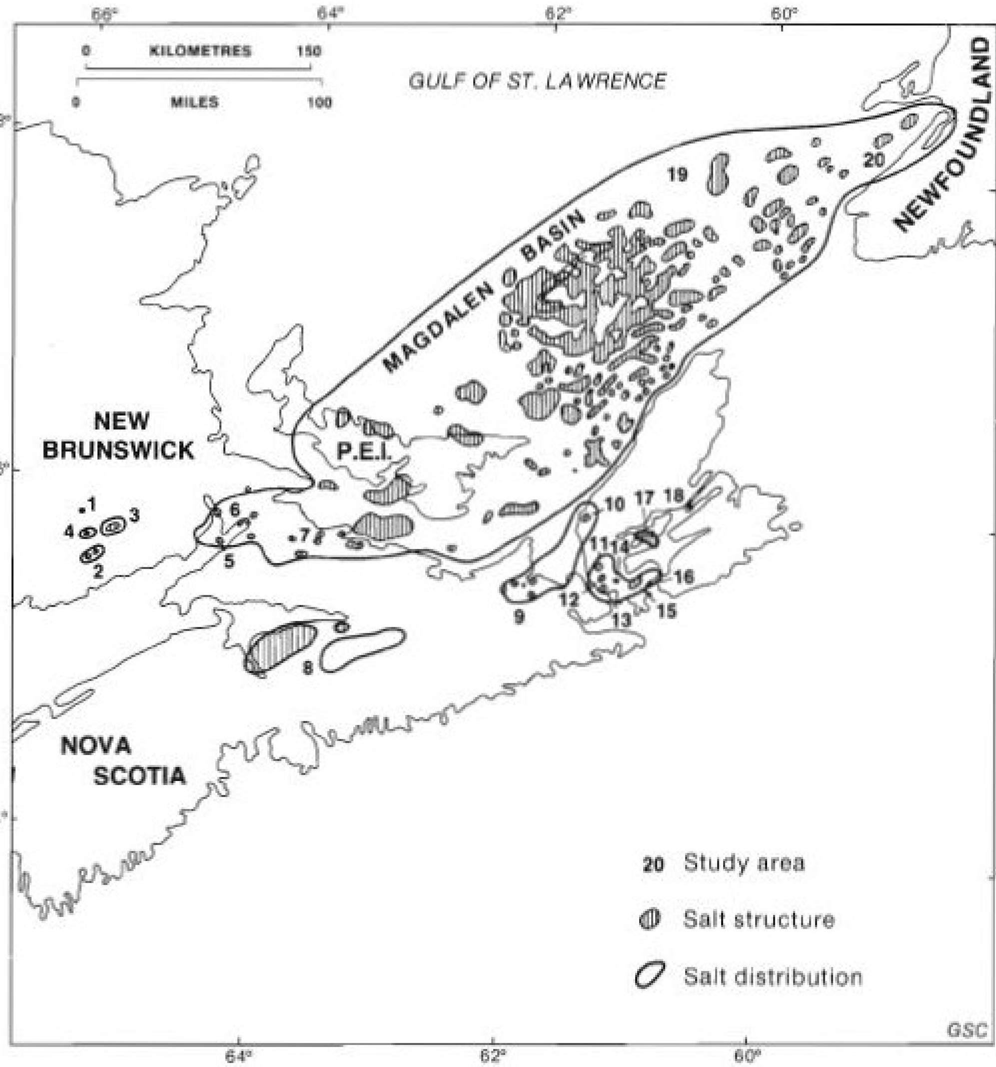

Figure 18 Distribution of the Windsor Group salt in Atlantic Canada (Image from Howie 1988)

Table 5 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

Label	Area	Approximate Depth (m)	Approximate Thickness (m)	Comments
				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.

Data from Howie (1988) and Webb (2009).

5.2 Renewable Energy Potential

5.2.1 Wind Energy Potential Data

The wind energy potential map was obtained from the Canadian Wind Energy Atlas which is hosted by Environment and Climate Change Canada (http://www.windatlas.ca/index-en.php). The Wind Energy Atlas has a geospatial database containing characteristics and statistics about the wind profile across Canada. The present study used the average annual mean wind energy at 80 m height, given in W/m^2 of blade swept area, as a representation of the potential wind power generation sites. The granularity of the wind energy map is fine enough to capture wind variations at the local regional scale (10 km) and is, therefore, more than sufficient for a first-order study investigating province-wide variations.

The Pacific and Atlantic coast lines of Canada have the most exceptional wind energy resources available in Canada. This is not surprising because strong and consistent winds are characteristic of most coastlines. Ontario's great lakes coast lines are also well endowed with wind energy. This is important because southern Ontario would otherwise have quite poor wind resources. The Prairie Provinces have 'spotty' wind energy which is typically poor to moderate except around Lake Winnipeg, foothills of the Rocky Mountains in the southern part of Alberta, and areas south of Calgary which are exceptionally strong. Select areas in southern Alberta and some locations in the mountain ranges of British Columbia and the Yukon have some of the greatest average wind energy in Canada, coastal areas included.

5.2.2 Solar Energy Potential Data

The solar potential map (global insolation map) was obtained from Natural Resources Canada (http://geoappext.nrcan.gc.ca/arcgis/rest/services/Energy/clean_energy_solar_radiation_insolation/MapServer). Interested readers can also obtain photovoltaic potential and insolation datasets from Canadian municipalities across Canada (http://www.nrcan.gc.ca/18366). This study used the mean daily global insolation, given in MJ/m^2 of panel area, as a representation of the potential photovoltaic power generation sites. The granularity for the insolation map is lower than that of the wind energy map; however, the insolation values do not vary dramatically as wind energy does. Notwithstanding the coarser nature of the insolation map, it is sufficiently precise for a first-order nation-wide CAES siting study. In spite of locating the original study which produced the insolation maps for Canada (Pelland et al., 2006), the author was unable to locate the completed GIS maps and attribute tables. The maps downloaded from Natural Resources Canada's website were not accompanied by attribute tables and thus could not be used for GIS mapping. To continue with the study, the solar insolation map with panel tilt equal to latitude was drawn by hand to reproduce the contours in a functional GIS file, which was used in the analysis. The extra step of redrawing this map by hand assumes that the area between contours has a constant insolation value. It is recommended that Natural Resources Canada make the full set of insolation maps produced available for download, with clear labelling, and accompanied by attribute tables and data for easy use within the GIS environment.

The solar potential across Canada is almost the opposite of the wind energy potential. The ocean coastlines receive relatively little solar energy due to cloud cover, and the prairies have good to excellent solar potential. The highest solar potential is in the south of Alberta, Saskatchewan, and Manitoba. In general, the farther south the location is within a province, the better the solar energy potential of the location is. However, despite Southern Ontario being the farthest south part of Canada, it only receives moderate amounts of solar energy, likely due to the surrounding Great Lakes.

5.3 Existing Infrastructure

Conventional CAES is both a form of energy storage and an extension of natural gas turbine technology. As a result, conventional CAES needs access to the electric transmission network and a steady supply of natural gas. However, when siting an adiabatic CAES facility, which does not use natural gas, the proximity to natural gas criterion can be neglected and the weightage of the remaining criteria can be proportionally adjusted to maintain the same ratios and achieve a total weighting of one.

5.3.1 Existing Electric Transmission Lines

The electrical lines in each province in Canada are operated and maintained by provincially owned entities, and as a result, there is a lack of coordinated information available on Canada's electricity infrastructure. The Canadian Electricity Association hosted a map from S&P Platts which showed the electricity transmission infrastructure for all of Canada. This map was recreated in GIS software by tracing over image files to produce maps of the transmission lines which are greater than or equal to 115kV for the relevant areas. However, at the time of releasing this document, the map was no longer available. A transmission line with 115 kV of capacity was assumed to be the minimum voltage line required to support a 100 MW energy storage facility. The proximity score was calculated using the nearest transmission line, and no preference was given to larger lines. It is recommended that future studies introduce a scoring preference for transmission lines of larger capacity; this may require breaking the evaluation into multiple criteria. Including transmission line capacity into the MCA would require a more in-depth study of the relationships between transmission line capacity and connecting the facility to the grid.

Areas of interest across Canada are, generally speaking, well covered by the existing transmission line network, and this criterion is not expected to be a limiting factor in the analysis. However, it should be reiterated that the issue of electric grid connection is far more complicated than it is represented in this analysis. The inclusion of more realistic constraints on electrical connections, such as substation locations, should be considered for more detailed studies.

5.3.2 Existing Natural Gas Transmission Lines

Only a limited amount of information on existing natural gas pipe network sizes and distributions is available in Canada. The lack of available information was expected because these pipe networks are proprietary assets and can be a contentious subject for residents near them. A map of pipelines was obtained from the Canadian Energy Pipeline Association's online map for western Canada (http://aboutpipelinesmap.com) and from Union Gas' website for Ontario (https://www.uniongas.com/storage-and-transportation/resources/maps). The GIS data associated with these maps was unavailable, so the author traced the location of the pipelines to create the maps in GIS. Owing to the lack of information available on pipe size and available capacity, any pipeline that was shown on these maps was assumed to be large enough to support a CAES facility.

Natural gas pipeline coverage of Alberta and southern Saskatchewan was comprehensive, which is partially a reflection of the superior data source. The connection of CAES to the natural gas network in the Prairie Provinces is not anticipated to be an issue, but more detailed investigations considering available capacity on pipelines of interest are necessary. Ontario's pipeline network is not as well documented, and only Union Gas pipelines were included. Pipeline coverage is in general good across southern Ontario as well, but network coverage reduces farther north of the Sarnia-Toronto-Montreal corridor. Southern Ontario also has a higher population density than many parts of western Canada, so available capacity on these lines may be a more prominent issue which also requires further study.

5.4 Energy Demand

Energy use data were obtained online from the National Energy Board. The average energy use per person was calculated for each province by adding the total energy consumption from residential, commercial, and industrial sectors and then by dividing by the population of the province. This information is summarised in Table 6. To obtain a map of the geospatial distribution of energy demand, the population of each federal electoral district was multiplied by the per person energy demand for its respective province. As described in Section 3.2.1, the criterion evaluates the total energy demand within a radius of the site in question.

Table 6 Population and energy consumption for provinces of interest

Province	Population (millions)	Total Energy Consumption (PJ/yr)	Energy per Capita (MWh/person·yr)
Alberta	4.12	3978	268.1
Saskatchewan	1.13	664	163.8
Ontario	13.7	3045	61.8
Nova Scotia	0.94	200	59.0
New Brunswick	0.75	239	88.1

Alberta and Ontario especially have high annual energy consumption, making them ideal for large-scale energy deployment. Alberta's and, to a lesser degree, Saskatchewan's and New Brunswick's energy demands are dominated by the industrial sector so the location of the energy demand in these provinces may deviate from the population centres more than those for other provinces. Industrial energy demand is typically larger than either residential or commercial energy demand and is typically highly fossil fuel reliant. The success of decarbonising Canada's energy supply will rely heavily on the progress of the industrial sector. Electrification and the use of waste heat are likely to be two prominent approaches to reducing the carbon footprint of industry.

6.0 CAES Siting Results

The results of the multi-criteria analysis are presented and discussed in this section. The results are separated into three different areas defined by the geologic basins. Each of these areas were analysed using the four different weighting scenarios: initial weighting estimate, informal survey weighting, adiabatic CAES, and geology neutral CAES. All 12 of the resulting maps can be found in Appendix C.

The first-order nature of this study means that the results presented herein are estimations of the suitability of a location for CAES development. The siting criteria focus on the technical suitability of a CAES facility; economic, environmental, and social considerations are considered at a provincial level as well as implicitly as part of the established criteria. The results demonstrate the hot-spots for CAES within each region. The relative scores between hot-spots across Canada provide a rudimentary comparison of feasibility and allow for some contrasts to be drawn.

6.1 Ontario

The results of the MCA for CAES potential in Ontario are shown in Figure 19. This figure contrasts the results of the estimated weighting set against the survey weighting set. There is very little difference between the results, which is not surprising because the two different weighting sets are similar. This comparison demonstrates that the MCA results are not highly sensitive to the weighting used and therefore subsequent results sections will only show the survey weighting results. Although the complete map for southern Ontario extends farther East than is shown in Figure 19, these images capture the full extent of the salt formations.

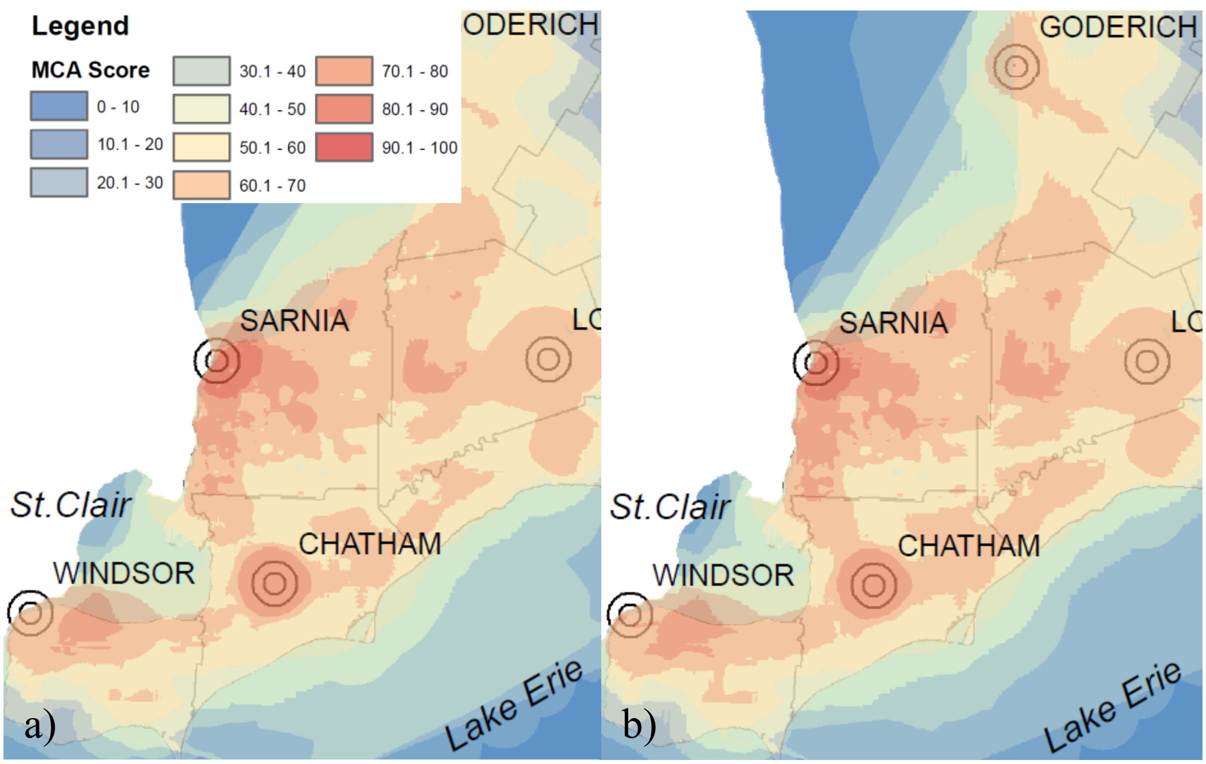

Figure 19 Multi-criteria analysis results for CAES potential in southwestern Ontario using a) initial weighting estimate and b) survey weighting

Salt units B and A2 both score high in the depth criterion, but unit B is preferable because of its relatively greater thickness. In the Goderich region, for example, Unit B is approximately 70 m thick and 390 m deep, Unit A2 is only 25 m thick and 510 m deep. Unit B is generally preferred across Ontario because of the relatively high score in the thickness criterion.

Given the larger weighting of the geologic criteria, the strongest potential for CAES in Ontario was found to be in the Sarnia area. Localised variations in the salt thickness create small pockets of better or worse potential in the area, and one of these unusually thick areas would make an excellent site for a CAES facility. In addition to the geology, the Sarnia region also has excellent access to natural gas and electric transmission lines and has a moderately high energy demand. As a result, Sarnia is considered the prime candidate for CAES in Ontario. Outside of Sarnia, there are three surrounding locations which represent a good opportunity for CAES siting: Windsor, Chatham-Kent, and Goderich. Chatham-Kent compares well to Sarnia, but its geologic conditions and energy demand are not as ideal as Sarnia. Windsor has the highest energy demand amongst the highlighted sites and has good access to renewable energy. Goderich has the best access to renewable energy but scores worse in all other categories compared to Sarnia.

Ontario was also evaluated for two alternative scenarios: adiabatic CAES and geology neutral CAES. The MCA results for adiabatic CAES (available in Appendix C) are similar to the base case results because southwestern Ontario has excellent natural gas infrastructure coverage. However, the similar results may be because of weaknesses in criteria selection; a more detailed study of the available capacity of natural gas pipes may reveal additional limitations to conventional fuel-fired CAES siting. The geology neutral weighting set has a much more significant impact on the MCA results, as seen in Figure 20. The reduction of the analysis to only three criteria, electric connection, electricity demand, and renewable energy potential, means that all of these criteria are highly influential on the results. While western areas such as Sarnia and Windsor still represent areas of good potential for CAES, the highly developed shoreline of Lake Ontario would be an exceptional location for energy storage. Shoreline areas have potential to be developed using underwater CAES, such as the system designed by Toronto based Hydrostor (https://hydrostor.ca/). These major urban centres, including inland cities such as London, should be investigated for favourable non-salt storage geology such as porous aquifers.

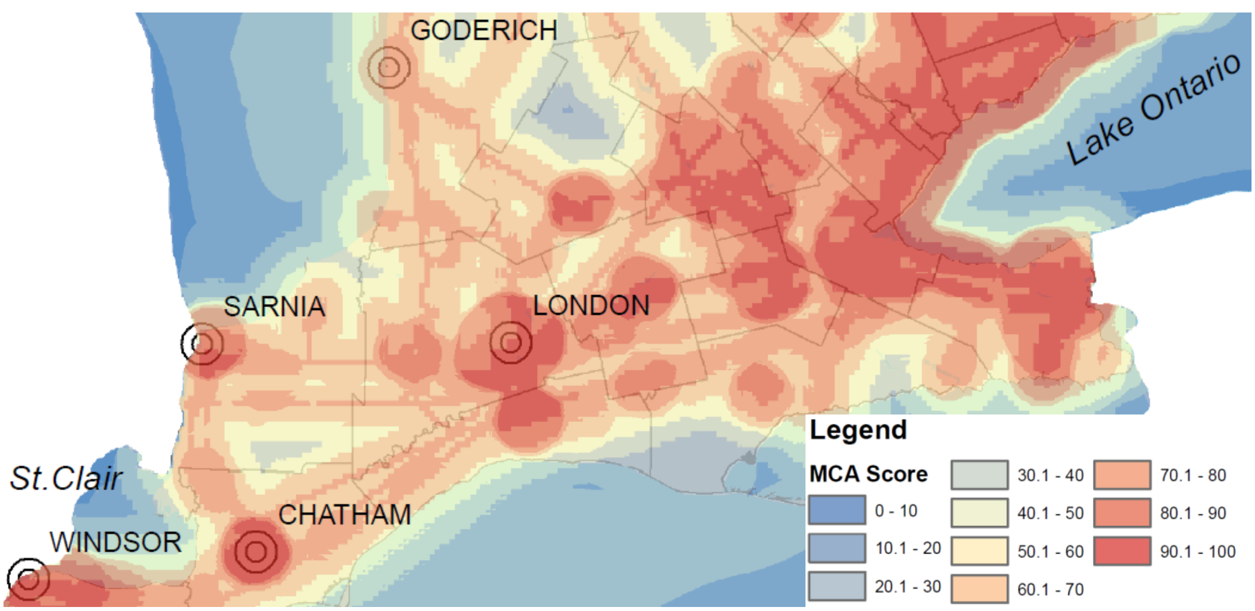

Figure 20 Geology neutral weighting scenario multi-criteria analysis results for CAES potential in Ontario

6.2 Western Canada

The results of the MCA for CAES potential in western Canada are shown in Figure 21, the complete map for western Canada can be found in Appendix C. The complete map for western Canada shows the potential of CAES across all of Alberta and Saskatchewan. Figure 21 captures the most promising areas for CAES; however, the band of strong CAES potential continues north out of the image towards the Fort McMurray area. The band of strong potential seen in this figure corresponds to the areas with suitable salt formations.

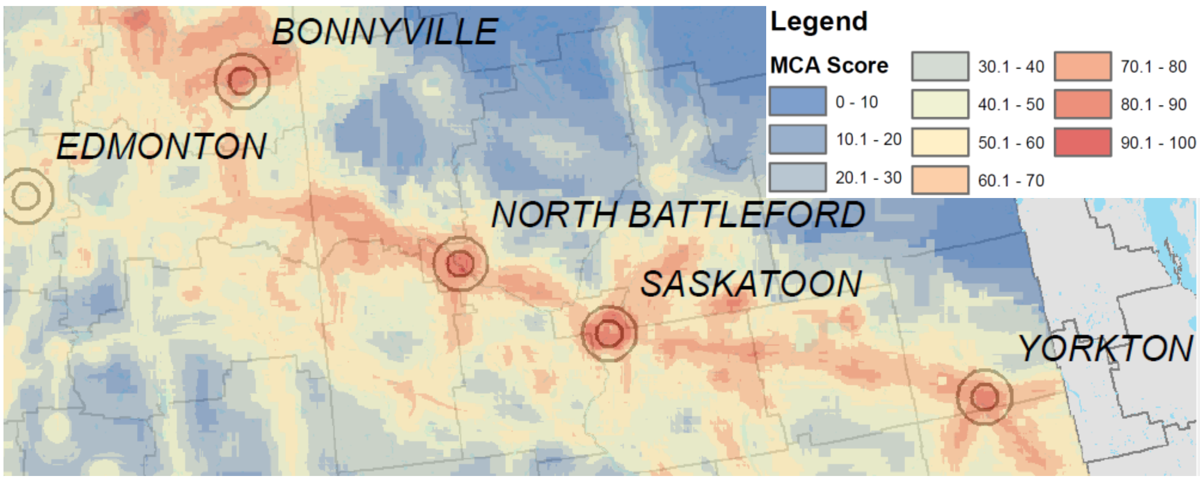

Figure 21 Multi-criteria analysis results for CAES potential in western Canada

The strongest potential for CAES in western Canada runs along a band overlying the salt formations where there is also a number of population centres running along Highway 16. This band runs through the middle of Saskatchewan including Yorkton, Saskatoon, North Battleford, and Lloydminster. Among these towns and cities, Yorkton, Saskatoon, and North Battleford have exceptional potential for CAES because of their high scores in every criterion. These CAES hot spots along with the great solar energy potential in southern Saskatchewan indicate that the province is well equipped to increase renewable energy penetration on their grid and decrease their reliance on coal power.

It is worth mentioning that the Prairie evaporates salt formation generally scores well on the thickness and depth criteria; however, this formation contains significantly more impurities in the salt. The inclusion of more geologic parameters, such as salt purity, is likely to make the other salt formation look relatively more favourable. Unfortunately, the other salt formations are not as extensive so more geologic criteria may result in a reduction of the higher scores across Saskatchewan and parts of Alberta.

The maximum potential for CAES in Alberta is concentrated near its eastern border and mostly in mid to northern areas. The highest potential areas include Cold Lake, Bonnyville, and Lac la Biche. Areas of interest with noteworthy potential include Edmonton and Fort McMurray, but these areas do not have ideal geologic conditions and have only moderate to poor renewable energy potentials. These areas are noted because they are known to have large industrial electricity and heat demands, which present possible synergies with CAES.

The adiabatic scenario MCA results do not reveal any significant potential differences between adiabatic and conventional CAES for western Canada. This similarity is because the natural gas pipe networks in Alberta and Saskatchewan are quite comprehensive across the well-populated areas. The geology neutral scenario changes the results dramatically; instead of the CAES potential being focussed along the northwest-southeast oriented strip of salt, CAES potential is concentrated around urban centres. Given the high solar energy potential in the south, the results suggest that CAES could be developed anywhere along a transmission corridor in the lower third of Alberta or Saskatchewan. There is also a notable band of strong CAES potential west and south of Calgary where the wind energy potential in the foothills is exceptionally strong. Figure 22 captures the highlights of the geology neutral weighting scenario MCA results for western Canada. Concentrated red areas in Figure 22 represent population centres and the network of lines crossing Alberta and Saskatchewan represent the electric transmission lines.

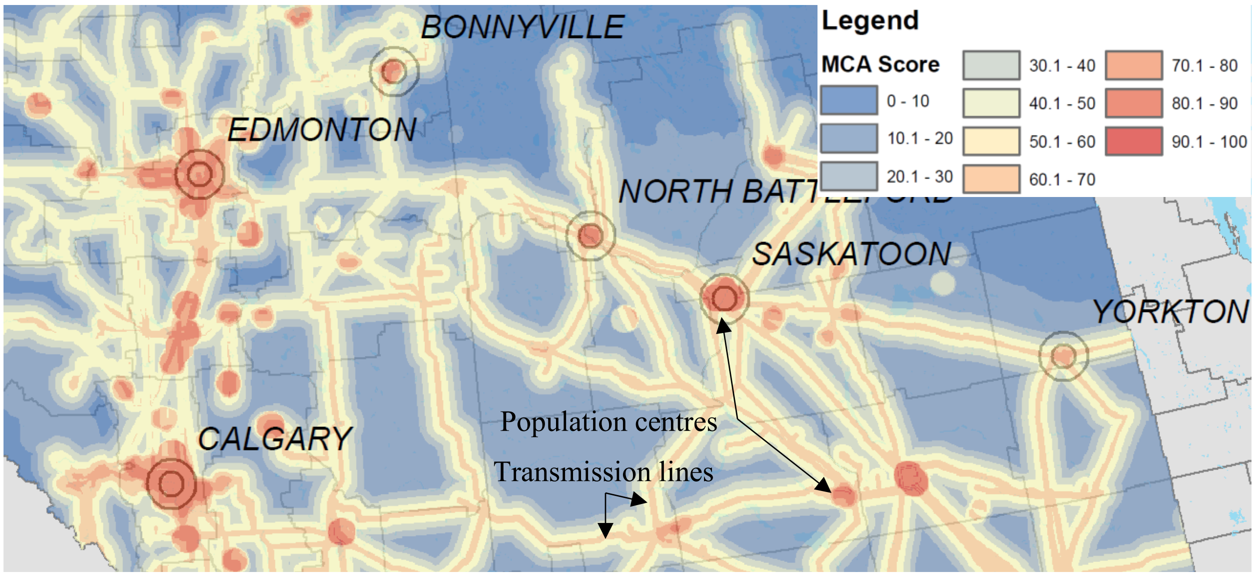

Figure 22 Geology neutral weighting scenario multi-criteria analysis results for CAES potential in western Canada

6.3 Maritime Provinces

The salt formation geology in the Maritimes Basin is significantly more complicated, and less information is available then compared with the other salt bearing basins. As a result of the limited information available, the MCA was constrained to a rectangular area surrounding the known salt deposits in Nova Scotia and New Brunswick. All of the MCA results for the Maritimes can be found in Appendix C. Figure 23 shows the highlights of the MCA results for the east coast of Canada. Concentrated red areas in Figure 23 generally represent areas underlain by salt and the infrastructure

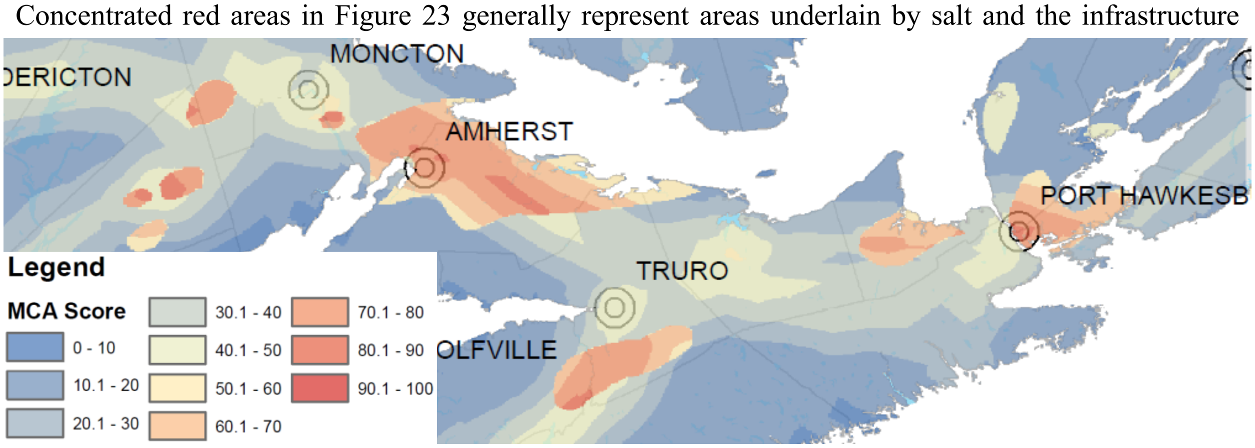

Figure 23 Multi-criteria analysis results for CAES potential in the Canadian Maritimes

corridors are roughly silhouetted by the bands of yellowish green.

New Brunswick has good CAES potential southeast, southwest, and west of Moncton. Although the high scoring areas are small, they are located near major urban centres and infrastructure. The renewable energy potential across the study area is as also quite strong, primarily because of strong and consistent winds. The high potential sites in NS are not as easily associated with cities, but areas of strong potential include the Amherst area, an area along highway 102 between Dartmouth and Truro, Antigonish, and Port Hawkesbury. Coal power generation is still the most prominent source of energy in Nova Scotia. However, with the thick salt domes present, and the strong coastal winds, Nova Scotia is well positioned to replace much of its fossil fuel power generation with wind energy supported by CAES.

As was the case for Ontario and Western Canada, the MCA results for adiabatic CAES potential in NS and NB were similar to the base case results. This is true despite NS and NB having a much smaller pipe network than other provinces in this study. Therefore, it can be concluded that Canada has reasonably comprehensive natural gas infrastructure coverage and that fuel-fired and adiabatic CAES have equal siting opportunities across Canada. Developers looking at potential fuel-fired CAES projects should consult with the relevant utility company to ensure that there is sufficient pipe capacity through the network to support the facility's operation.

Figure 24 illustrates the geology neutral CAES potential for the Maritimes provinces. The geology neutral scenario favours any location along the electricity transmission corridors in NS or NB. Given the relatively small area covered by the MCA in the Maritimes, much of the study area is quite close to feasible salt formation storage geology. However, Saint John does not have access to salt and would be an excellent location for CAES. Interested parties should look for other suitable storage geology in the vicinity of Saint John or consider underwater CAES storage. In Nova Scotia, interested parties should look for alternative compressed air storage mediums in Truro and Dartmouth. Although tidal energy was not included in this study, the Bay of Fundy represents a huge opportunity for clean, renewable energy. To support the development of tidal energy, further studies should investigate the shore lines of the Bay of Fundy for potentially suitable storage mediums which can be used for CAES development.

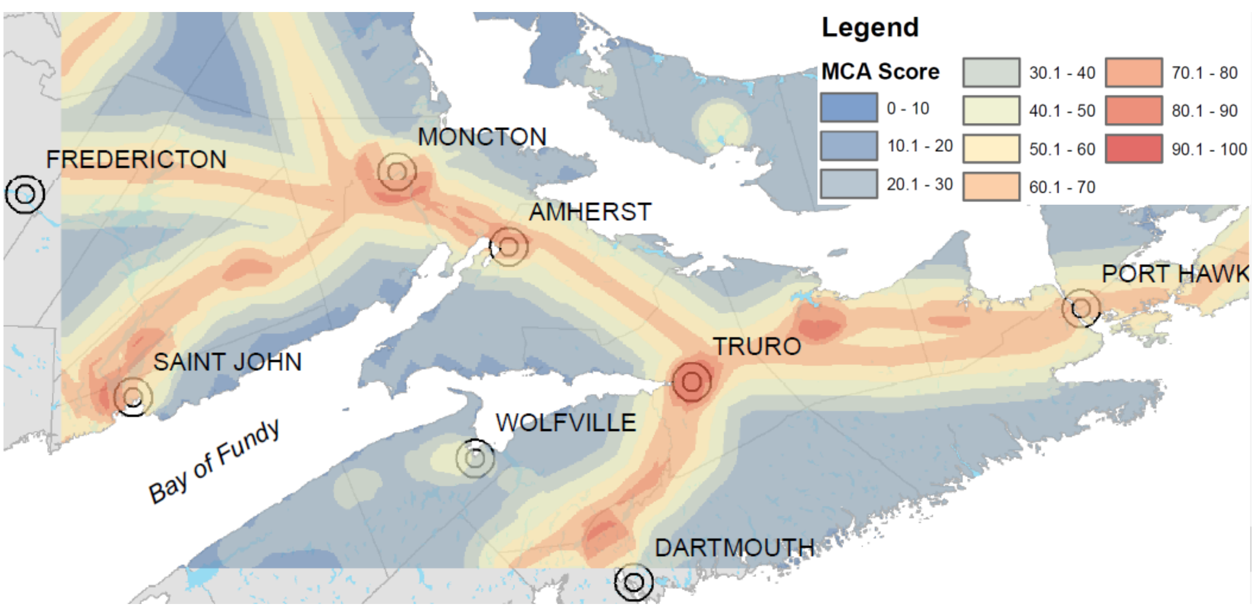

Figure 24 Geology neutral weighting scenario multi-criteria analysis results for CAES potential in the Canadian Maritimes

7.0 CAES Siting Conclusions

Spatially distributed multi-criteria analysis is a viable but data intensive methodology. A discrete analysis which selects and compares only a few key alternatives is likely to be a simpler and less resource intensive investigation for most cases. This can be particularly true at different scales where a higher quality of data is needed to produce reliable results. Fortunately, the MCA results determined in this study illustrate the key areas that should be considered for a more in-depth discrete analysis. Such a study could focus on including a more comprehensive list of criteria and their scoring systems.

There is, with regards to technical feasibility, equally strong potential for CAES in Ontario, Saskatchewan, Alberta, Nova Scotia, and New Brunswick. Given the heavy weighting for geologic criteria, it is not surprising that location score is highly dependent on the depth and thickness of available salt formations. However, this emphasises the need for high-quality geologic data, a more comprehensive list of geologic criteria, and the need for further studies into alternative storage mediums such as porous aquifers. The geology neutral MCA scenario suggests that investigations into alternative storage mediums should prioritise urban centres and then areas of high renewable energy potential near electric transmission corridors for investigation.

According to survey respondents, the proximity of a site to existing electrical transmission infrastructure is also an important consideration. This accentuates the need to address the assumptions made in the evaluation of this criterion, namely that a CAES facility could connect to the electric grid at any point and that transmission congestion is not an issue.

Areas such as Sarnia and Windsor in southwestern Ontario are ideal for their salt presence, nearby wind and solar energy potential, available infrastructure, and high energy demand stemming from a large industrial sector. Saskatchewan and Alberta rely on coal and fossil fuels for a significant portion of their energy demand, but they both have access to large salt formations and strong solar energy potential. The salt formations in western Canada also happen to underlie several areas of heavy industry which use huge amounts of energy. CAES is uniquely capable of synergizing with industrial heat demands while also being able to increase clean, renewable energy penetration.

Despite having a complex geologic setting, the Maritimes provinces have a number of confirmed salt formations which are ideal for salt cavern storage. While the salt domes present in Nova Scotia and New Brunswick limit the number of locations CAES can be developed, their exceptional thickness makes them well suited to support cavern development. Nova Scotia is well positioned to make use of CAES to support its strong coastal winds and reduce its dependence on coal power.

Although there are elements of uncertainty in the MCA conducted in this study, the methodology established was proven to be robust and detailed enough to indicate, at a first-order level, the areas that are promising for CAES development. Unfortunately, the methodology is data intensive, and the availability of data on public natural and technological assets needs to be improved to make its use more viable for most Canadian businesses.

8.0 Introduction to the Global Warming Impacts of Balancing Renewables

Part 2 of this document looks at the GWP impacts associated with flexible power generation needed to balance intermittent renewable energy. As discussed previously, the role of balancing is presently primarily achieved with gas turbines in Canada. This component of the research will assess what, if any, GHG emission reductions could be achieved by using CAES instead of SCGT for this balancing role.

Out of the potential sites identified for CAES in Canada, the LCA will focus on Ontario as a case study. Ontario was chosen for detailed analysis because it has the most pressing need for energy storage: it is the largest electricity market in Canada, has a significant portion of inflexible nuclear and hydro power generation (see Figure 25), has relatively high renewable energy penetration, and the electricity prices are already being impacted by renewable energy curtailment (Adams & Luft, 2016). Furthermore, natural gas power accounts for most of the GWP impact associated with electricity production in Ontario. This is especially interesting given that natural gas plants produced 9% of the energy in 2016, but accounted for 28% (9943 MW) of the installed generating capacity at the time (Independent Electricity System Operator, 2016). The need for energy storage in Ontario will be further accentuated if Ontario's long-term energy plan is carried out. The energy plan calls for an increase in installed wind and solar power capacity from 13% of Ontario's total generating capacity at the beginning of 2017 to 23% in 2025 (Ministry of Energy, 2013).

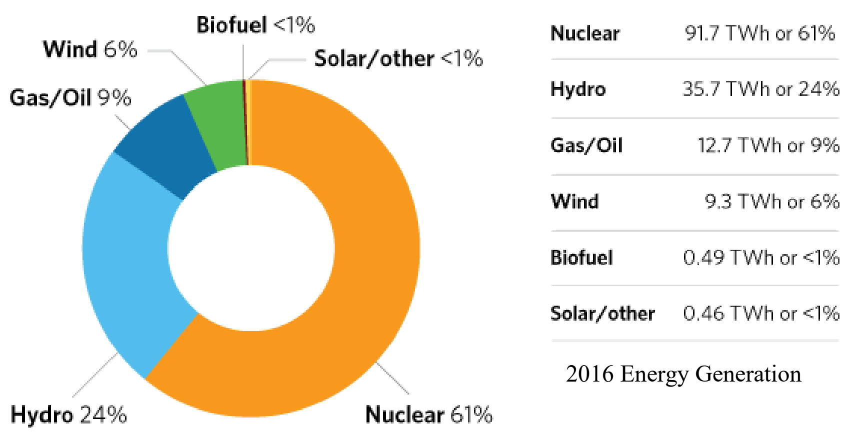

Figure 25. Ontario's energy generation by fuel type in 2016 (Image from Independent Electricity System Operator, 2016).

8.1 Review of CAES LCA Literature

Beyond the technical, social, and economic requirements of energy storage, technologies viable for wind power balancing must be assessed and compared to determine the environmental benefits and drawbacks. The inclusion of environmental considerations creates a well-rounded comparison and informs designers and policy makers so that new electrical assets and systems can be more sustainable.

Denholm & Kulcinski (2004) and Pembina Institute (2017) established that the environmental performance of energy storage systems is highly dependent on the source of energy used for charging. In an electric system with plenty of low-carbon energy, such as Ontario, energy storage is ideal for reducing greenhouse gas emissions. In provinces such as Alberta which are dependent on coal power, energy storage may not be a low-carbon solution until cleaner energy sources are installed to charge the storage. Bouman, Øberg, & Hertwich (2013) and Bouman et al. (2016) looked specifically at CAES, adiabatic CAES, and CCGT with carbon capture and storage (CCS) for balancing wind power and found that wind+CAES energy outperformed or was similar to CCGT+CCS in every impact category except mineral resource depletion (largely from the wind power generation). These studies also indicate that natural gas supply and combustion accounts for the majority of impacts in most categories and ~98% of the GWP impact. Bouman et al. (2016) also investigate the impacts of various storage sizes on the system capacity factor, which is important in determining the capital equipment impacts on a per-kWh basis. However, the system capacity factor has no impact on the natural gas consumption, which accounts for the majority of a CAES system's impacts. Furthermore, these studies assume that all these systems are operating at their design power output, or design load, all of the time. This assumption has an important impact on the amount of natural gas combusted and thus the system impacts. A facility intended to balance the wind power will need to fluctuate rapidly and frequently, making maintaining a design point impossible. This dynamic aspect of turbine operation has not been captured in LCAs which have investigated CAES. Although studies which capture comprehensive gas turbine inputs data over an extended period would capture this dynamic aspect, the data collection appears not to exist for a gas turbine operating specifically for intermittent power balancing. Differing operating settings and purposes will influence the impacts of a facility.

8.2 Operating Characteristics of CAES and Gas Turbines

To include dynamic aspects of turbine operation into the LCA, a closer look at how both technologies function is necessary. CAES is a mechanical form of energy storage which operates similarly to combustion turbines but with the ability to store air between the compression and expansion stages. Another key difference is that the compressor and expander trains are physically separated in CAES, allowing for independent operation of the turbo-machinery and better control of air flow. The separation of stages and the ability to store air in CAES offers several definitive operating advantages over gas turbines. Perhaps, the most important advantage of CAES is that it has excellent partial load efficiency, low minimum operating loads, rapid ramp rates, and a faster start-up time.

CAES and SCGT both operate on the same basic principles of energy extraction, the same principles that aeroplane engines use. Figure 26 illustrates the three basic steps of these systems: compression of the intake air, combustion of the fuel to generate heat and increase pressure, and expansion of the hot pressurised air to produce work (labelled as "turbine" in Figure 26). The work generated by this process

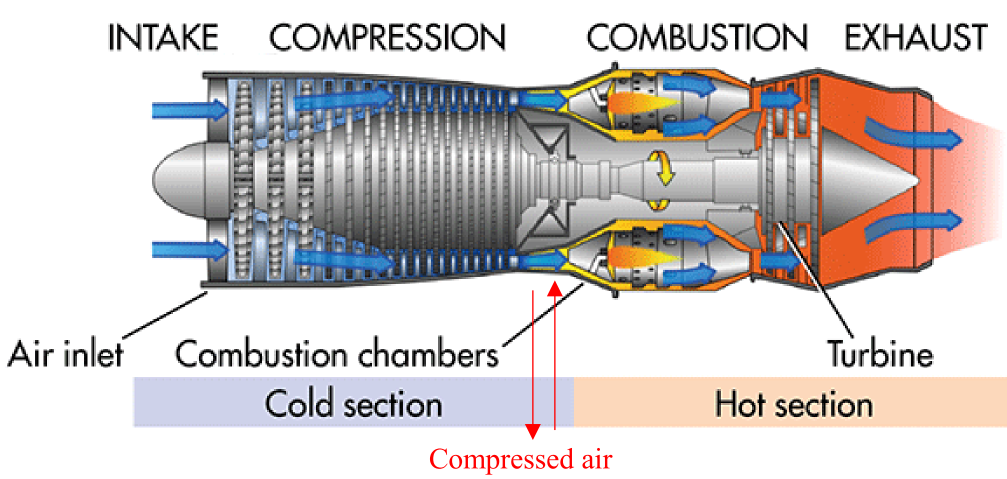

Figure 26. Typical layout of a gas turbine (After http://www.machinedesign.com/motorsdrives/what-s-difference-between-turbine-engines accessed 10/05/17)

creates torque which turns a generator to produce electricity in CAES and gas turbines. Note that CAES has an extra step which allows it to store energy by storing the air in its compressed state. This air can be stored in a vessel or underground cavity in a high-pressure state which can later be reheated and used for expansion. This additional step means that the compression and expansion stages of the process must be physically separated so that the compressors and expanders are independent pieces of machinery. This creates additional capital cost but much more favourable operating characteristics.

The differences in CAES and SCGT operating characteristics stem primarily from the fact that the compressor and expander trains are separate pieces of machinery which can operate independently. This is important because at lower power outputs the expansion train on a gas turbine must continue to dedicate energy to spinning the compressor to maintain stable air flow patterns. At the design point of an SCGT, approximately one-third of the energy generated is used to drive the compression train; below the design point, this fraction of compressor dedicated energy grows. What this means for SCGT operation is that gas turbines lose efficiency rapidly when operating below rated power output when compared to CAES. Furthermore, gas turbines must usually operate at 40-50% capacity as a minimum, making it much less flexible to balance power output when compared to CAES, which can operate at virtually any capacity. This has important implications for intermittent power balancing because for gas turbines to make the rapid adjustments necessary to counter fluctuations in the wind, it must have at least half of its generating capacity online. This operating characteristic makes it difficult to replace fossil fuel power with renewable power without wasting the excess energy from one source or the other. CAES' minimum load of 10% allows for greater use of renewables without the need for large quantities of fuel-fired power online. Note that turbines must maintain minimum speeds of rotation so that they remain synchronous with the electric grid and can then make rapid adjustments to respond quickly to changes. CAES gains an additional advantage in flexibility when the compressor train is also utilised for power regulation. This is known as 'down-regulation' when you have a rapid response energy sink in place which can absorb excess energy. This allows CAES to use excess clean energy produced to help meet demand at a later time, effectively lowering the installed capacity necessary for CAES to balance power output as effectively as a gas turbine. Detailed discussions of CAES systems can be found in a large selection of existing literature (Budt et al., 2016; McGrail et al., 2013; Succar & Williams, 2008).

9.0 Life Cycle Assessment Methodology

Power generation facilities can serve a variety of roles on the electric grid; even a single facility can provide several ancillary services, often simultaneously, making it difficult to compare different technologies. However, CAES and SCGT power plants offer similar functionality which allows for a balanced comparison. To avoid complicated system modelling without neglecting the context, a simplified operation scenario will be analysed for this study. The facility in question will provide electrical energy on demand to the grid for the purpose of balancing intermittent renewable power output. As with similar energy LCA studies, one kWh produced at the facility will be used as the functional unit.

This study will consider a gate-to-gate LCA approach which neglects the impacts of capital equipment, construction, maintenance, and facility end-of-life treatment. Bouman et al. (2016) found that these aspects of the LCA of CAES accounted for ~1-2% of the total climate change impacts over the lifetime of the facility and similar results are expected for an SCGT. Materials and energy used in the operation phase will be accounted for back to the point of entry into the technosphere.

9.1 LCA Models and Inputs

The LCA was conducted in the software GaBi by Thinkstep™. GaBi process diagrams represent the mass and energetic steps and inputs which go into producing electricity from SCGTs or CAES. Figure 27 illustrates the process to create 1 kWh of electricity from an SCGT; percent values shown on each process indicate the relative contribution of each process to the total GWP impacts. This analysis utilises a built-in GaBi process for the production, processing, and delivery of natural gas to the user. The US process is used because 75% of Ontario's natural gas comes from the US ((S&T)2 Consultants Inc., 2013). Natural gas undergoes complete combustion, and the resulting thermal energy heats the compressed air which is used to generate electricity. The compression of the air is a "dummy" or proxy process for visualisation because the energy needed to compress the air is accounted for in the energy output of the expansion process. Similarly, Figure 28 illustrates the process to create 1 kWh of electricity from fuel-fired CAES. In CAES the air is compressed by a separate compressor train which is driven by electricity from the grid instead of the expander train. This electricity is assumed to come entirely from excess wind power and is subject to an Ontario average transmission loss of 2.5% before being used at the CAES plant (Independent Electricity System Operator, 2017). The compressed air is then stored underground, typically in highly impermeable salt caverns, and a conservative 1% loss from storage is assumed. This air is then heated and fed into the expansion process like in an SCGT.

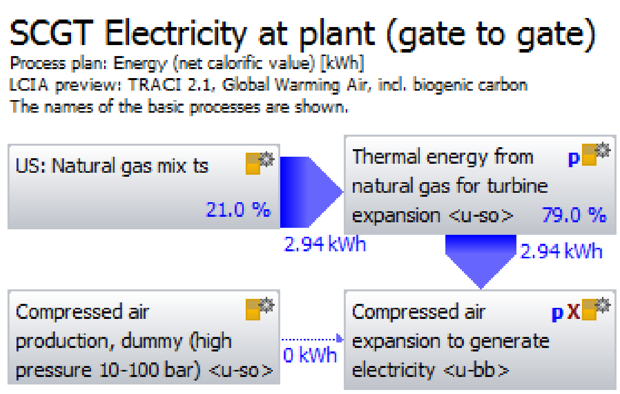

Figure 27. SCGT process diagram as represented in the GaBi model. Dotted line flows are mass flows and the thicker lines are energy flows.

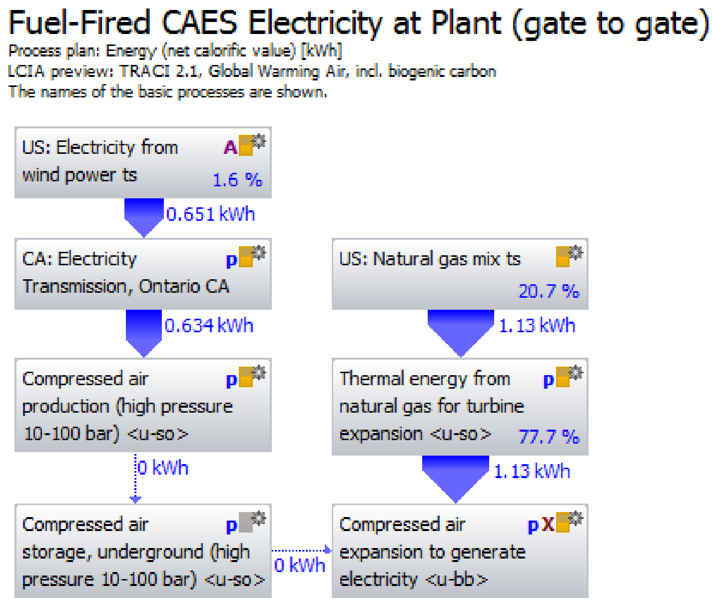

Figure 28. Fuel-fired CAES process diagram as represented in the GaBi model. Dotted line flows are mass flows and the thicker blue lines are energy flows.

In this study, the performance of the expander train is considered dynamic and varies with the load or power output of the facility; these performance curves are shown in Figure 29. CAES and typical SCGT performance curves were obtained from Dresser-Rand's SmartCAES system brochure and personal communication (March 10, 2017) with the company. The performance curve for a typical SCGT was normalised and applied to the design point heat rate for two different SCGTs, Siemen's SGT5-2000E (187 MW) and General Electric's ZF.05 (231 MW). For the purpose of operation modelling, both of these turbines were assumed to have the same capacity as the CAES system (160 MW). Key static parameters for both technologies are provided in Table 7.

Table 7 Key static LCA model parameter inputs

Parameter		Unit	Value
Natural gas lower heating value (net calorific value)[1]		MJ/kg	40.3
Emission factors for natural gas combustion[1]	CO_2	kg/MJ	5.87E-02
	CO	kg/MJ	3.70E-06
	SO_2	kg/MJ	1.73E-05
	NO_X	kg/MJ	3.35E-05
Combustion efficiency[1,2]		-	100%
Compressed air storage losses[3]		-	1.00%
Electricity transmission losses[4]		-	2.50%
CAES compressor specific air output[3]		$kg_{comp-air}$/ kWh_{used}	6.5

Sources:
[1] GaBi 'electricity from natural gas process.'
[2] Personal communication March 10, 2017
[3] Berest et al. 2001
[4] Independent Electricity System Operator 2017

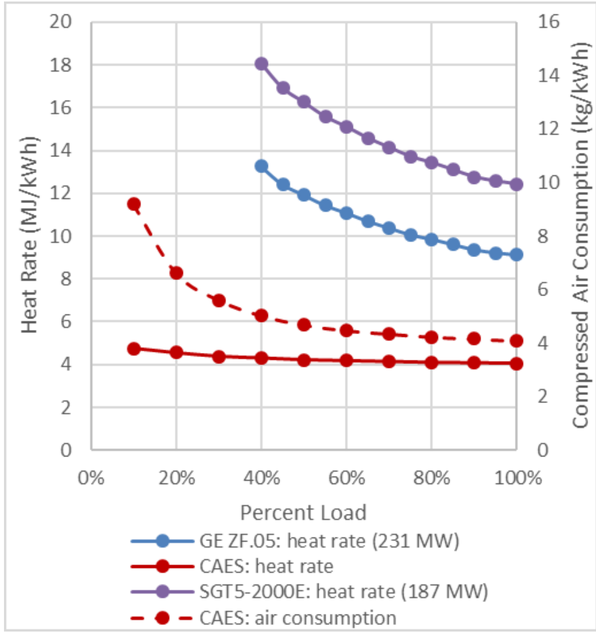

Figure 29. Dynamic performance of CAES and two commercially available SCGTs

9.2 Dynamic Technology Operation Model

To be able to address the question of partial loading inefficiencies it is important to be able to estimate how much power the facility will produce at different percent loads, relatively speaking. However, creating realistic but manageable operating scenarios can be quite challenging given the dynamic, variable, and competitive nature of Ontario's electricity market. This study will neglect most market aspects of the electric grid, including exports and imports, and assume that flexible electricity with which intermittent power sources can be balanced comes solely from one SCGT or CAES plant. Additionally, CAES is assumed not to be limited by storage capacity; this assumption is not impactful in this analysis because system capacity only influences the environmental impacts of capital equipment, and reliability is not being addressed in this study. Furthermore, CAES storage can be quite large because the incremental cost of adding more storage is usually low. As can be seen in Figure 30, the actual electricity supply is much more complicated. However, since hydropower is cheap and clean, it is fair to assume that it is already being utilised to its maximum potential in the obtained data. Note that the demand is lower than the total supply due to transmission losses, electricity exports, and other factors. Total non-hydro renewables include solar, wind, and biofuels energy production. Although biofuels are a controllable resource, their contribution is small and was therefore clumped in with the intermittent renewables for this illustration. In Figure 30, the individual energy types are stacked, but the calculated net energies and demand are not. Since nuclear and hydropower have limited dispatch ability, a net energy demand is calculated by subtracting these energy sources from the total demand (OSPE-PEO Energy Task Force, 2013). After these inflexible generators, the total intermittent renewable energy sources are subtracted; the resulting curve is referred to as the net flexible energy demand.

To create a realistic operating scenario for a single facility to balance wind power in isolation, the net flexible energy demand was scaled down so that 160 MW was sufficient capacity to meet the demand 85%, 90%, and 95% of the time. The 90% base case scaled scenario with SCGT and CAES operations

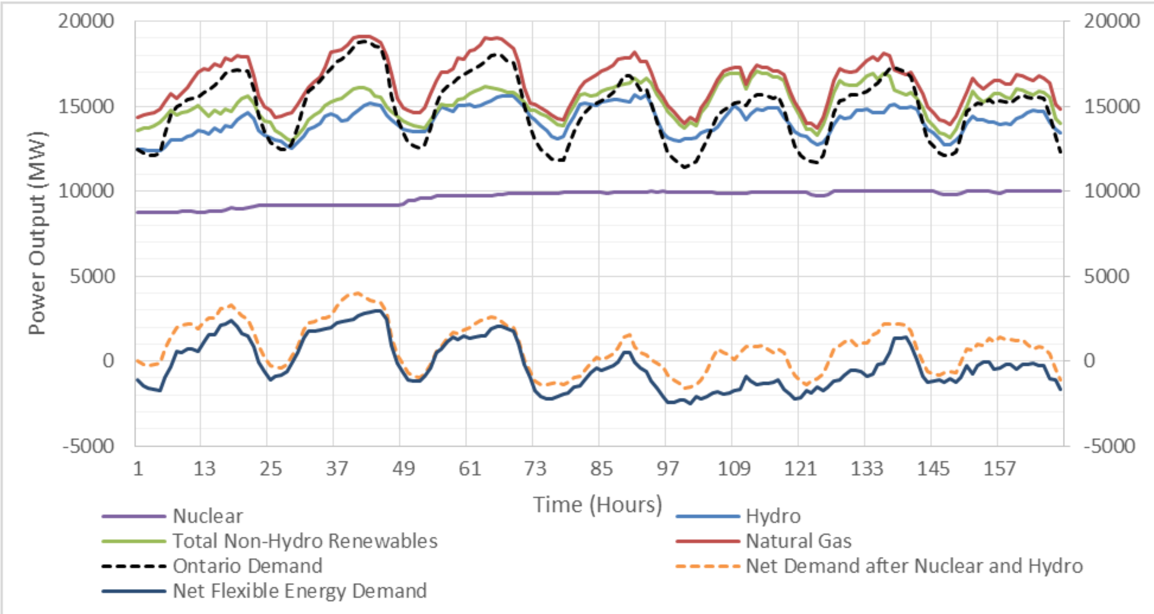

Figure 30. Power production and demand in Ontario for the first week of June 2016 (Independent Electricity System Operator, 2016). Output curves from different energy sources are stacked but demand curves are not.

is shown in Figure 31. Given this demand curve, an operating model was created for CAES and SCGTs. Whenever there is a net positive need for flexible energy, then the facilities turn on and ramp up as necessary. These operating models try to match the hourly demand precisely but are limited by their 160 MW capacity and minimum loads. If the demand is greater than zero but less than the minimum load, then the facilities operate at their minimum load and any excess energy produced is considered waste. This modelling was completed for all of 2016 and the fraction of energy generated over the year at different loads was used in the LCA model, along with the technology performance curves in Figure 29, to determine GWP. The fractions of energy produced at different loads for each of the three normalisation scenarios are shown in Figure 32. It is clear that, compared to CAES, an SCGT produces a larger portion of the power needed to meet the flexible energy demand at minimum load.

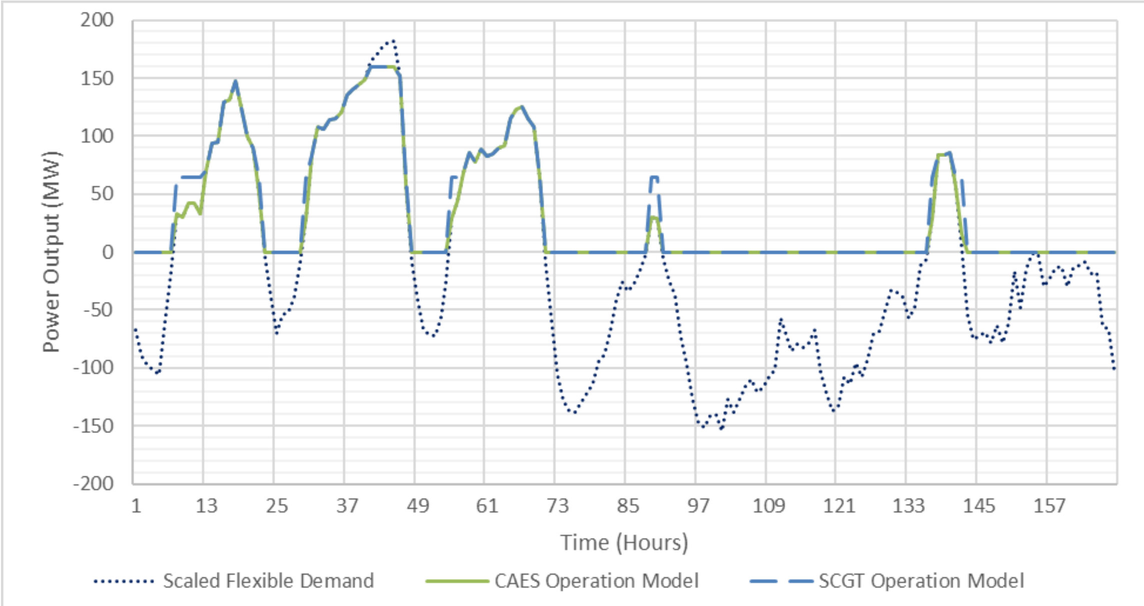

Figure 31 Scaled net flexible demand scenario and the resulting operating models for CAES and SCGT for the first week in June 2016.

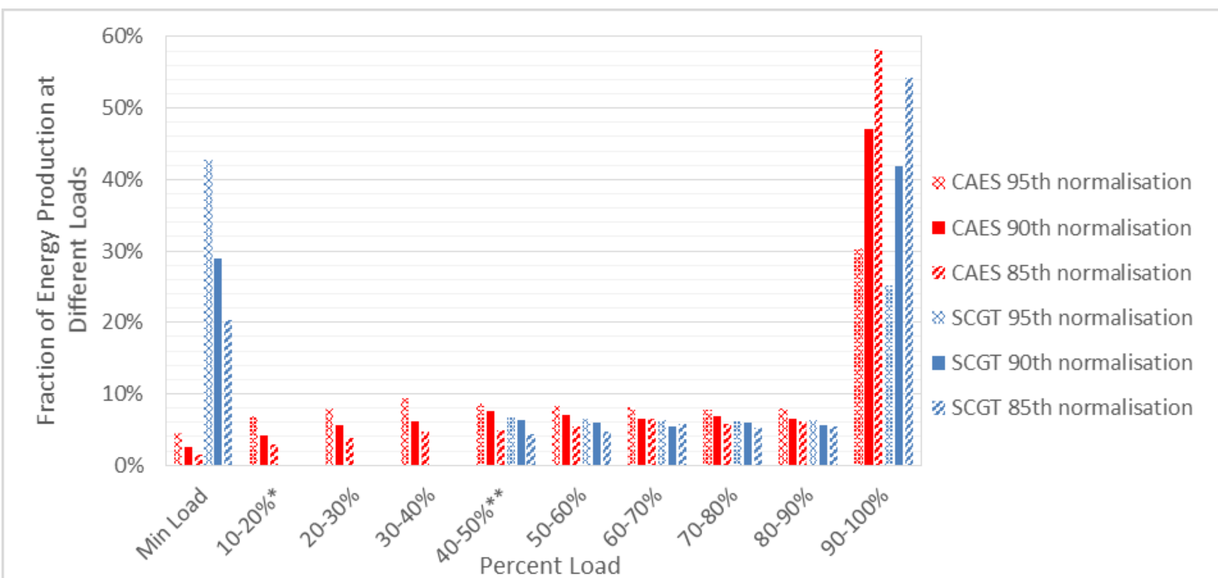

*Figure 32. Fraction of energy produced at different loads for three different normalisation scenarios for CAES and SCGT. *Not including energy generated at CAES' minimum load (10%). ** Not including energy generated at SCGT's minimum load (40%).*

10.0 Life Cycle Assessment Results

The operations model reveals the first challenge and weakness of balancing intermittent renewables with SCGT energy; the 40% minimum load of the gas turbine results in 15.9% of the gross energy produced in the year being wasted because it was more than what was needed at the time. In contrast, 1.3% of the annual energy from CAES was wasted under a 10% minimum load. These numbers are exaggerated by the low system capacities obtained from the model, 27.2% and 23.2% for SCGT and CAES respectively. However, even at a system capacity of 80%, if the same amount of energy was wasted it would still account for 5.4% of the gross annual energy production for the SCGT.

It is apparent from Figure 32 that the energy generation profile of the facilities is sensitive to the size of the market or grid within which they are operating. Relative to the base case, the 85th percentile normalisation scenario represents a somewhat larger market in which demands are larger in comparison to the facility capacity. Larger demand overall means that the facility is operating at high power outputs, and more efficiently, more often. Note that while operating at full load more frequently improves environmental performance, it also means that the facility was unable to meet the demand by itself more frequently. Conversely, the 95th percentile scenario represents a smaller market in which the facility is more often larger than needed for the demand and will generally run at lower capacities. From this sensitivity analysis, it can be extrapolated that facilities which operate in relative isolation or on smaller grids will generally emit more GWP impacts per unit of energy produced. Therefore, smaller and isolated systems should consider this issue carefully when choosing, sizing, and deploying gas turbine technology.

Before including partial loading inefficiencies and operating scenarios, the GWP of CAES, GE's SCGT, and Siemens' SCGT energy generation at full load was determined to be $3.07*10^{-1}$, $6.78*10^{-1}$ and $7.40*10^{-1}$ kgCO_2e/kWh, respectively. The GWP impact per kWh of energy produced from CAES is approximately half of that of energy produced from an SCGT when these technologies operate at peak efficiency or design load. The results for CAES closely match those found in similar studies, as illustrated in Figure 33. Therefore, it is believed that the LCA models are accurate enough to be used for further analysis. However, the influence of turbine technology on the impacts of SCGT generation is notable, design point heat rates vary, and larger turbines are typically more efficient on a per kWh basis. Although the SGT5-2000E 187 MW turbine is closer in power rating to the 160 MW CAES system under consideration, the heat rate of the 231 MW GE ZF.05 turbine was used in the dynamic analysis to ensure that the comparison was conservative in favour of SCGTs. In SCGT generation, approximately

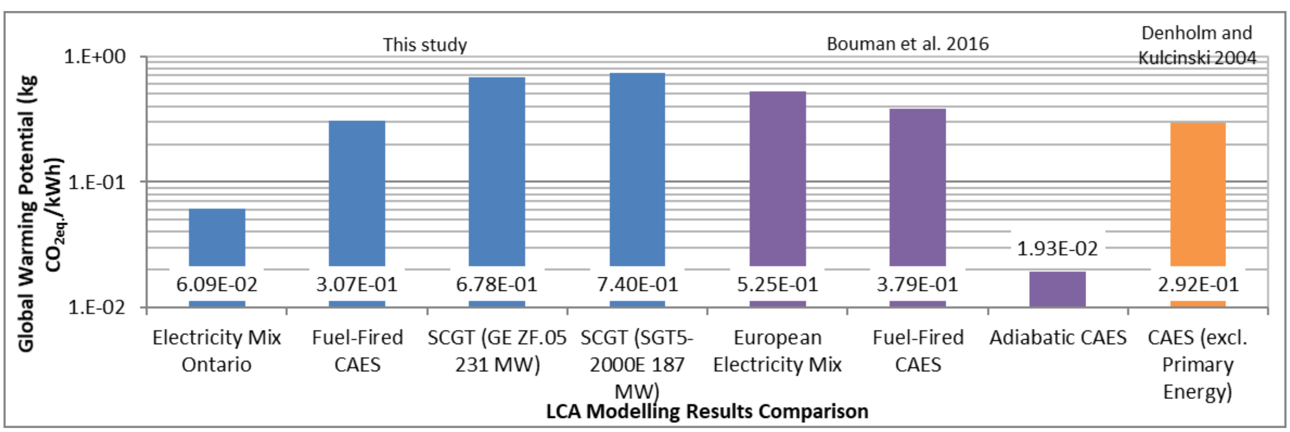

Figure 33. Global warming potential results for fuel-fired CAES and SCGT operation at design point. Results from other studies included for comparison: purple results from Bouman et al. (2016), orange results from Denholm and Kulcinski, and blue results are from this study.

80% of the impact comes from the combustion of natural gas with the remainder attributed to the production and transportation of the supplied natural gas. In CAES the majority of impacts are still from the supply and combustion of natural gas, but 1.6% of the GWP impact comes from the wind energy used to compress air.

At peak efficiencies CAES has a significantly lower GWP impact than an SCGT, regardless of manufacturer. However, the environmental superiority of CAES becomes even more prominent when partial loading is incorporated through operating scenario modelling. The GWP of CAES and SCGT energy under three scenarios for balancing intermittent power and the impact per kWh are shown in Figure 34. Also shown in this figure is the relative contribution of different load ranges to the total impacts. For the 90^{th} percentile normalisation base case operation models, the GWP impacts of producing energy from CAES and SCGT under realistic operating conditions are $3.16*10^{-1}$ and $8.08*10^{-1}$ $kgCO_2e/kWh$. The dynamic operation modelling estimates a 19% increase in SCGT's GWP per kWh over design point operation and only a 3% increase for CAES. The increase in impacts over design point operation are shown in Figure 35. In general, greater impacts are associated with load ranges that represent larger portions of the total energy produced. However, the contribution of impact from CAES at low loads (minimum to 40%) is clearly much smaller than the contribution of low loads for SCGT for the same range (0-40%). This observation points to the significance of SCGTs' high minimum load and poor partial load fuel efficiency, the results of which are increased carbon intensity per kWh.

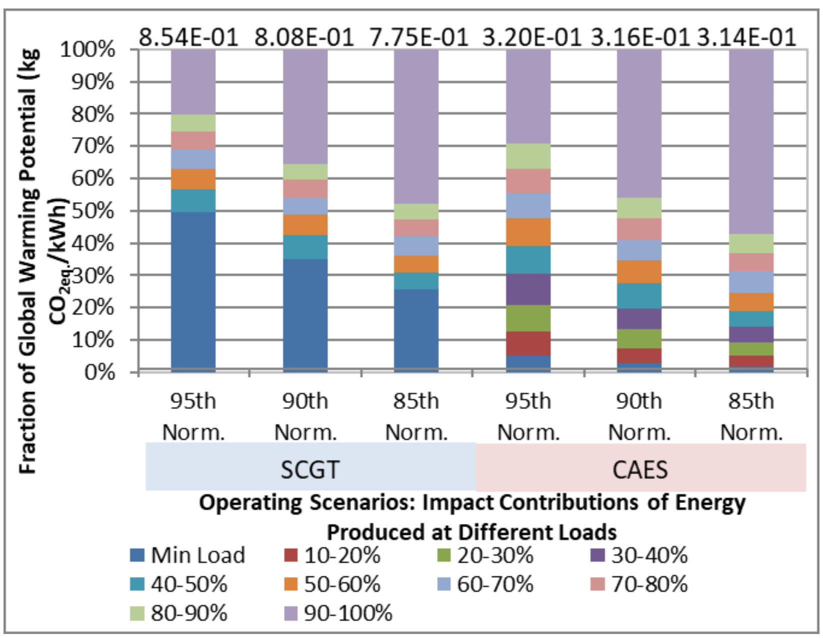

Figure 34. Breakdown of global warming potential impacts for different demand normalisation scenarios. GE FZ.05 SCGT results shown on the left and CAES on the right.

10.1 Levelised Cost of Energy and Carbon Pricing

The levelised cost of energy (LCOE) for a power plant is the total cost of creating, running, and decommissioning a facility divided by all the energy that facility will produce over it's operational lifetime. The result is an effective metric for the average cost over energy production which allows for comparison between different technologies and alternatives. LCOEs will vary over time and geography

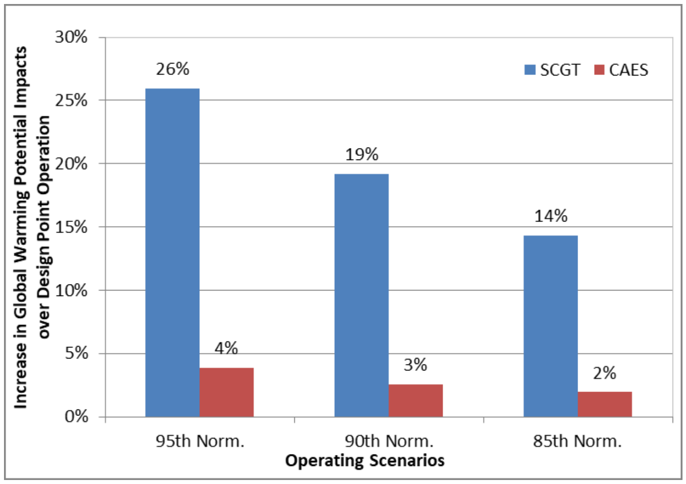

Figure 35 Increase in global warming potential impacts over design point operation for CAES and SCGT

and may differ depending on what assumptions go into the calculation. As a result, a wide range of LCOE values can be found in the literature for CAES and SCGTs. This is especially true for CAES which involves site specific storage cost estimates and limited availability of data and experience owing to the fact that only two commercial facilities have been installed. However, two recent studies that are detailed and relevant can be used for investigating the influence of carbon pricing on the economics of CAES and SCGTs. McGrail et al. (2013) conducted a detailed feasibility study for the implementation of CAES in the pacific northwest of the USA and found that at 6.4 ₵/kWh fuel-fired CAES, with the same capacity factor (25%), was less expensive than a new SCGT at 8.1 ₵/kWh. While a 25% capacity factor is low by the standards of most power generation facilities today, it is generous for 'peaking plants' and is consistent with the operational modelling completed in this study. Within the Canadian context, a study by the Pembina Institute (2017) for the Alberta electricity market found that energy from SCGTs cost 5.4 ₵/kWh while fuel-fired CAES cost 4.7 ₵/kWh if charged using excess renewable energy and 6.5 ₵/kWh if charged using electricity and prices from the spot market at the time of charging. The lower LCOE of SCGTs in this study may be due to differing system capacity factors and differing natural gas market conditions. However, carbon pricing is to be implemented across Canada soon, and Ontario has already implemented a carbon cap and trade system. The LCOE values reported above do not include any carbon pricing. Figure 36 uses the Pembina Institute's values as a base LCOE and illustrates how these values change under carbon pricing. In Ontario where renewable energy penetration is greater than other provinces, and there is an excess of must-run baseload, the CAES (RE) pricing may be most representative and is already cheaper than SCGT energy. Alternatively, the market energy based CAES (market) cost curve is cost competitive with SCGT energy at a carbon pricing of 21.85 \$/tonne CO_2e, which is only slightly higher than the minimum price of carbon of 18 \$/tonne CO_2e in Ontario's cap and trade market and double the 10 \$/tonne CO_2e mandated by the federal government for 2018. Given the significantly greater emissions of SCGTs, fuel-fired CAES is much less susceptible to carbon pricing, for example, at 50 \$/tonne CO_2e an SCGT will cost an extra 4.0 ₵/kWh to run compared to just 1.6 ₵/kWh extra for CAES. In this context, it is especially important to accurately estimate the GHG emissions of different technologies because a 20% increase in carbon emissions will result in an increased carbon cost by the same factor.

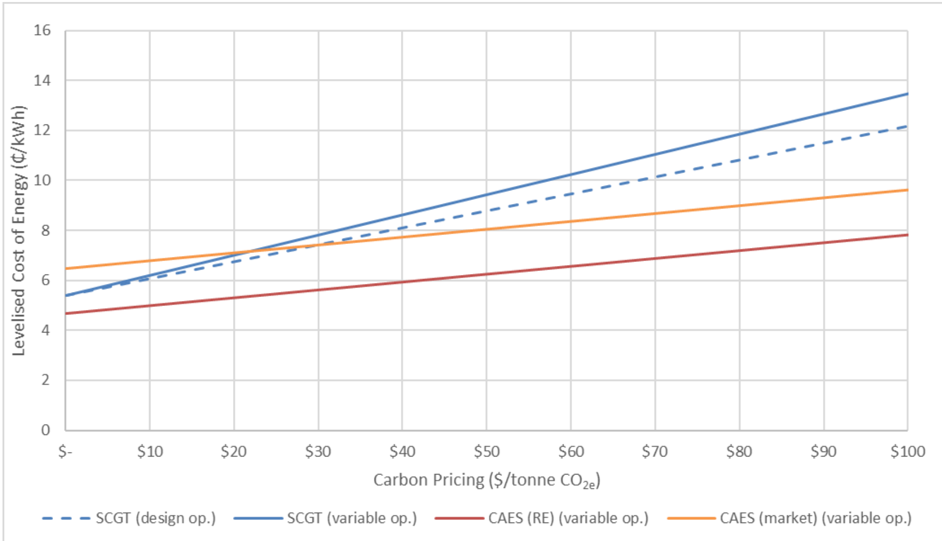

Figure 36 Impact of carbon pricing on the levelised cost of energy of CAES and SCGTs. Solid lines reflect carbon pricing associated with variable operation and dashed lines reflect the same for design point operation. The red CAES (RE) lines reflect CAES charged using excess renewable energy and the orange CAES (market) lines reflect CAES charged using spot prices on the Alberta electricity market. Base energy costs from Pembina Institute (2017).

11.0 Life Cycle Assessment Conclusions

Ontario's energy supply has limited flexibility and a significant proportion of must-run power capacity. This largely inflexible generating base relies heavily on natural gas to provide a relatively small but vital supply of highly flexible energy. However, this portion of the supply mix accounts for a disproportionately large part of the electric grid's carbon footprint. While large-scale energy storage options in southern Ontario are limited, CAES is viable. Environmentally, CAES outperforms SCGTs during ideal design point operation by a factor of approximately 2.2, $3.07*10^{-1}$ compared to $6.78*10^{-1}$ $kgCO_2e/kWh$, respectively. However, this difference increases to a factor of approximately 2.5 when realistic intermittent loading and partial load inefficiencies are accounted for, $3.16*10^{-1}$ compared to $8.08*10^{-1}$ $kgCO_2e/kWh$, respectively. Given the difference in emissions between these technologies is $4.92 *10^{-1}$ $kgCO_2e/kWh$ it is possible to estimate GWP impact reductions for Ontario given some scenarios. In 2016 2244 GWh of wind was curtailed and 665 GWh of nuclear power was reduced due to congestion or surplus baseload power (Independent Electricity System Operator, 2016). If all 2909 GWh were stored in CAES then 4473 GWh of SCGT produced energy could be displaced, resulting in a reduction of 2.20 $MtCO_2e$, about 2.8% of the total emissions from Canada's electricity sector in a year. Storing and producing that much energy in a year would require more than a 160 MW facility; however, it is easy to imagine how this technology could start reducing emissions from Canada's electricity sector if implemented. Beyond this simple example, many more advantages and uses of CAES can be capitalised on, it is therefore concluded that fuel-fired CAES is a good candidate for providing flexible energy while working towards a low-carbon electric grid. However, provinces such as Alberta, Saskatchewan, and Nova Scotia which have a heavy reliance on coal power will not benefit from as significant of a reduction in GHG emissions immediately (Pembina Institute, 2017). This is a result of charging energy storage, in part, with carbon intensive coal power. However, installing energy storage will be vital to allow for increased renewable energy penetration onto the grid and will in the medium to long-term achieve huge GHG emission reductions by displacing coal power.

Regarding future LCA work pertaining to energy systems, this research demonstrates that partial loading inefficiencies are an important consideration for power generating plants intended for balancing intermittent energy sources such as wind and solar power. It may be possible to use adjustment factors to correct static operation models but more modelling needs to be completed, and these factors would be technology dependent. As a 'ballpark' estimate, it is suggested that realistic impacts for fuel-fired CAES will be 1-5% greater than design point operation and the impacts of SCGTs will be 10-30% greater. These adjustment factors should only be considered for impact categories which are largely dependent on natural gas supply and combustion. Using these adjustment factors for land use impacts, for example, is likely not an appropriate application and therefore professional judgement is required.

12.0 Recommendations and Outlook for CAES in Canada

The process of setting up the methodology and obtaining data for the MCA study, as well as the results that were produced, lead the author to make several recommendations regarding CAES in Canada. These recommendations are given below.

12.1 General Recommendations for Extended MCA Studies

- It is recommended that a second set of geologic criteria be included to address the potential for using brine-compensated constant-pressure CAES in salt cavern operation. This type of cavern operation imposes different loading conditions on the surrounding rock, and a new criteria selection and scoring process should be completed to reflect these differences. Note that the surface brine pond needed for this type of cavern operation may prove costly and difficult to obtain permits for and appropriate criteria should be included to reflect this additional challenge if possible.
- It is also recommended that this study is expanded to include the potential for CAES in porous aquifers, and the possibility of using abandoned underground mines for storage. This should include underground hard rock mines and salt mining operations which were not solution mined.
- Another criterion that should be investigated further and potentially added is the proximity of sites to existing natural gas storage infrastructure. This is important because natural gas service for a large facility must be reserved a day in advance or longer for the weekends. This means that a CAES operator must estimate their natural gas needs a day or more in advance, and they must reserve the necessary capacity along natural gas transmission lines from their facility all the way to the natural gas storage site. The challenge of predetermining operational needs is exceptionally challenging when operating as a balance for unpredictable renewables. Siting a facility closer to existing natural gas storage infrastructure would make operation simpler and cheaper. Alternatively, CAES developers may choose to create their own natural gas storage on-site, which would also alleviate this issue.
- The weight of criteria reflects the preferences of a handful of experts and different parties may be more or less interested in different parameters. For this reason, it is recommended that any individual or organisation wishing to apply the developed process for their own purpose should carefully examine the weights chosen to ensure that the weights are appropriate for their own purposes and preferences.

12.2 Recommendations for Detailed Studies

- It is recommended that other individuals or organisations undertaking more in-depth siting studies for CAES integrate the criteria which were discussed in this report but not included in the calculations, for example, a monetary assessment and the inclusion of caprock conditions and salt impurity.
- In the analysis, it was assumed that a potential CAES project could connect to existing natural gas and electrical infrastructure at any point. It was also assumed that the transmission line connected to would have sufficient capacity to support the facility. These assumptions are amongst the most difficult to justify in this study, and further efforts should focus on addressing these assumptions.

- The selection of criteria weights is a difficult and contentious task, and the results of the study should be cemented by a formal expert elicitation process which better supports the determined criteria weights.
- A detailed study for regional CAES siting would likely be better off using a discrete location methodology. Discrete MCA studies work on all of the same principles except that instead of requiring GIS integration and maps, a matrix of criteria and alternatives is used to calculate the results. For discrete studies, the user must select the alternatives to be evaluated at the beginning of the processes, and the results do not produce reliable contour maps. On the regional scale, for example just southwestern Ontario, data quality may be insufficient to produce reliable results across the study. Preselecting alternatives based on results from broader studies such as this one will help to reduce the quantity of data necessary significantly. Furthermore, spatially continuous analysis on smaller scales is more likely to be influenced by erroneous anomalies and inaccuracies associated with interpolating spatial data.

While the siting and design of CAES are not simple endeavours, and detailed engineering studies are needed to implement this technology, these studies have taken some early steps towards simplifying this process and justifying the effort. Key areas across the country in Alberta, Saskatchewan, Ontario, Nova Scotia, and New Brunswick are technically viable and hold great potential for CAES. The environmental and economic benefits of CAES compared to gas turbines are apparent, SCGTs are not a good long-term investment and are poorly equipped for meeting the needs of the electric grid in the future. It is also important to note that due to the maturity of fuel-fired CAES technology, it can be implemented in the near future and can, therefore, start having meaningful impacts for carbon reduction and grid stability quickly. Adiabatic CAES is a carbon-free energy storage option but this technology has yet to be proven at a commercial scale and is therefore still a higher risk option. Adiabatic CAES will likely be the preferred option for electric grids in the future when trying to eliminate fossil fuels from electric grids completely. Retrofitting fuel-fired CAES with thermal energy storage may also be a desirable option in the future.

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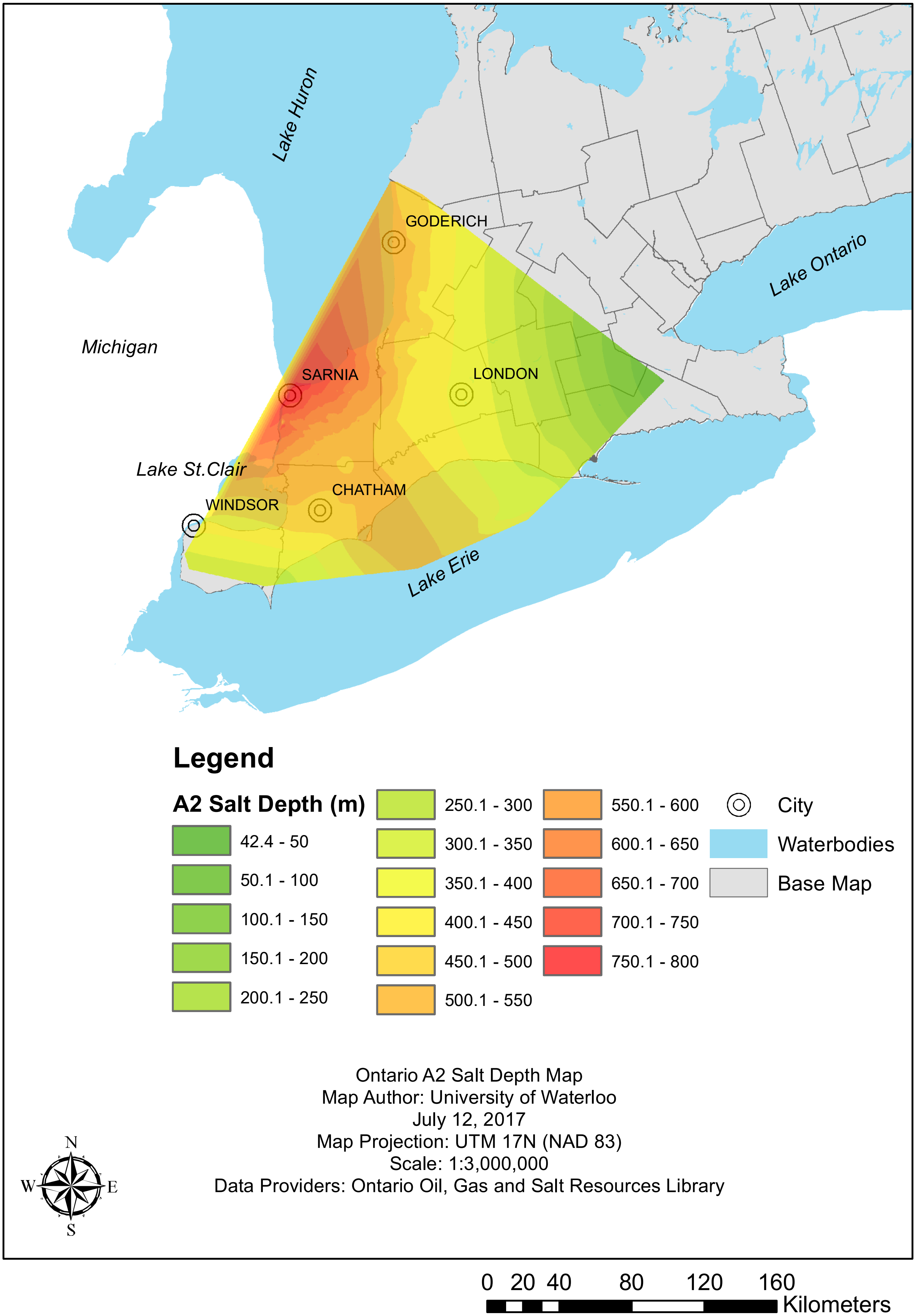
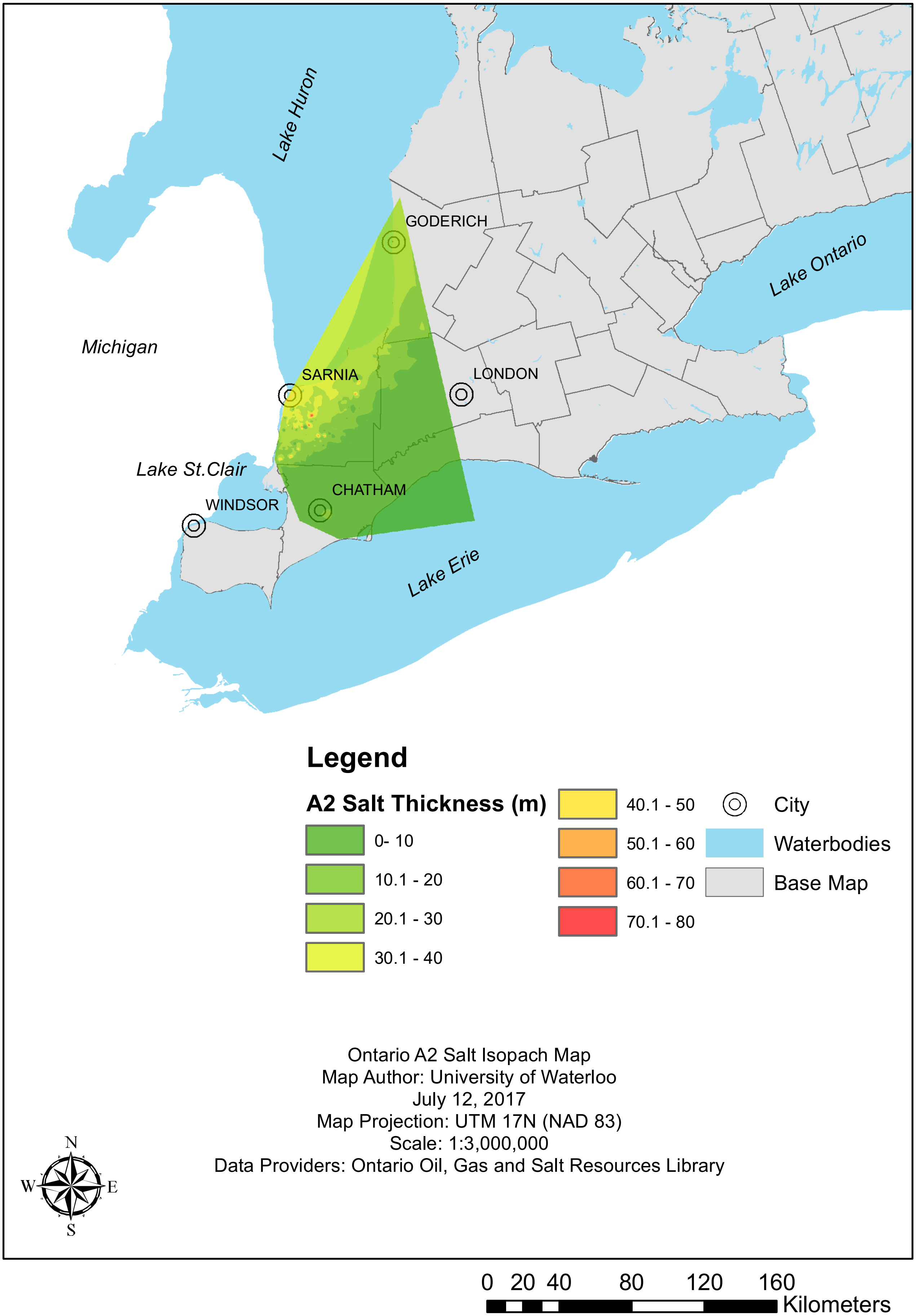
Appendix A: Input Data Maps

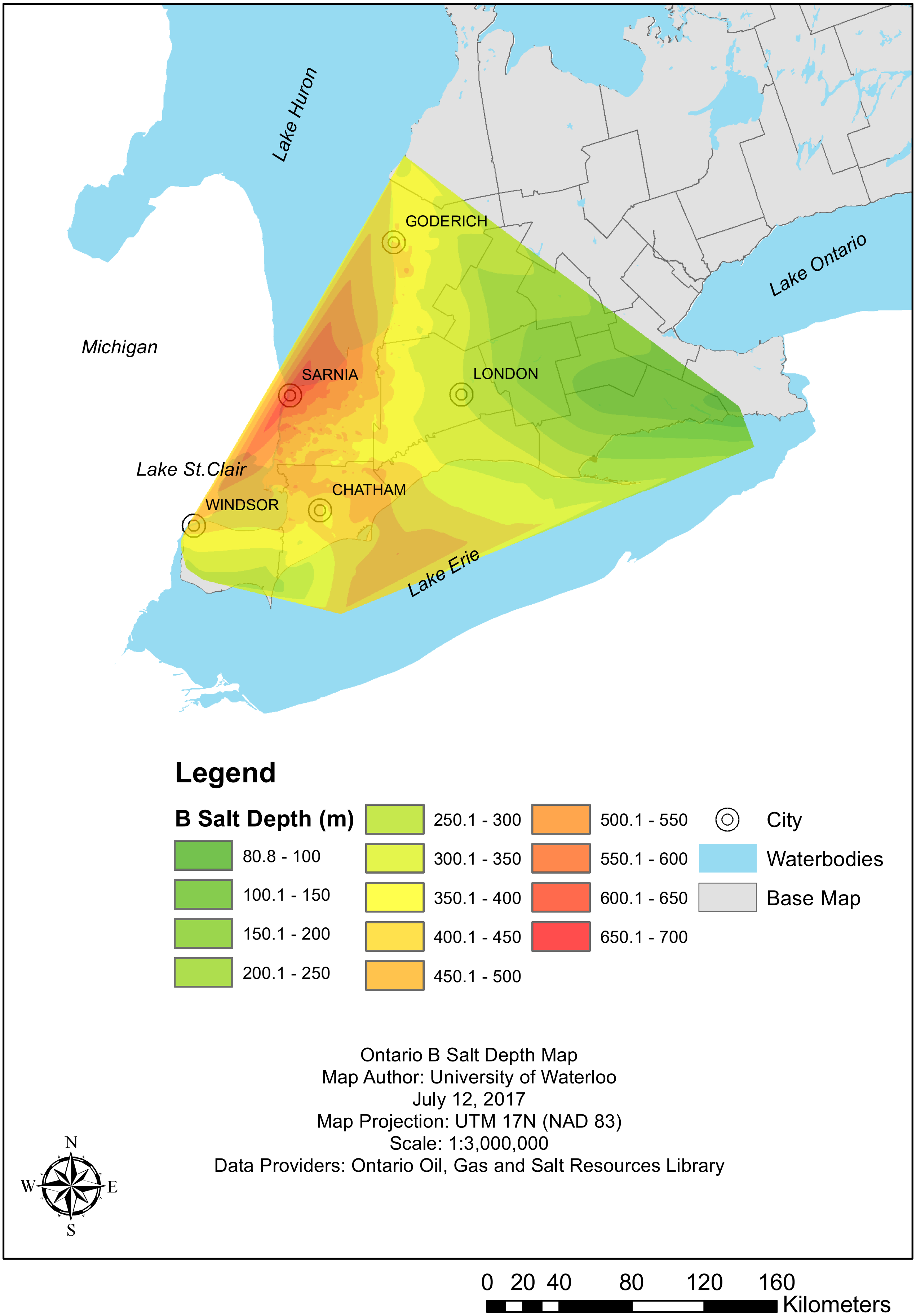
Ontario A2 Salt Depth Map



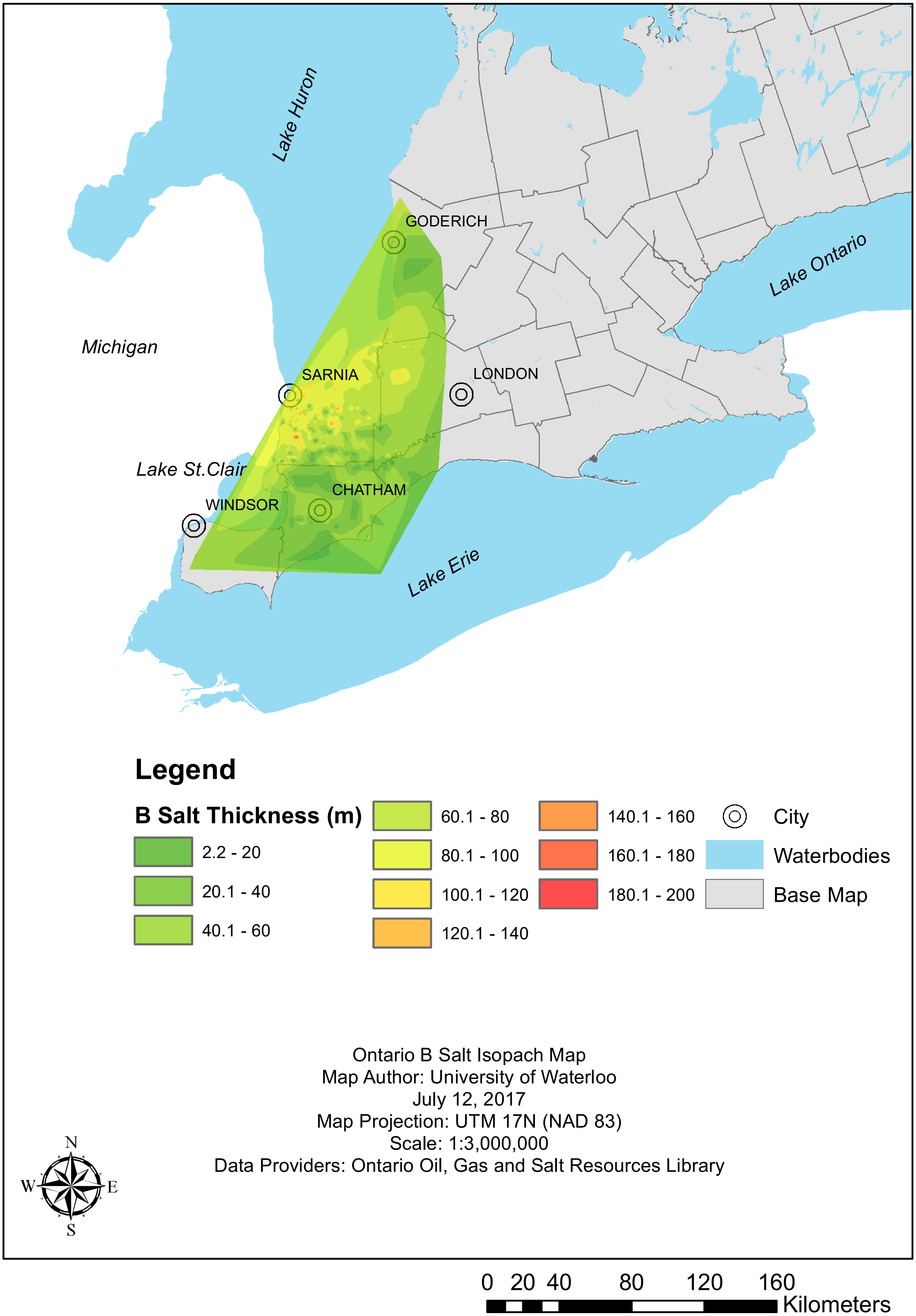
Ontario A2 Salt Isopach Map



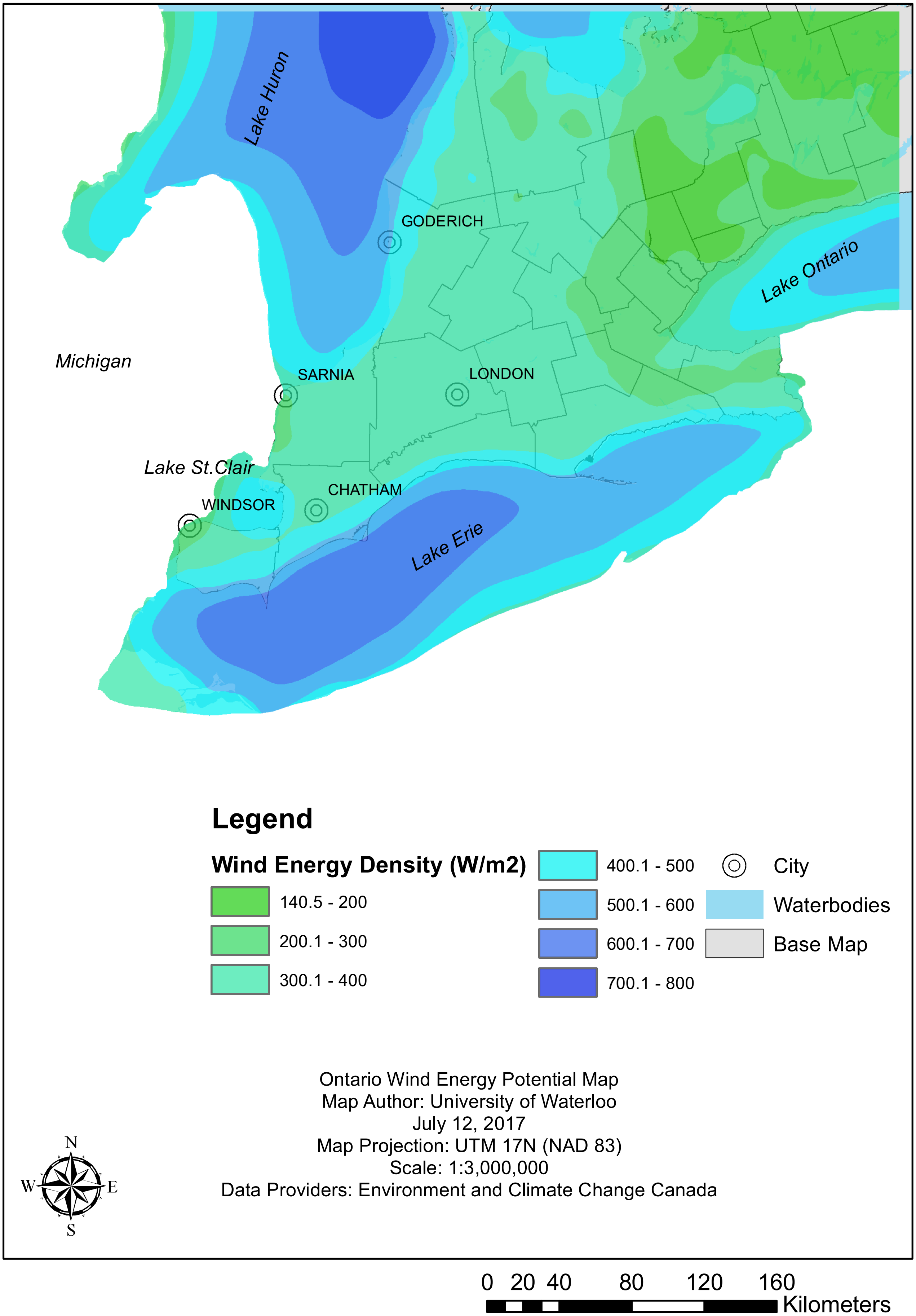
Ontario B Salt Depth Map



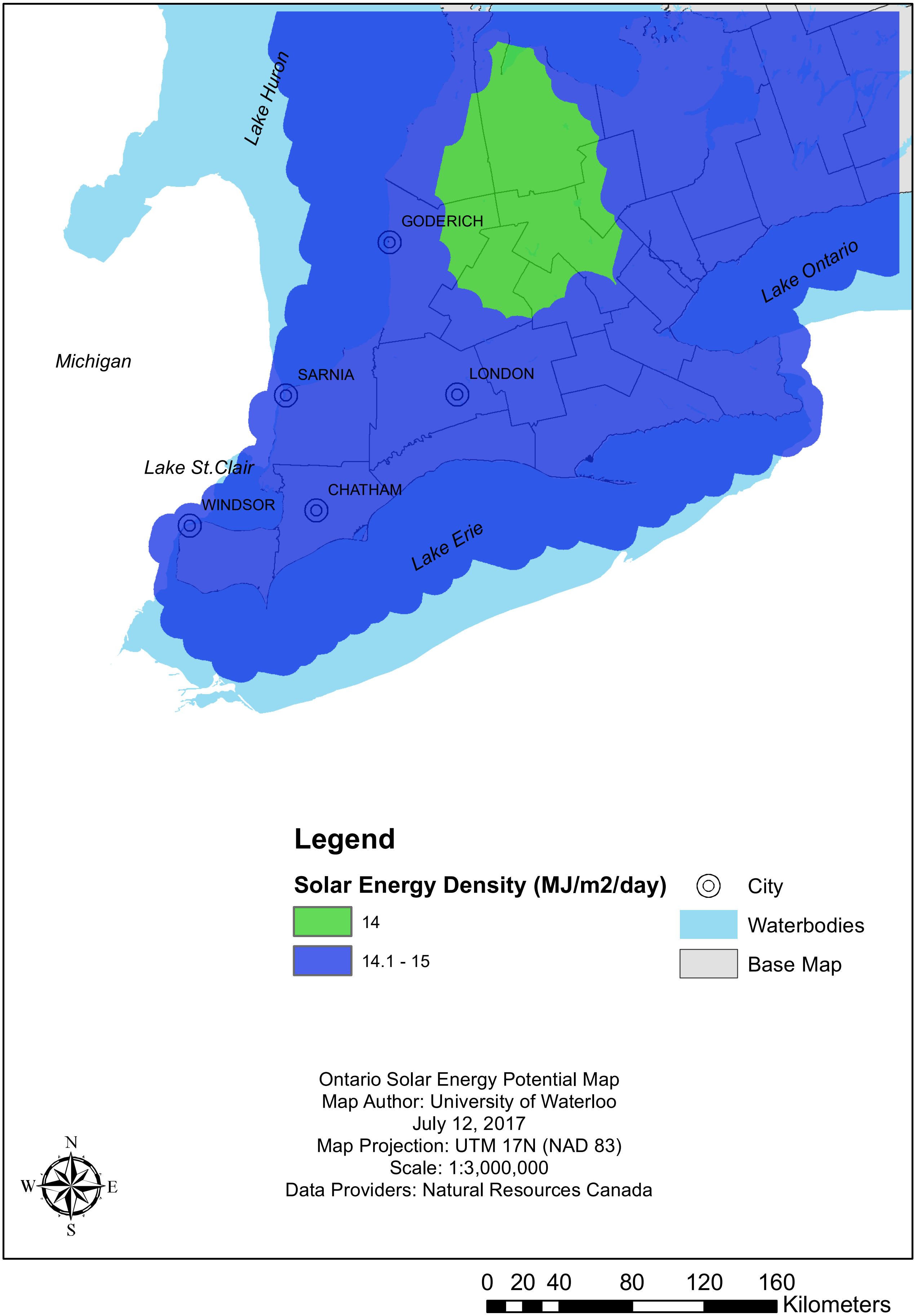
Ontario B Salt Isopach Map



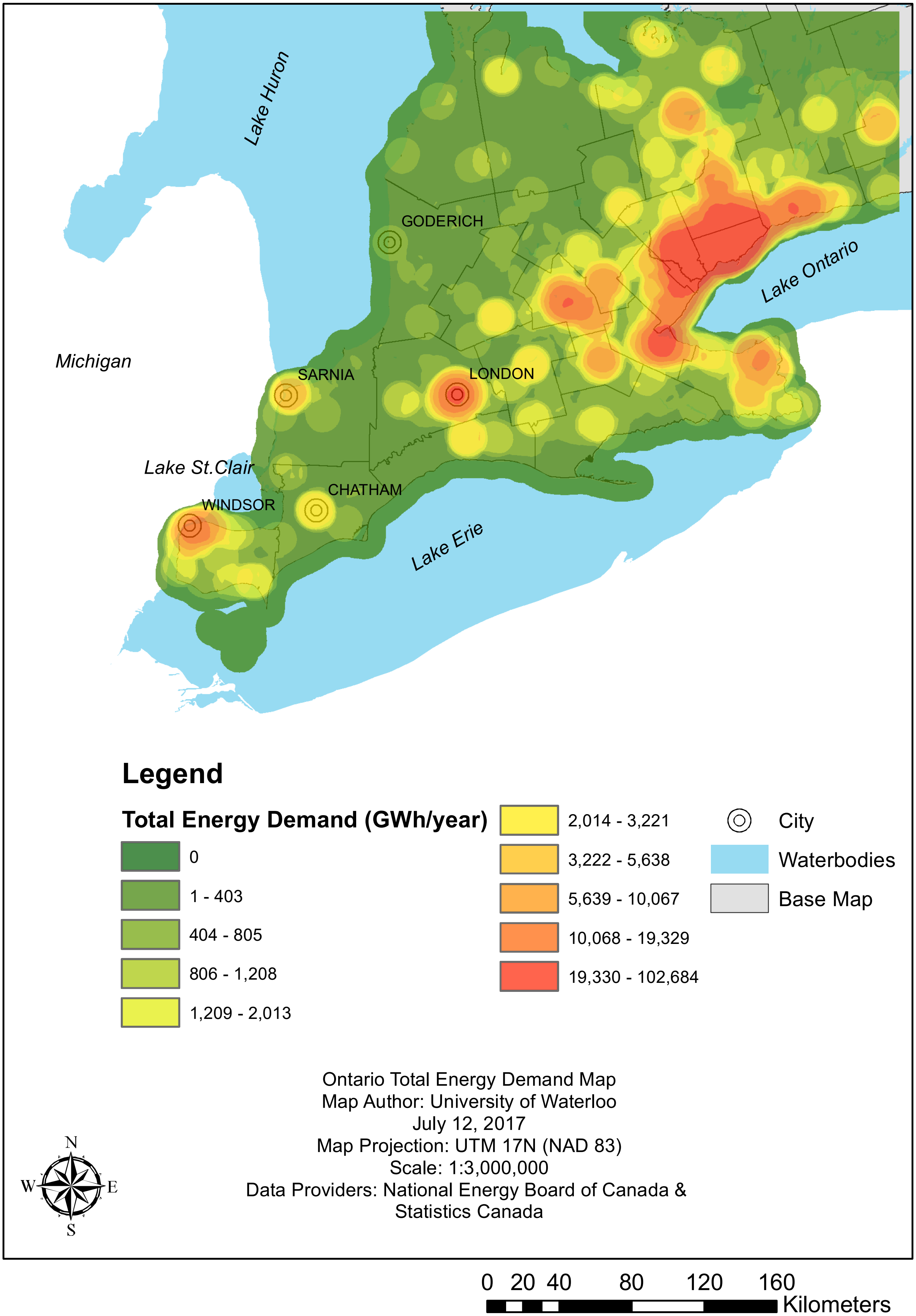
Ontario Wind Energy Potential Map



Ontario Solar Energy Potential Map



Ontario Total Energy Demand Map



Ontario Infrastructure Map

Legend

Natural Gas Pipelines

Natural Gas Pipelines

Electrical Transmission Lines

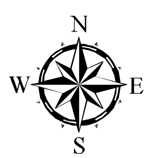
Electrical Transmission Lines

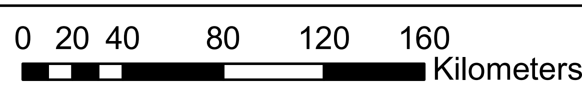
City

Waterbodies

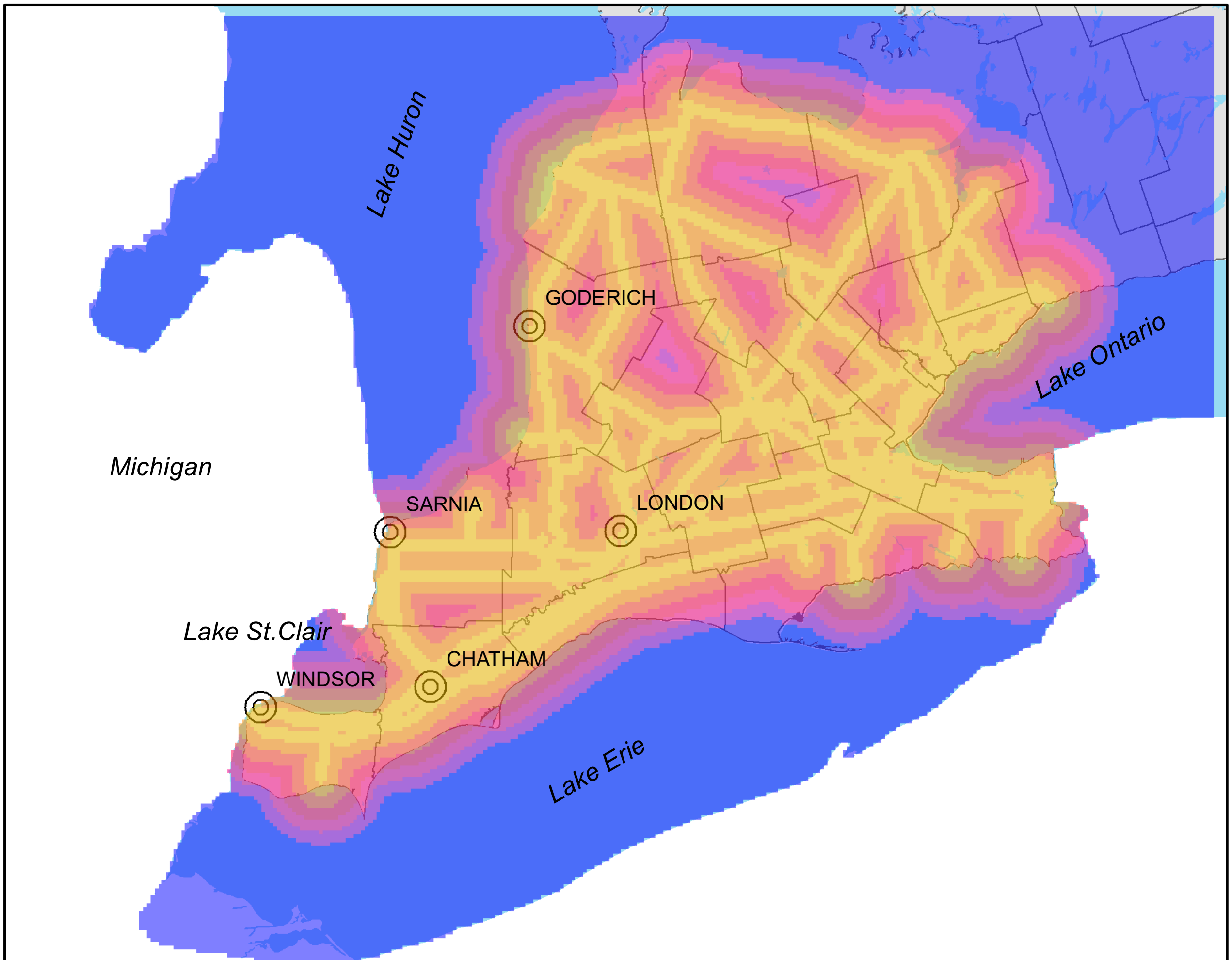
Base Map

Ontario Infrastructure 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,
Union Gas &
National Topographid Data Base (Natural Resources Canada)





Ontario Proximity to Electric Transmission Lines Map



Legend

Proximity to Transmission Lines (m)

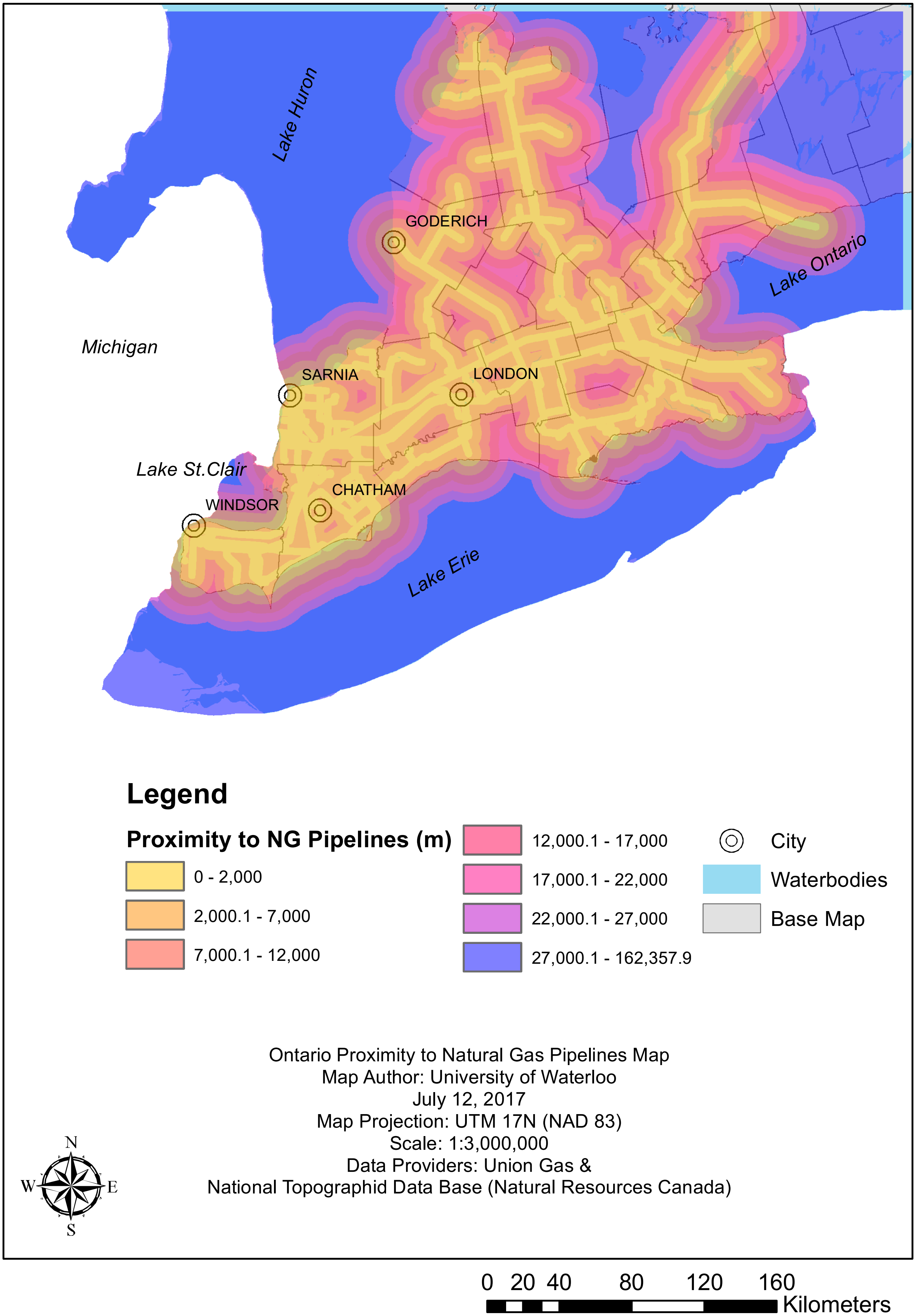
- 0 - 2,000
- 2,000.1 - 7,000
- 7,000.1 - 12,000
- 12,000.1 - 17,000
- 17,000.1 - 22,000
- 22,000.1 - 27,000
- 27,000.1 - 167,501.7

- City
- Waterbodies
- Base Map

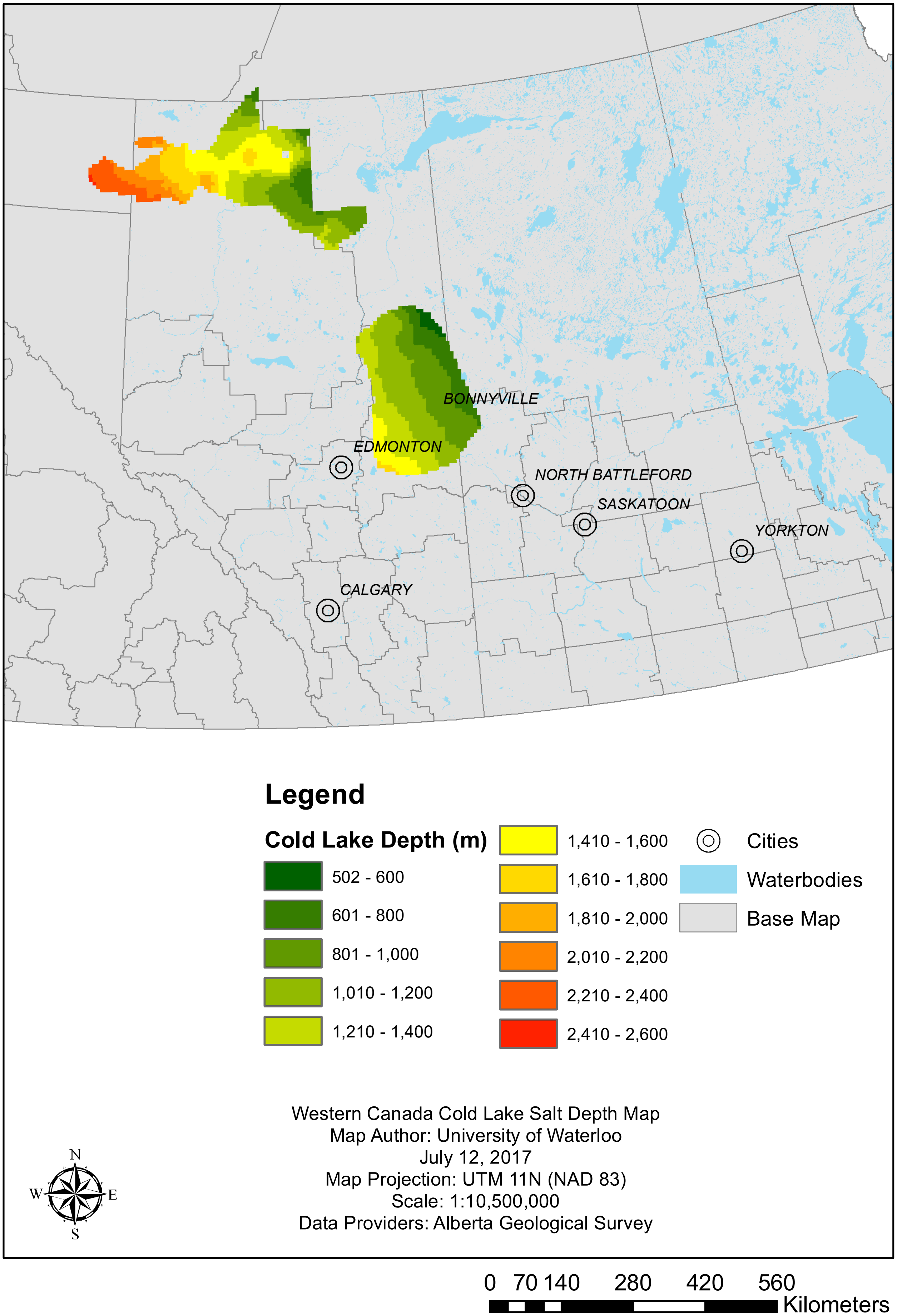
Ontario Proximity to Electric Transmission Lines Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 17N (NAD 83)
Scale: 1:3,000,000
Data Providers: Canadian Electricity Association &
National Topographid Data Base (Natural Resources Canada)

0 20 40 80 120 160 Kilometers

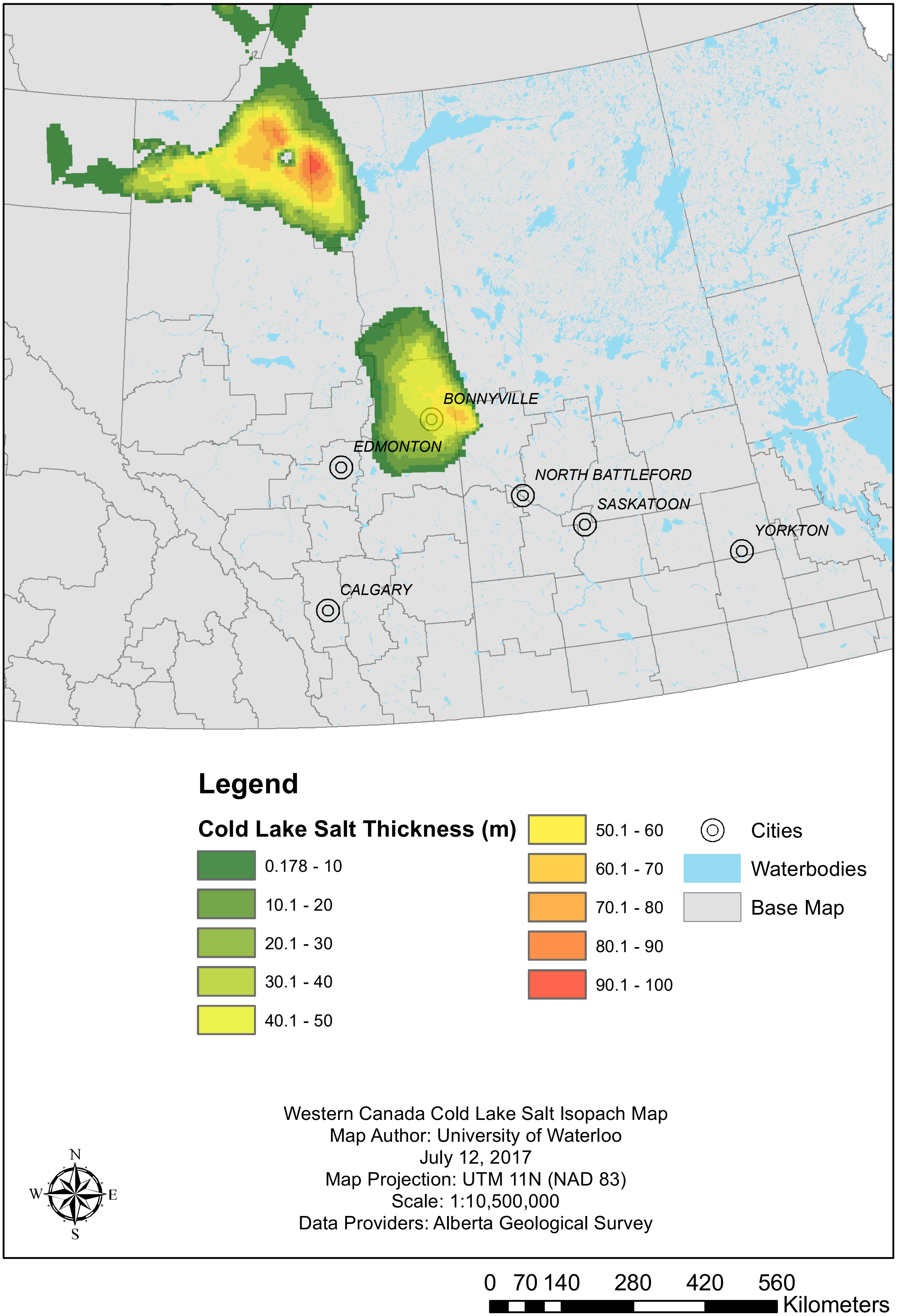
Ontario Proximity to Natural Gas Pipelines Map



Western Canada Cold Lake Salt Depth Map

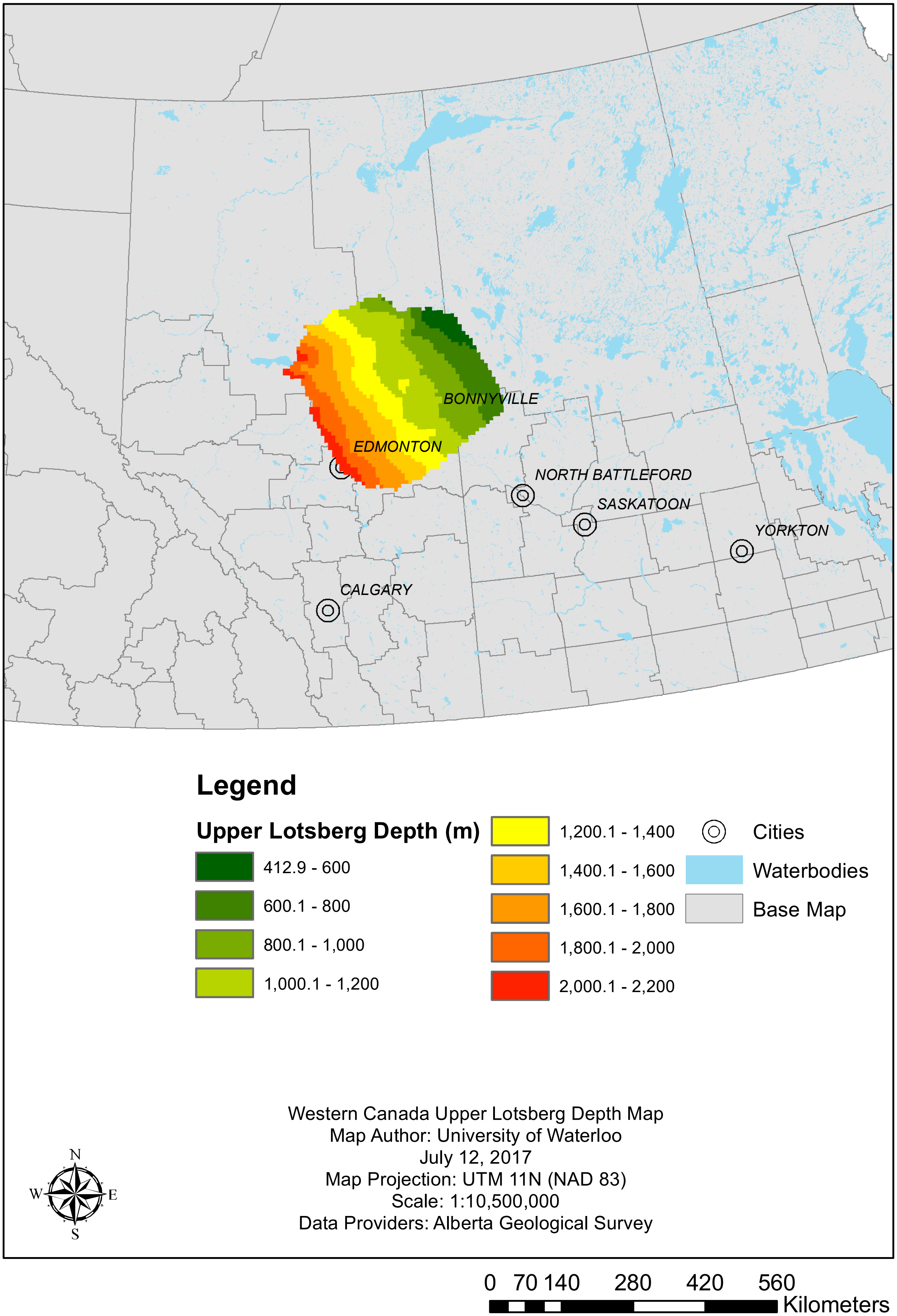


Western Canada Cold Lake Salt Isopach Map

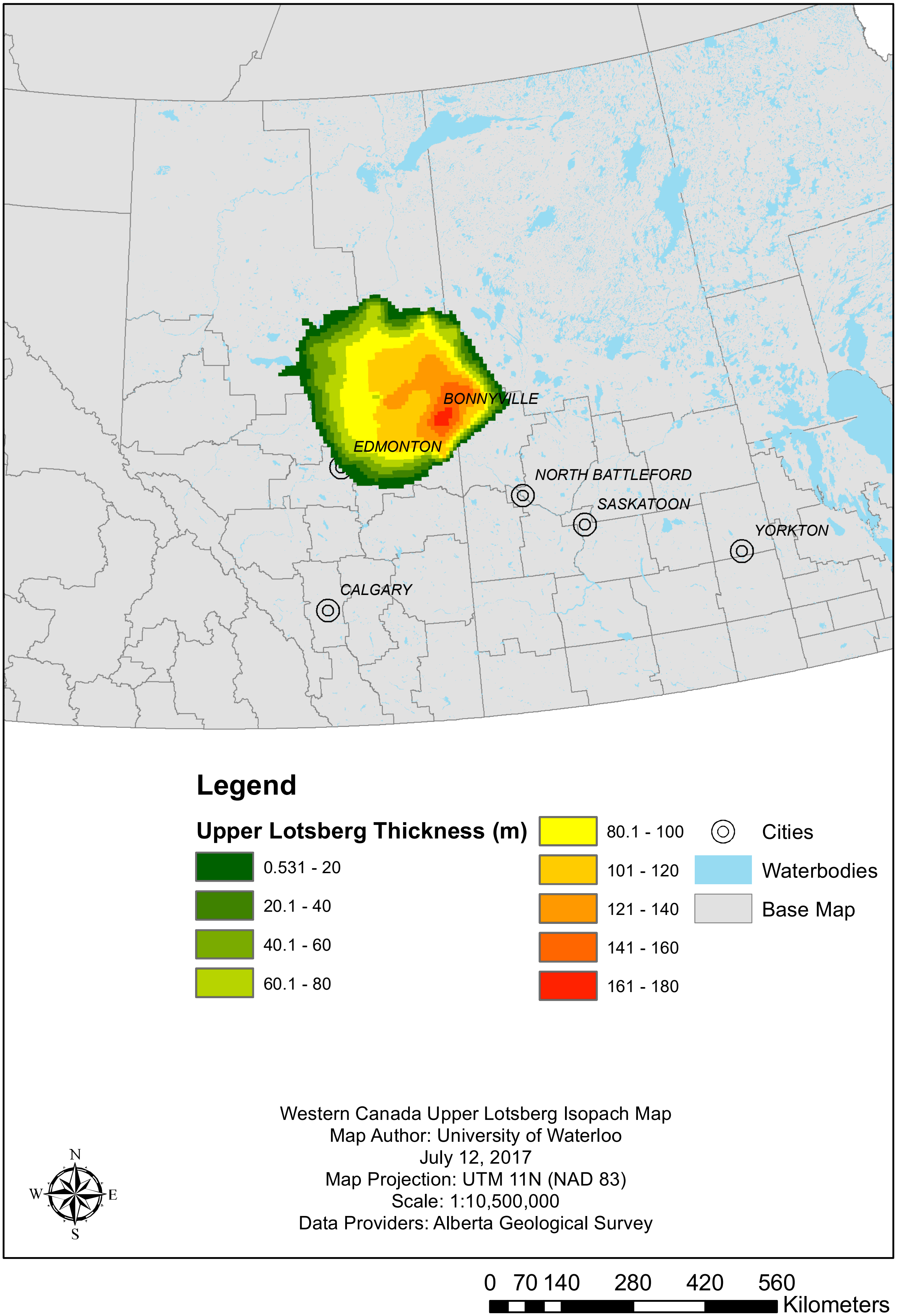


Western Canada Cold Lake Salt Isopach Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000
Data Providers: Alberta Geological Survey

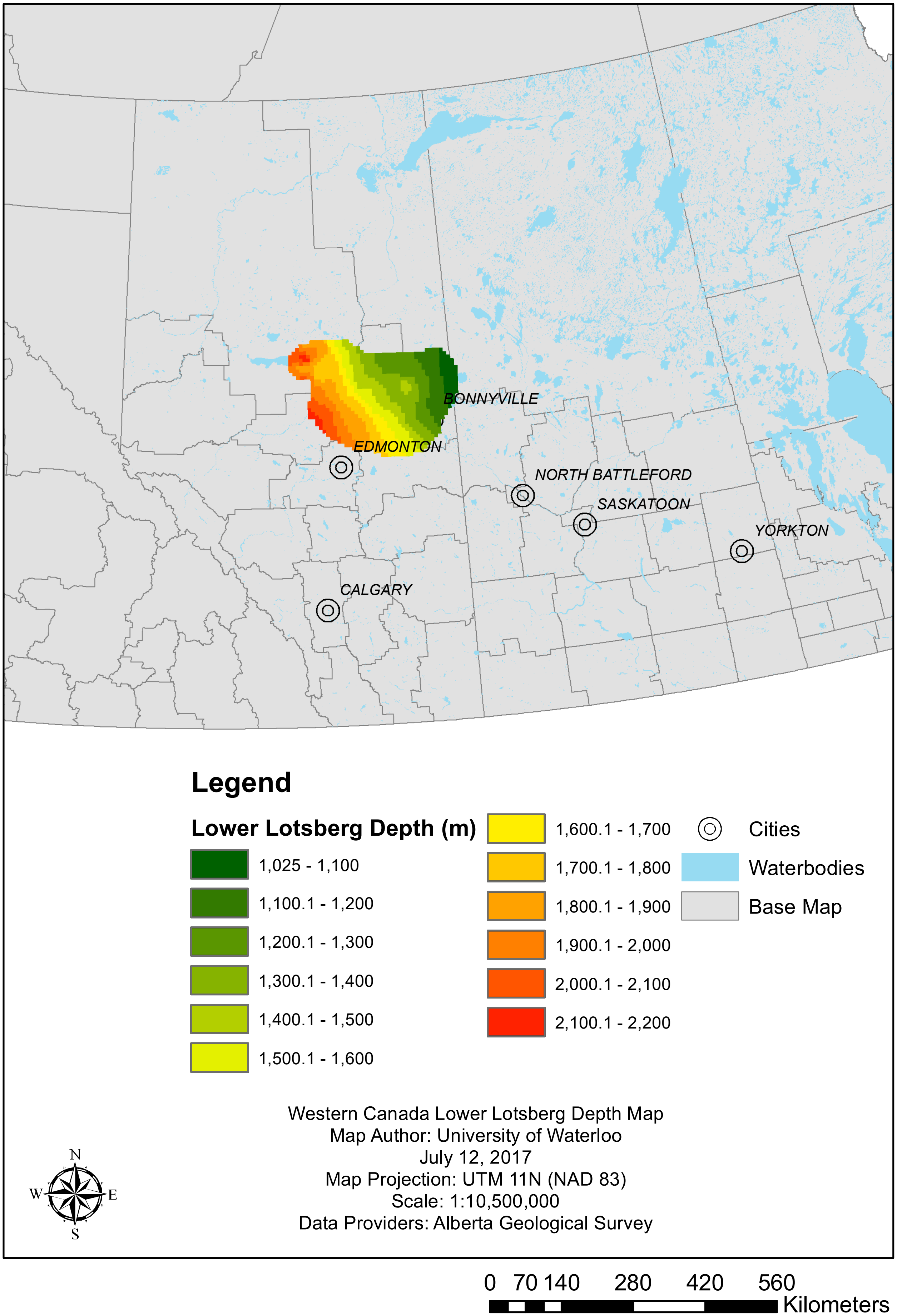
Western Canada Upper Lotsberg Salt Depth Map



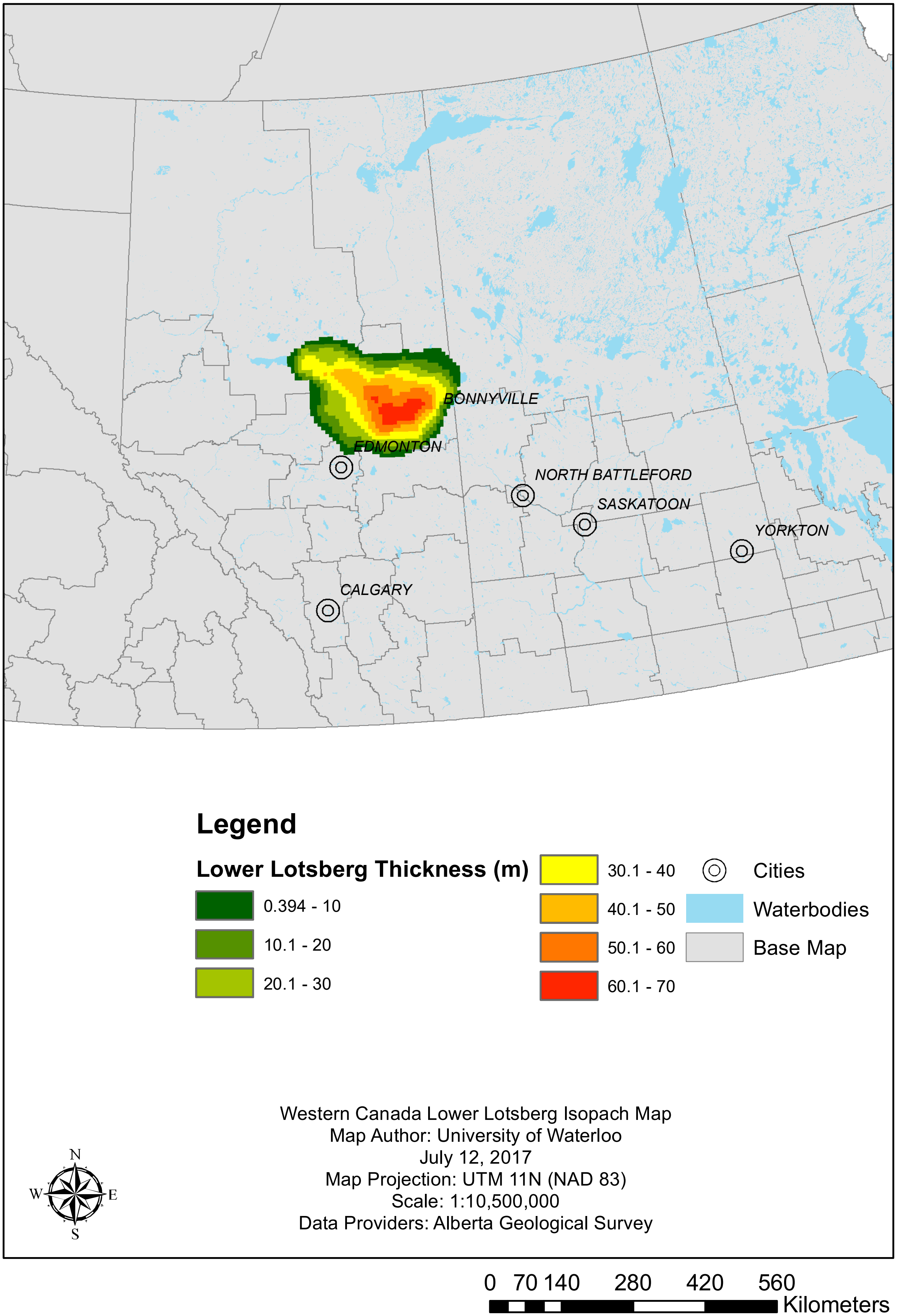
Western Canada Upper Lotsberg Salt Isopach Map



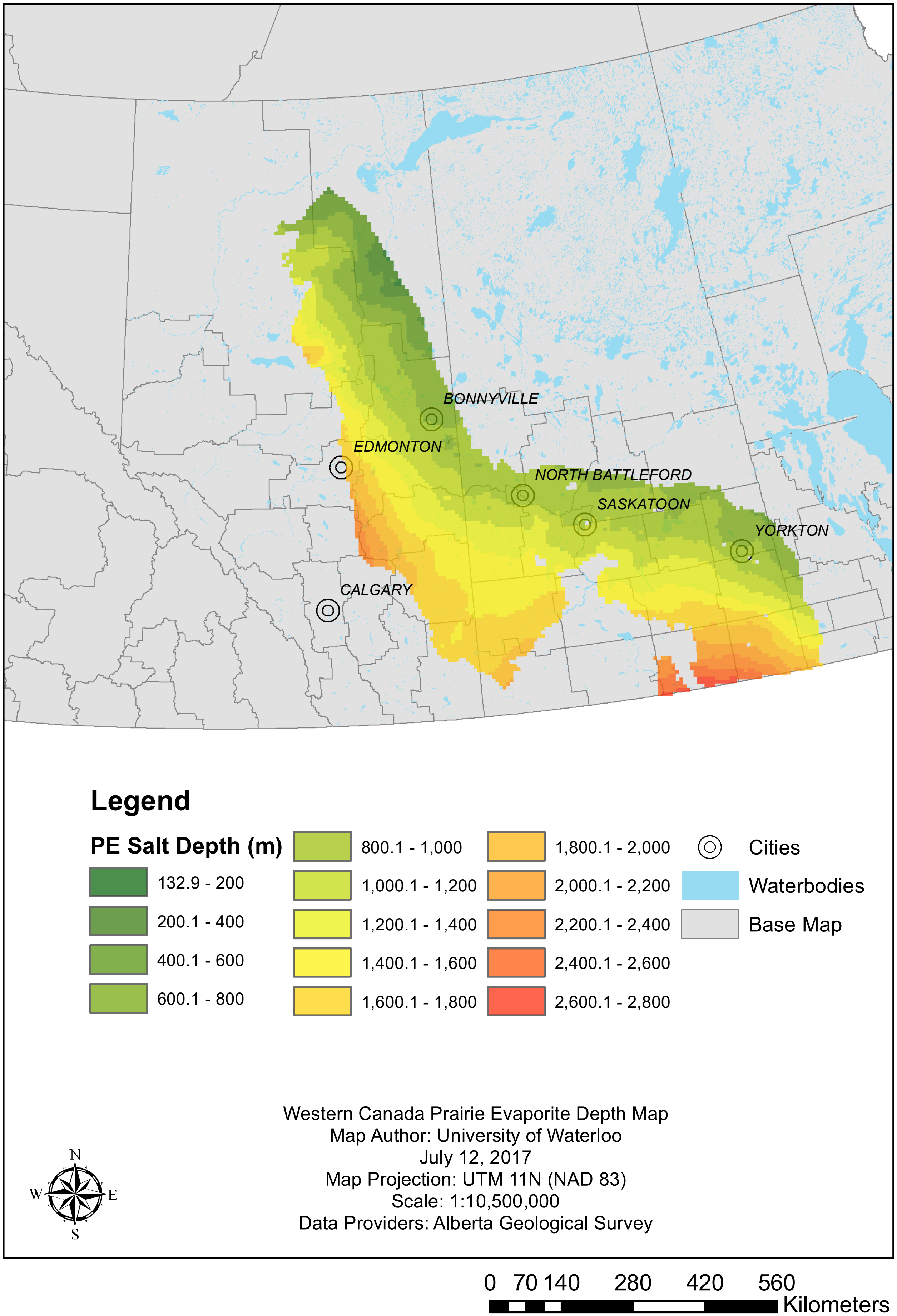
Western Canada Lower Lotsberg Salt Depth Map



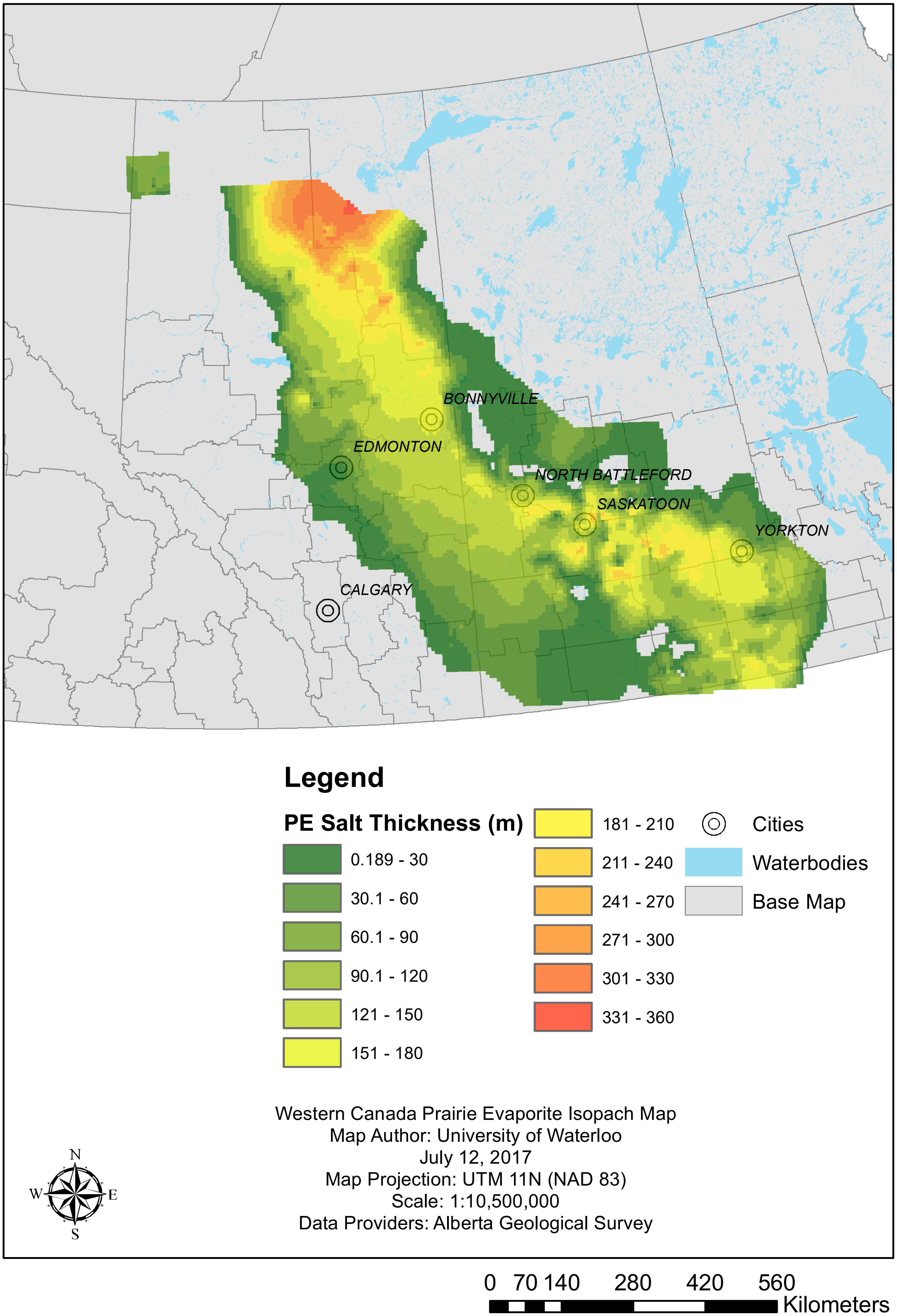
Western Canada Lower Lotsberg Salt Isopach Map



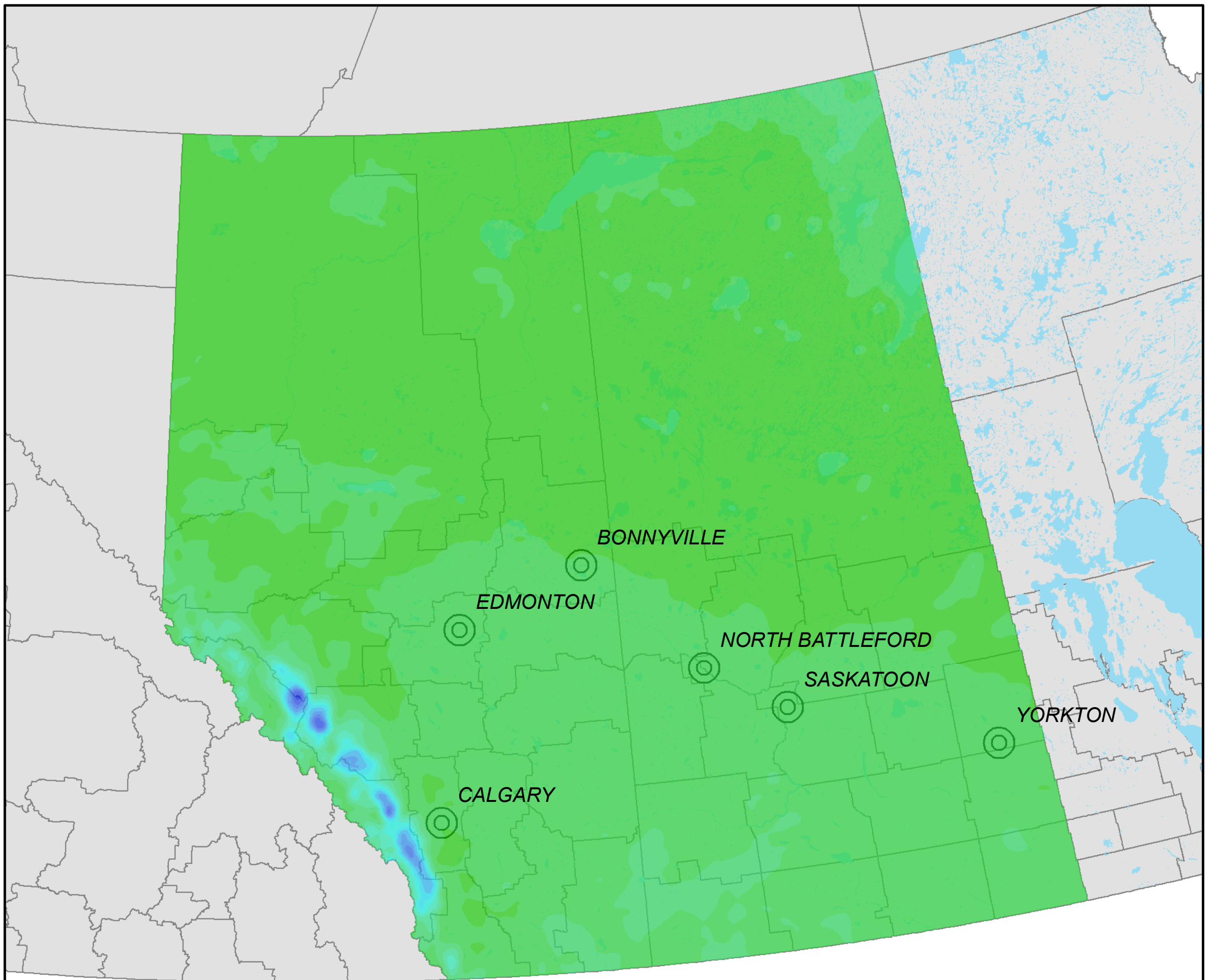
Western Canada Prairie Evaporite Salt Depth Map



Western Canada Prairie Evaporite Salt Isopach Map



Western Canada Wind Energy Potential Map



Legend

Wind Energy Potential (W/m2)

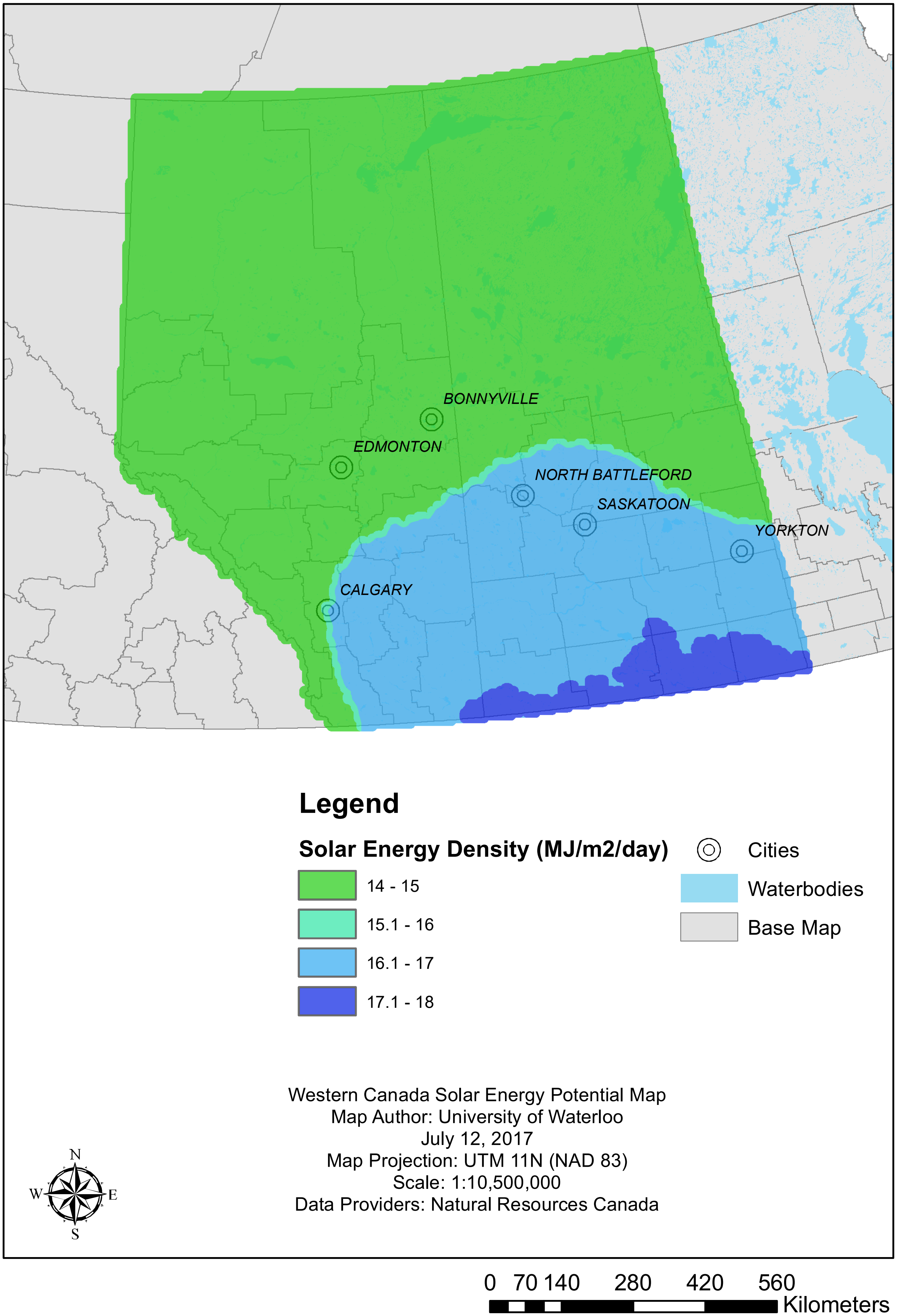
- 58.7 - 200
- 200.1 - 400
- 400.1 - 600
- 600.1 - 800
- 800.1 - 1,000
- 1,000.1 - 1,200
- 1,200.1 - 1,400
- 1,400.1 - 1,600
- 1,600.1 - 1,800
- 1,800.1 - 2,000
- 2,000.1 - 2,200
- 2,200.1 - 2,400

- Cities
- Waterbodies
- Base Map

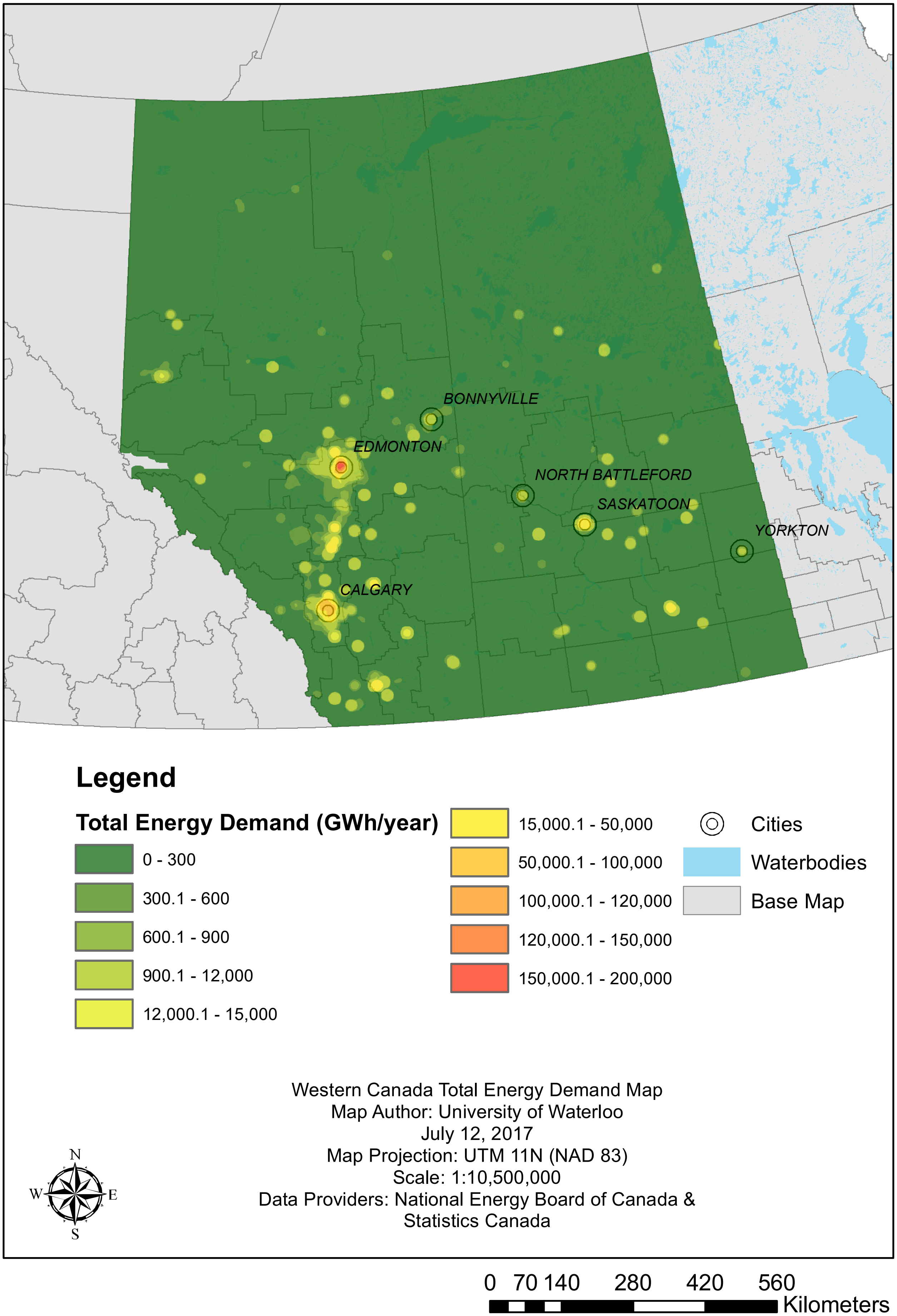
Western Canada Wind Energy Potential Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000
Data Providers: Environment and Climate Change Canada

0 70 140 280 420 560 Kilometers

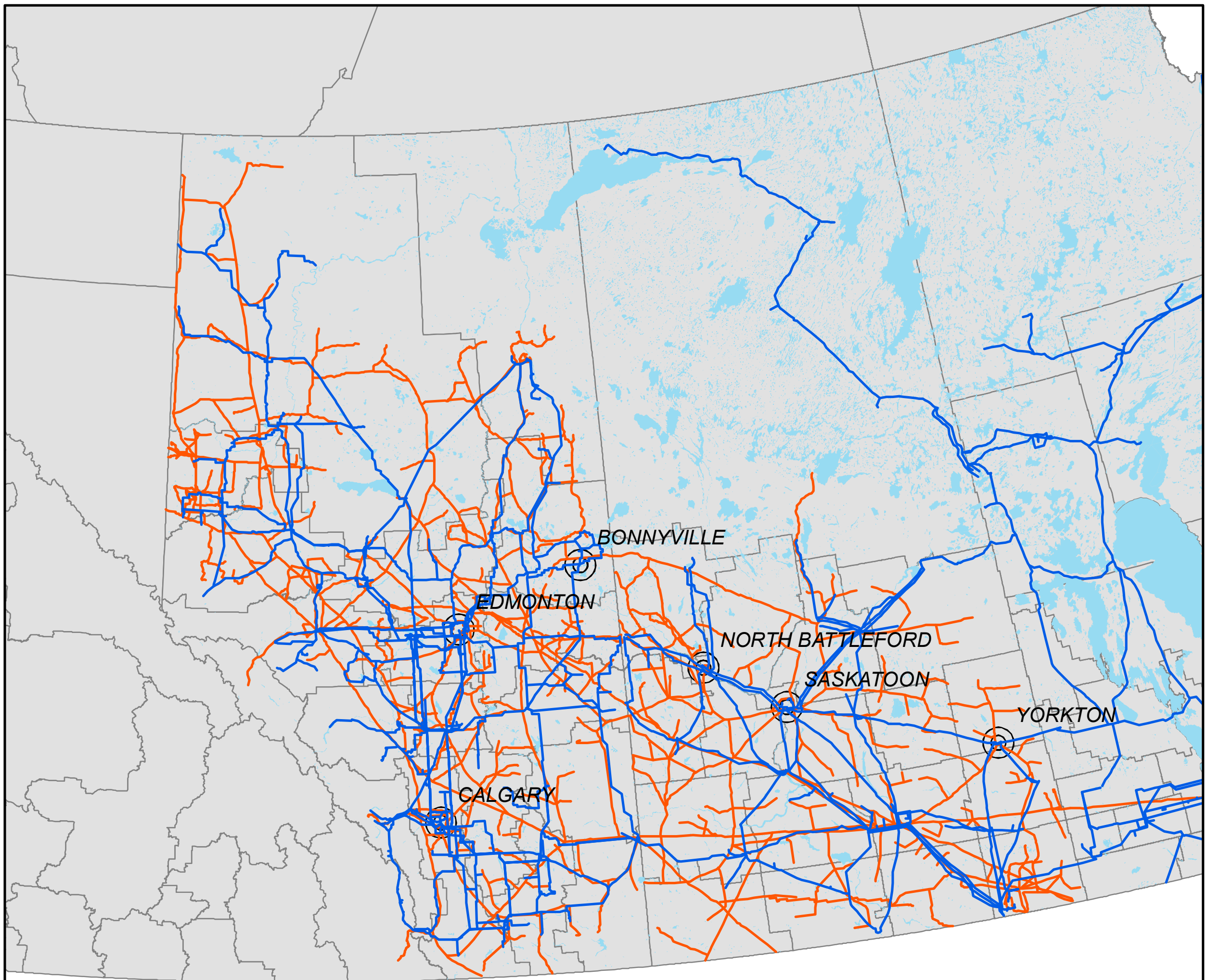
Western Canada Solar Energy Potential Map



Western Canada Total Energy Demand



Western Canada Infrastructure Map



Legend

Electric Transmission Lines

Electric Transmission Lines

Natural Gas Pipelines

Natural Gas Pipelines

Cities

Waterbodies

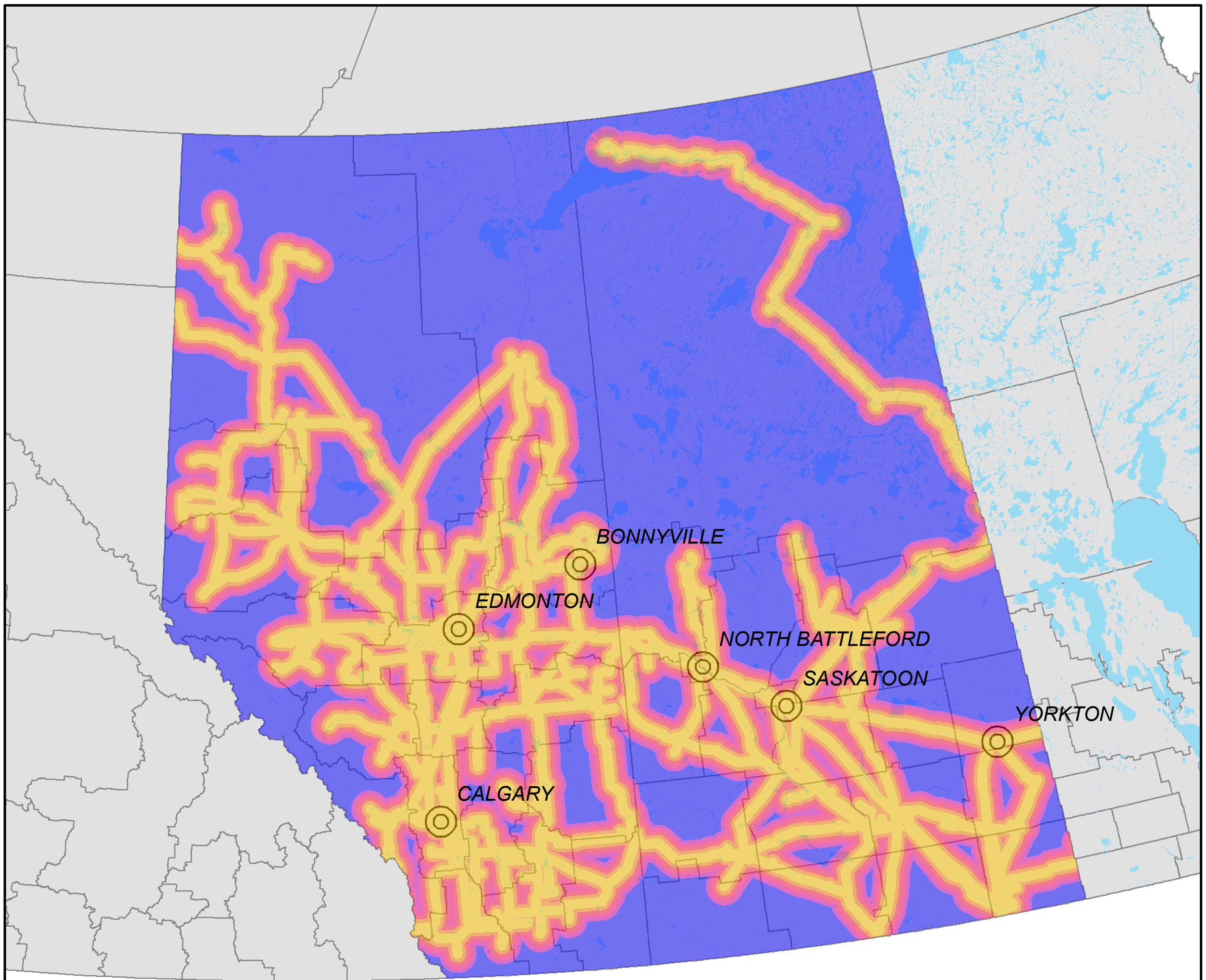
Base Map

Western Canada Infrastructure 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 &
Canadian Energy Pipeline Association

N W E S

0 70 140 280 420 560 Kilometers

Western Canada
Proximity to Electric Transmission Lines Map



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

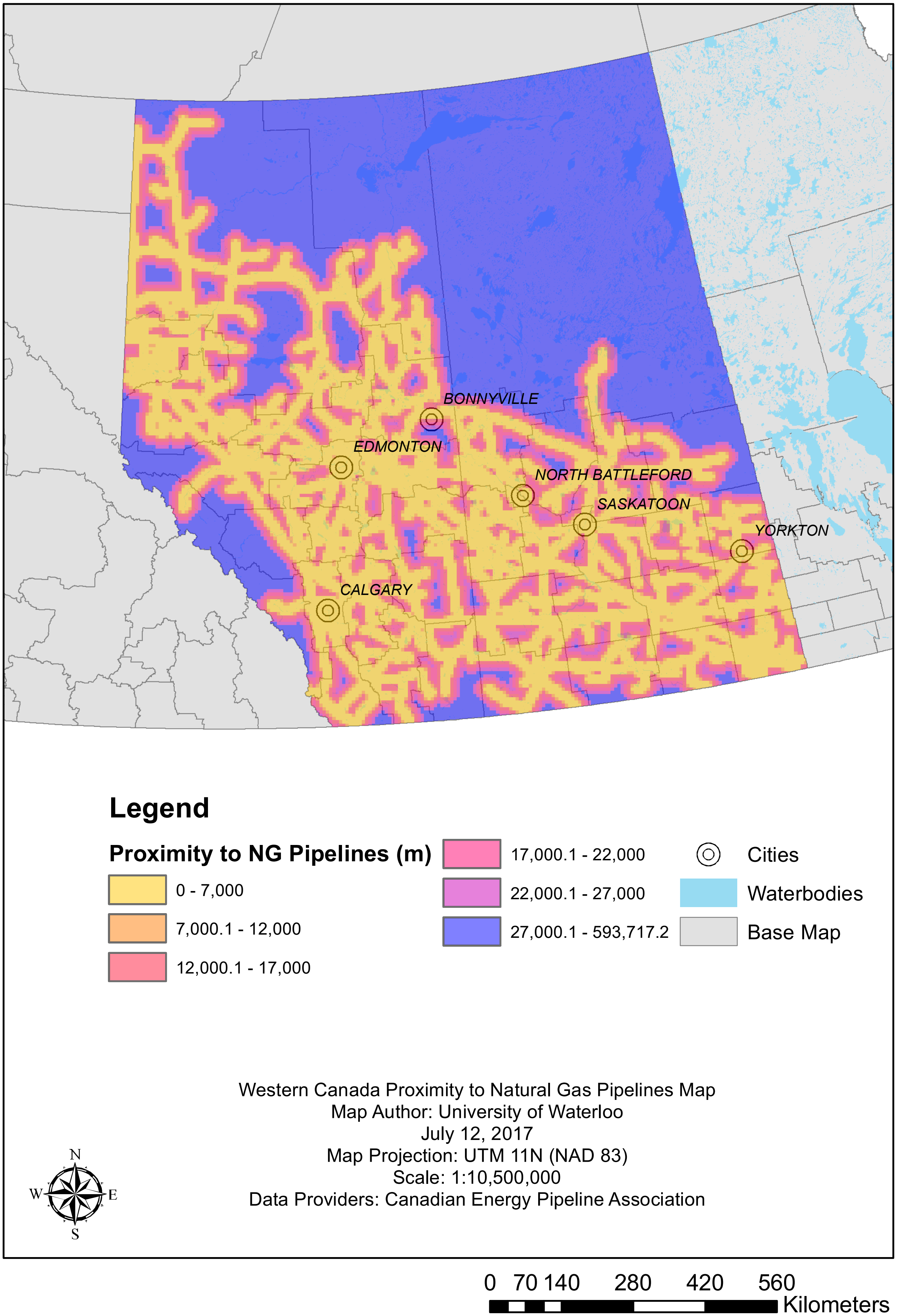
- Cities
- Waterbodies
- Base Map

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

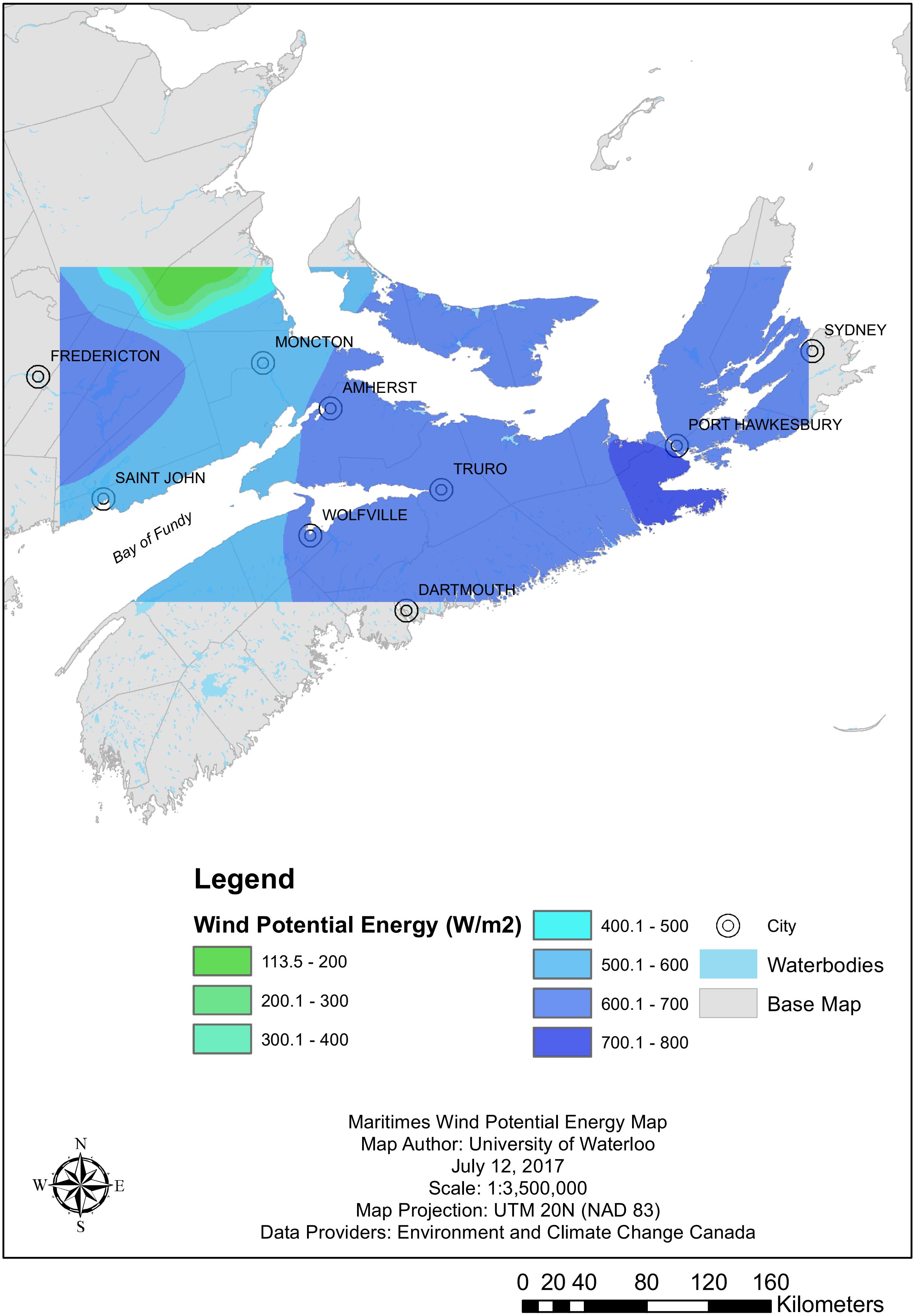
N W E S

0 70 140 280 420 560 Kilometers

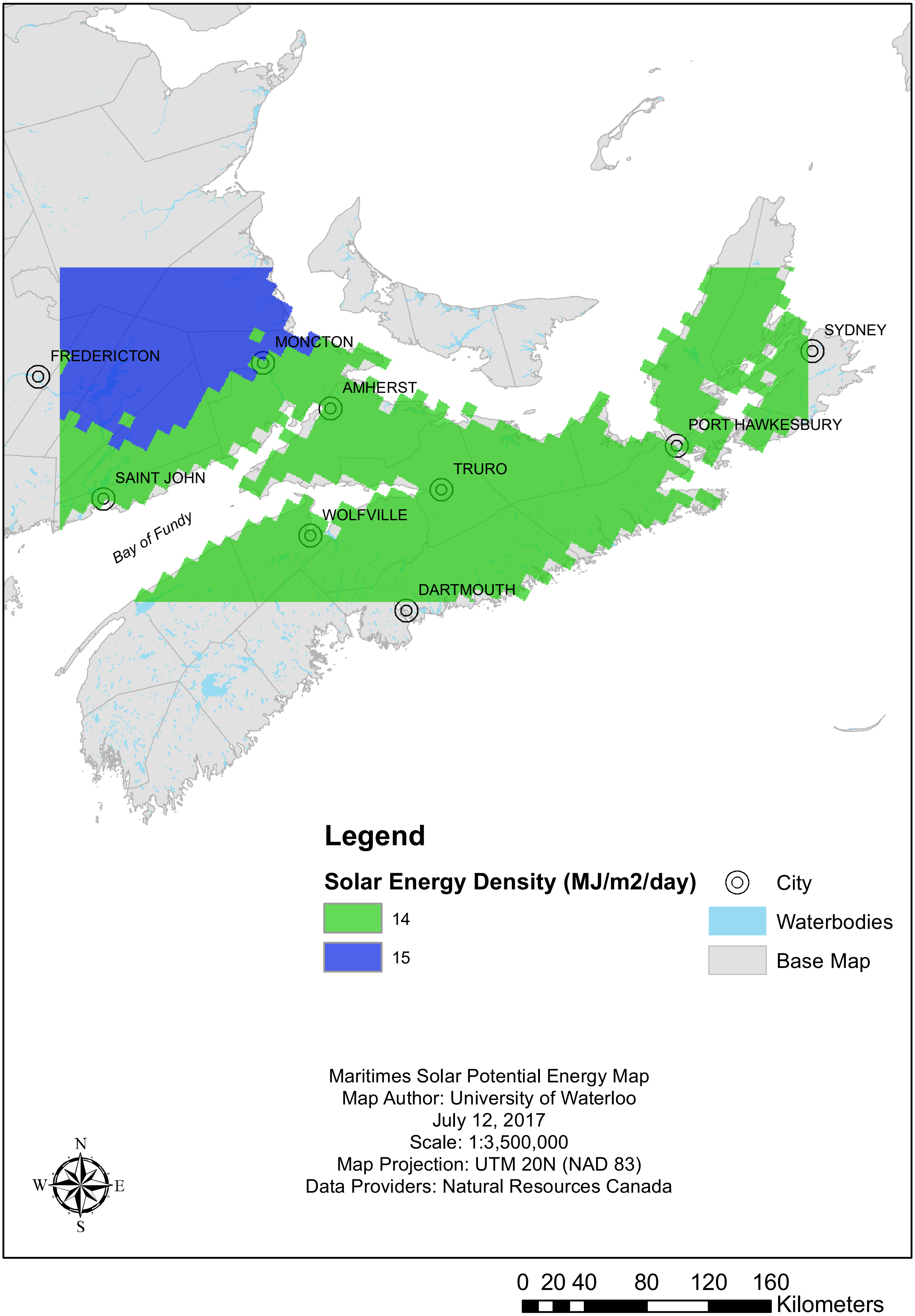
Western Canada Proximity to Natural Gas Pipelines



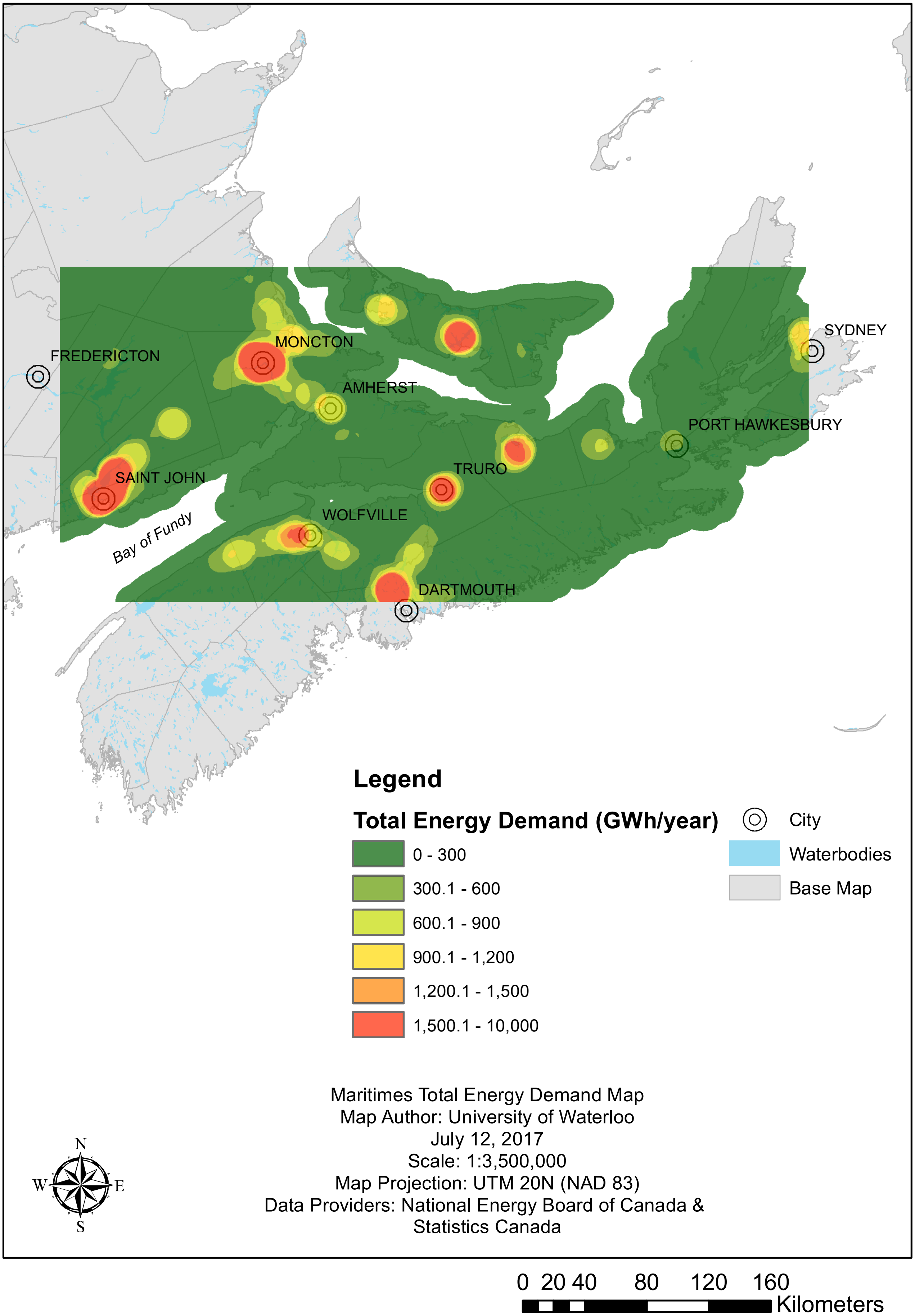
Maritimes Wind Potential Energy Map



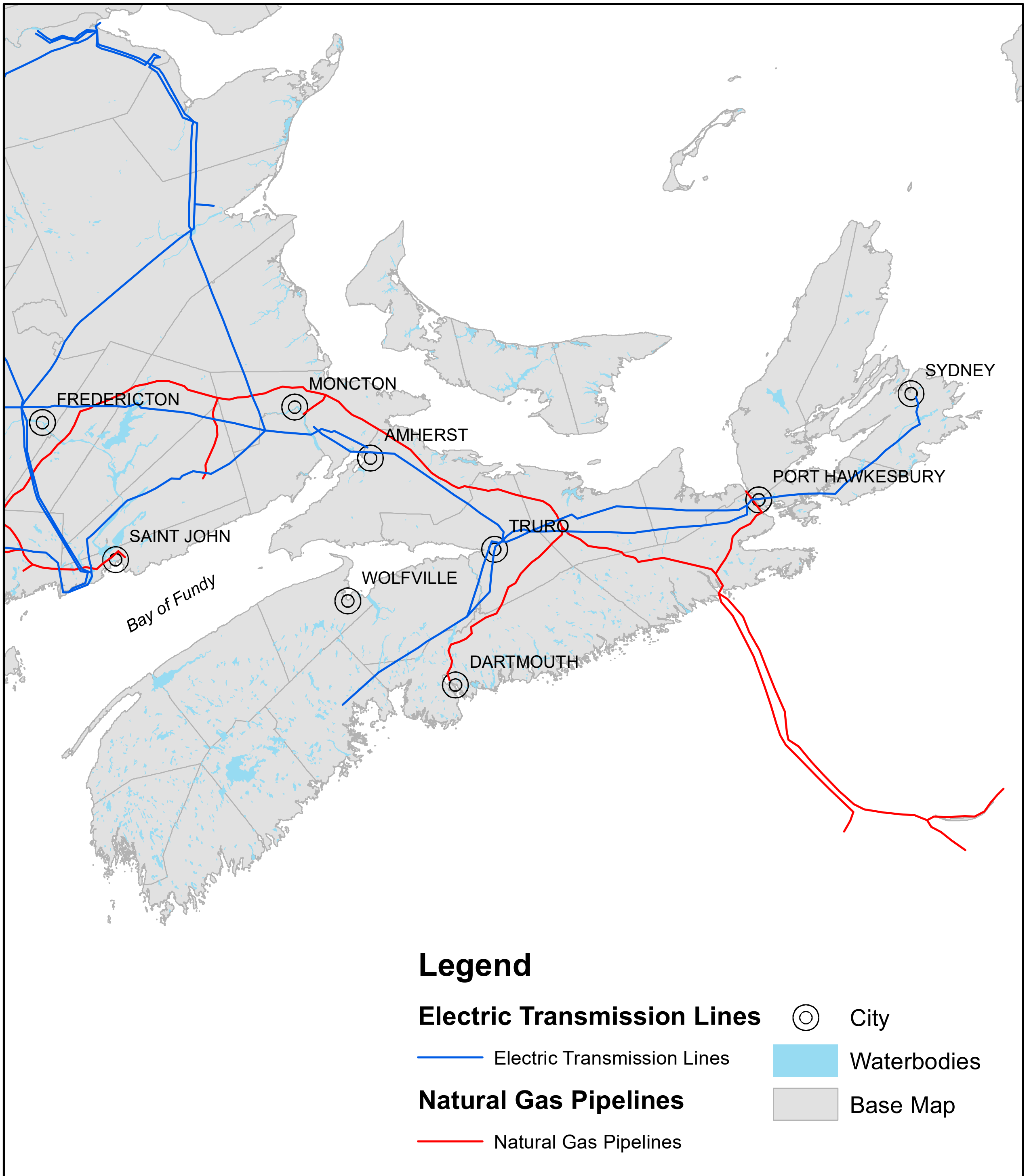
Maritimes Solar Potential Energy Map



Maritimes Total Energy Demand Map



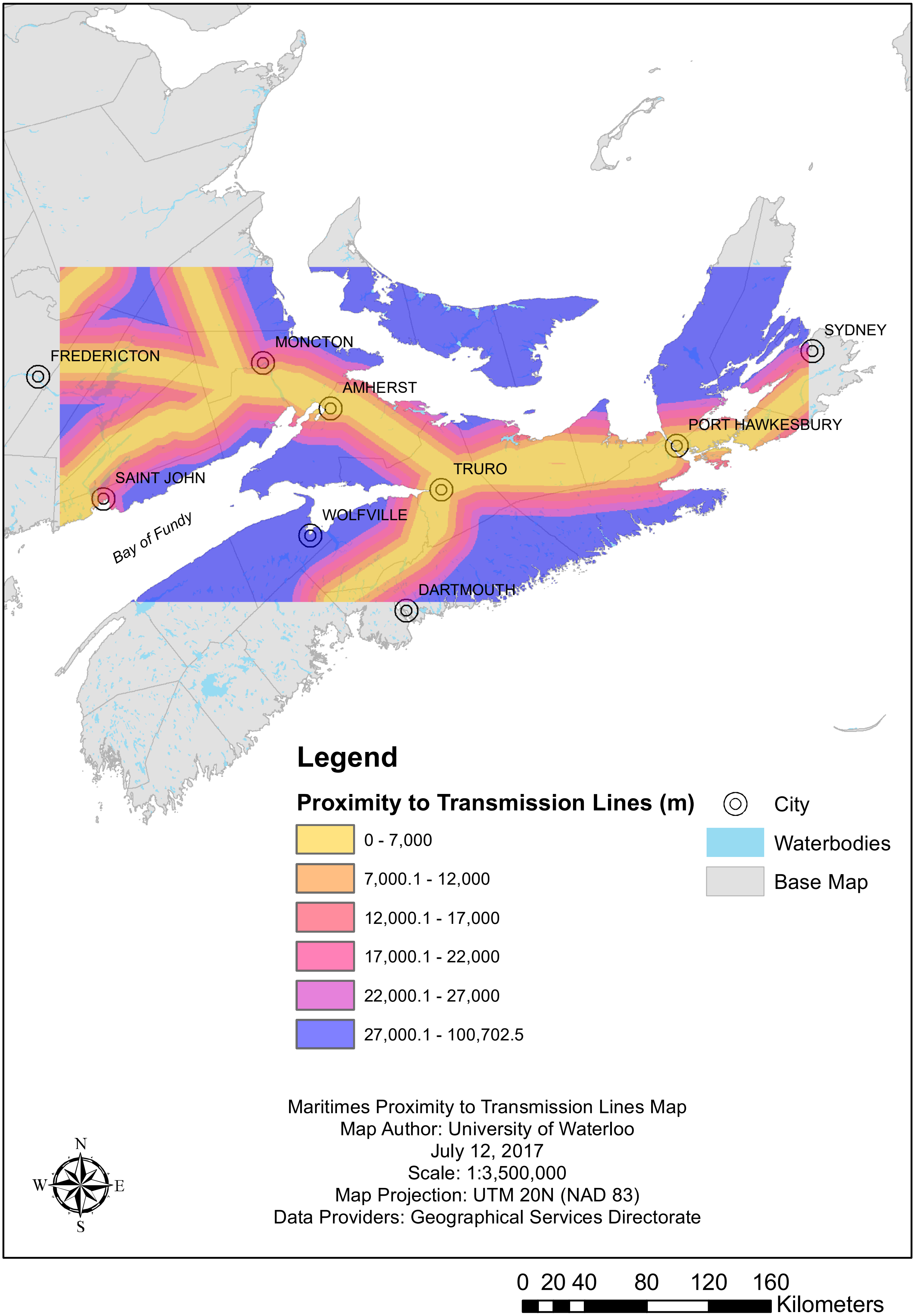
Maritimes Infrastructure Map



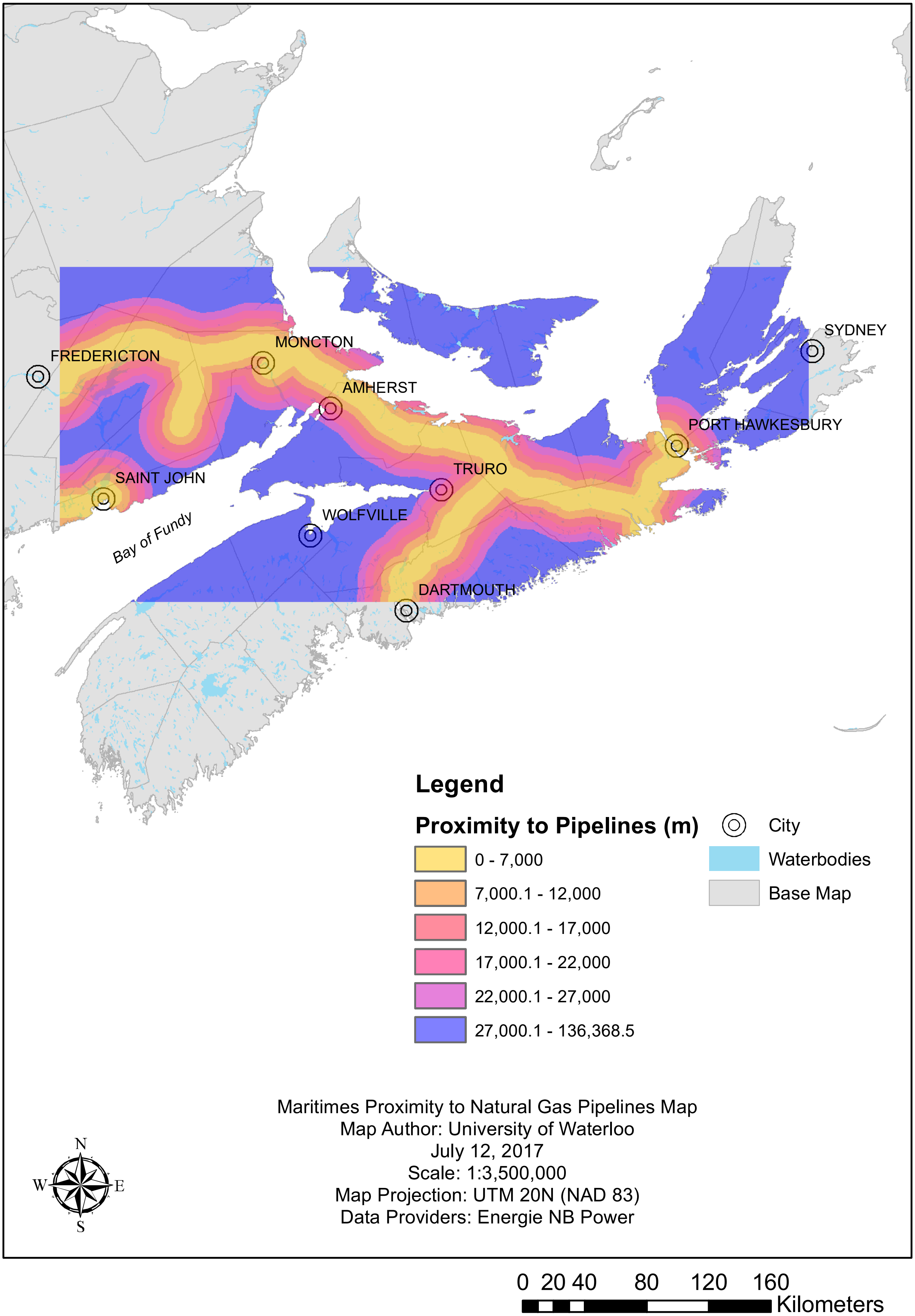
Maritimes Infrastructure Map
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)
Data Providers: Geographical Services Directorate &
Energie NB Power

0 20 40 80 120 160
Kilometers

Maritimes Proximity to Transmission Lines Map

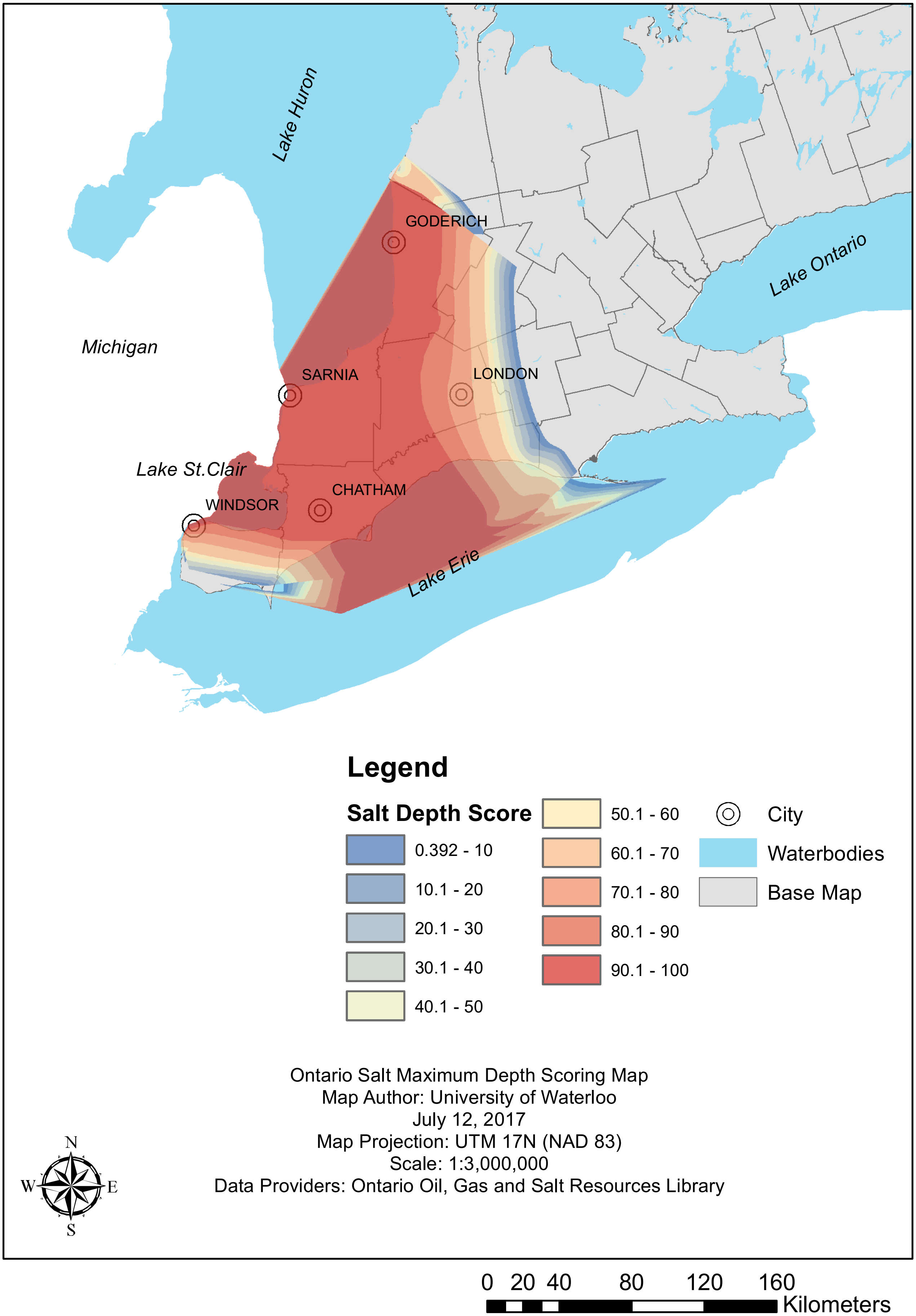


Maritimes Proximity to Natural Gas Pipelines Map

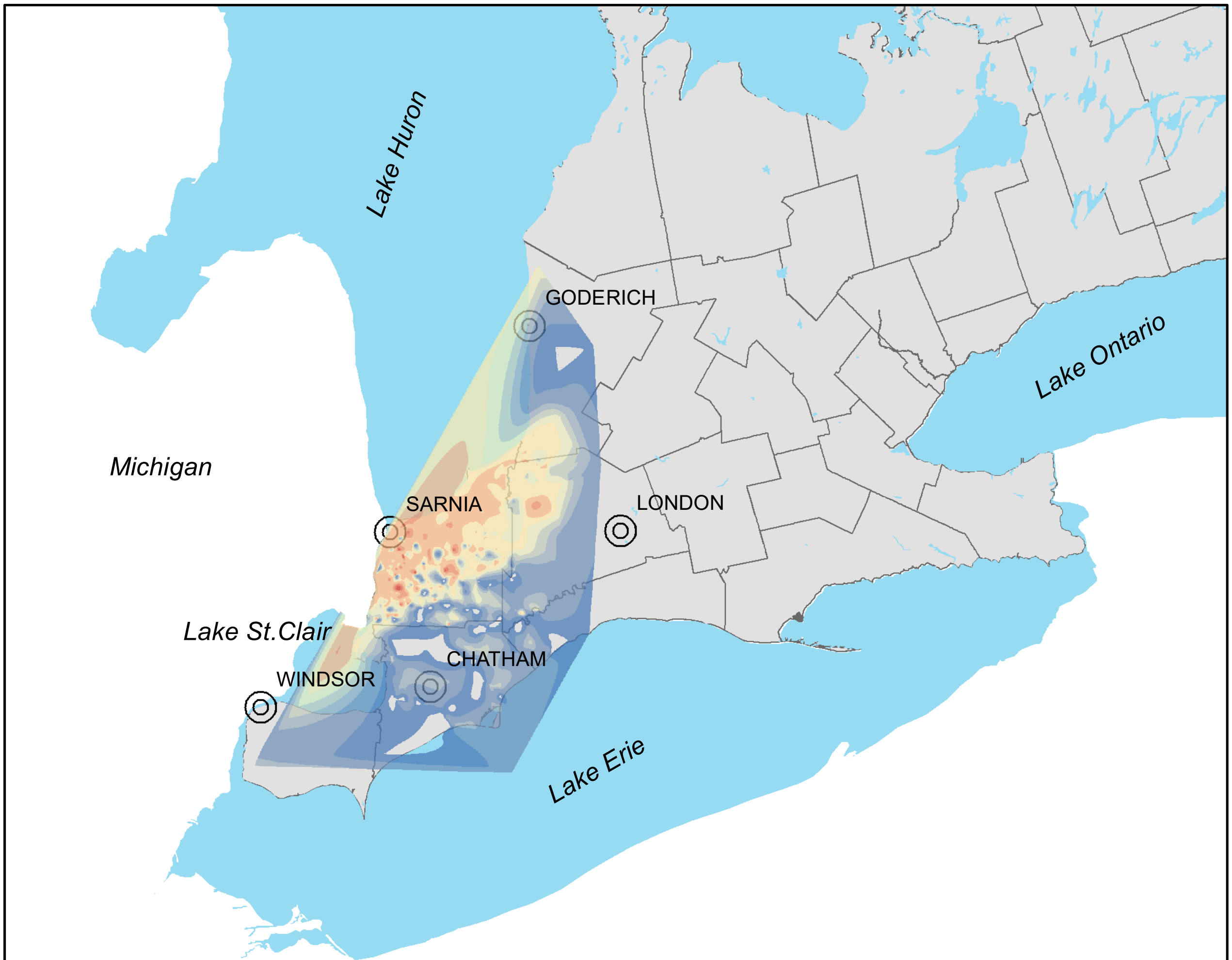


Appendix B: Multi-Criteria Analysis Scoring Maps

Ontario Salt Maximum Depth Scoring Map



Ontario Salt Maximum Thickness Scoring Map



Legend

Salt Thickness Score

- 0.392 - 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

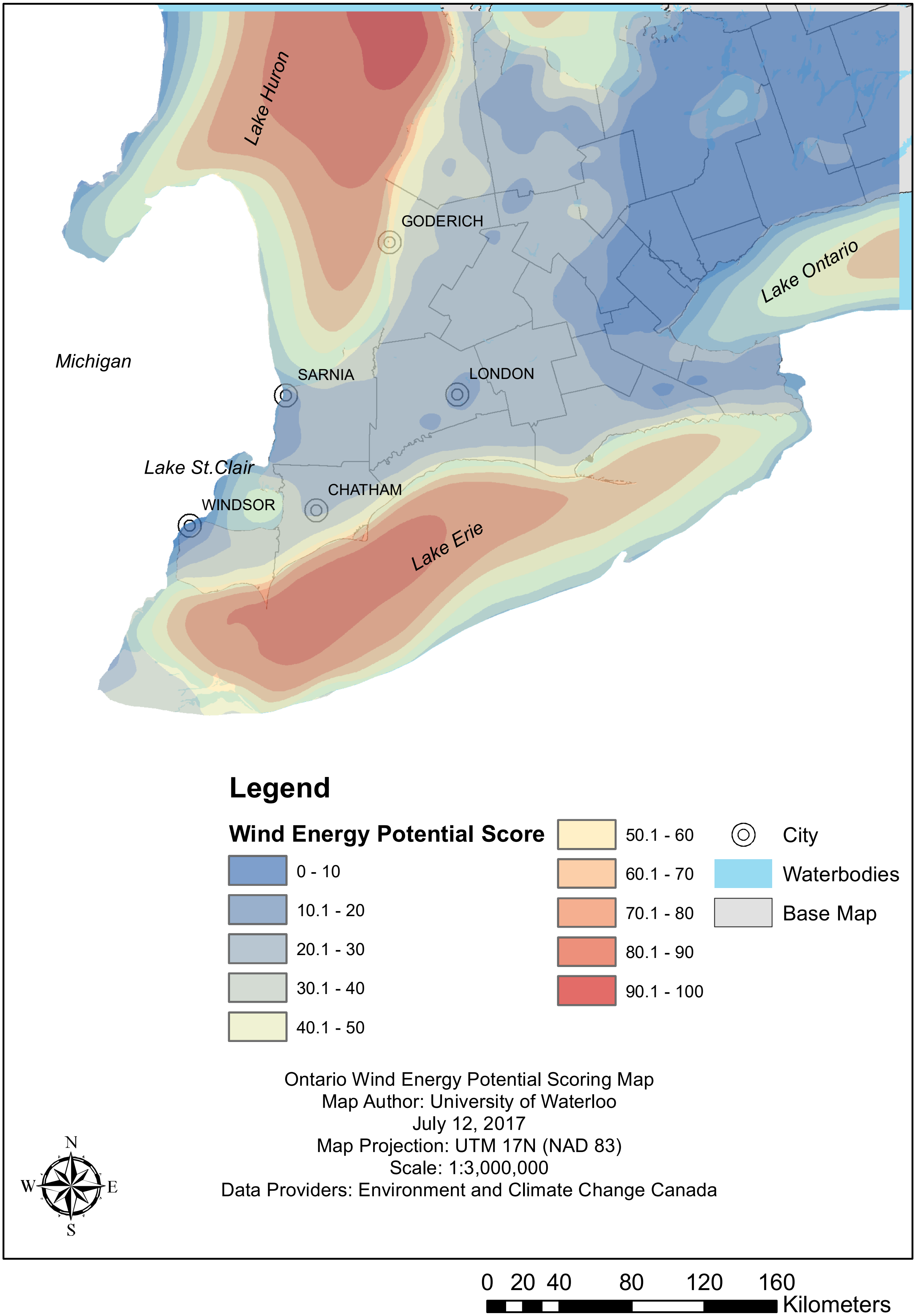
- City
- Waterbodies
- Base Map

Ontario Salt Maximum Thickness Scoring Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 17N (NAD 83)
Scale: 1:3,000,000
Data Providers: Ontario Oil, Gas and Salt Resources Library

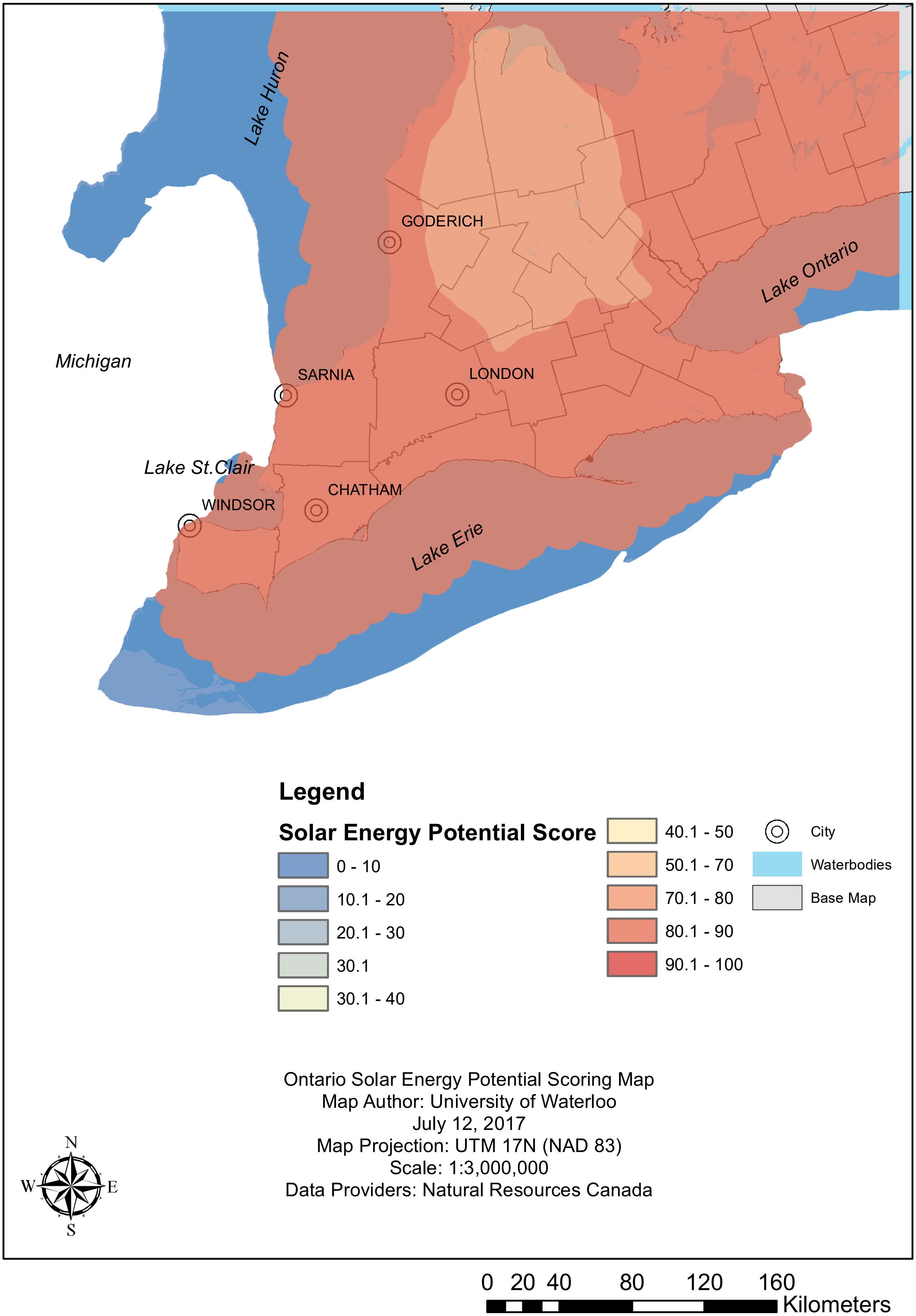
N W E S

0 20 40 80 120 160 Kilometers

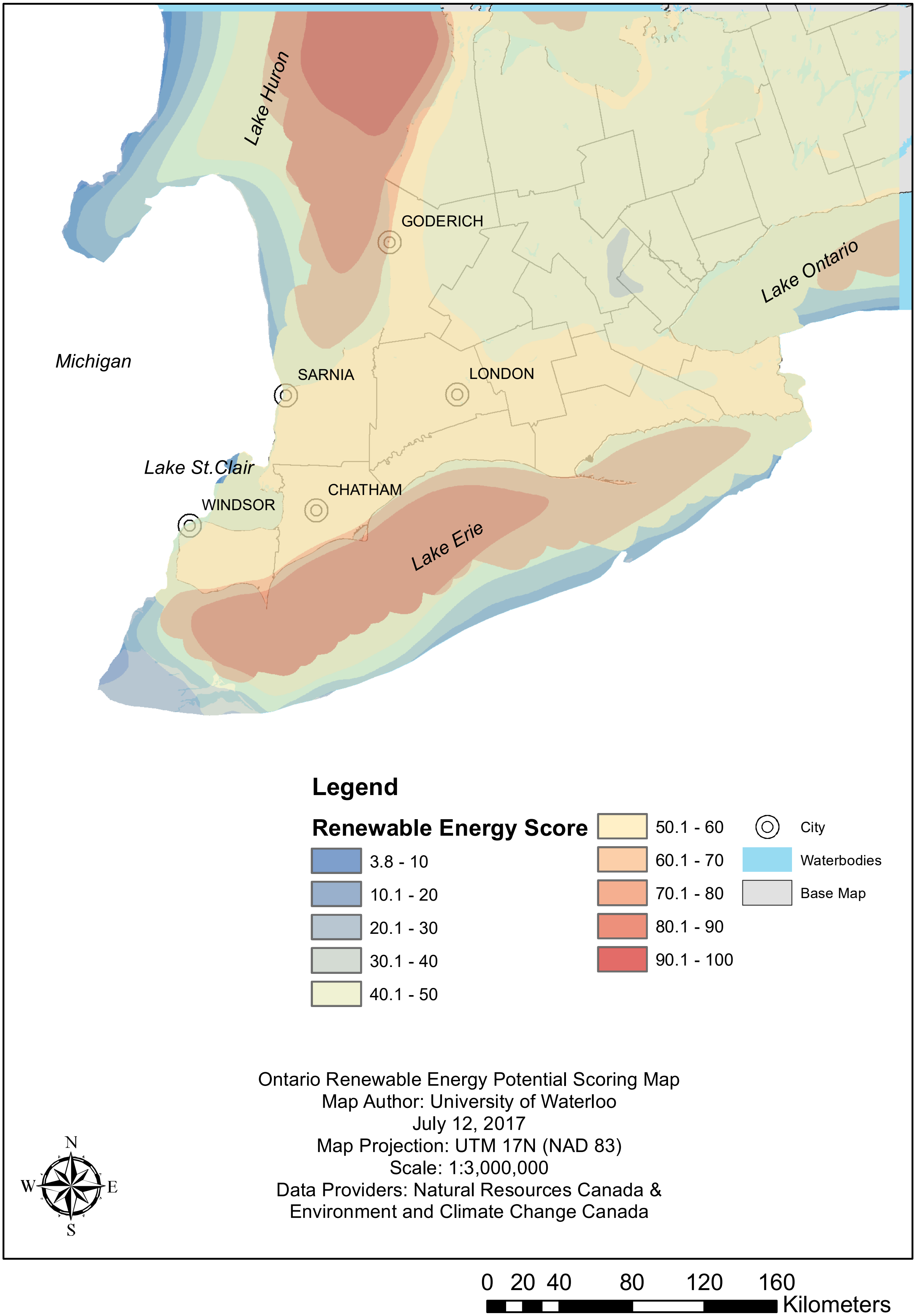
Ontario Wind Energy Potential Scoring Map



Ontario Solar Energy Potential Scoring Map

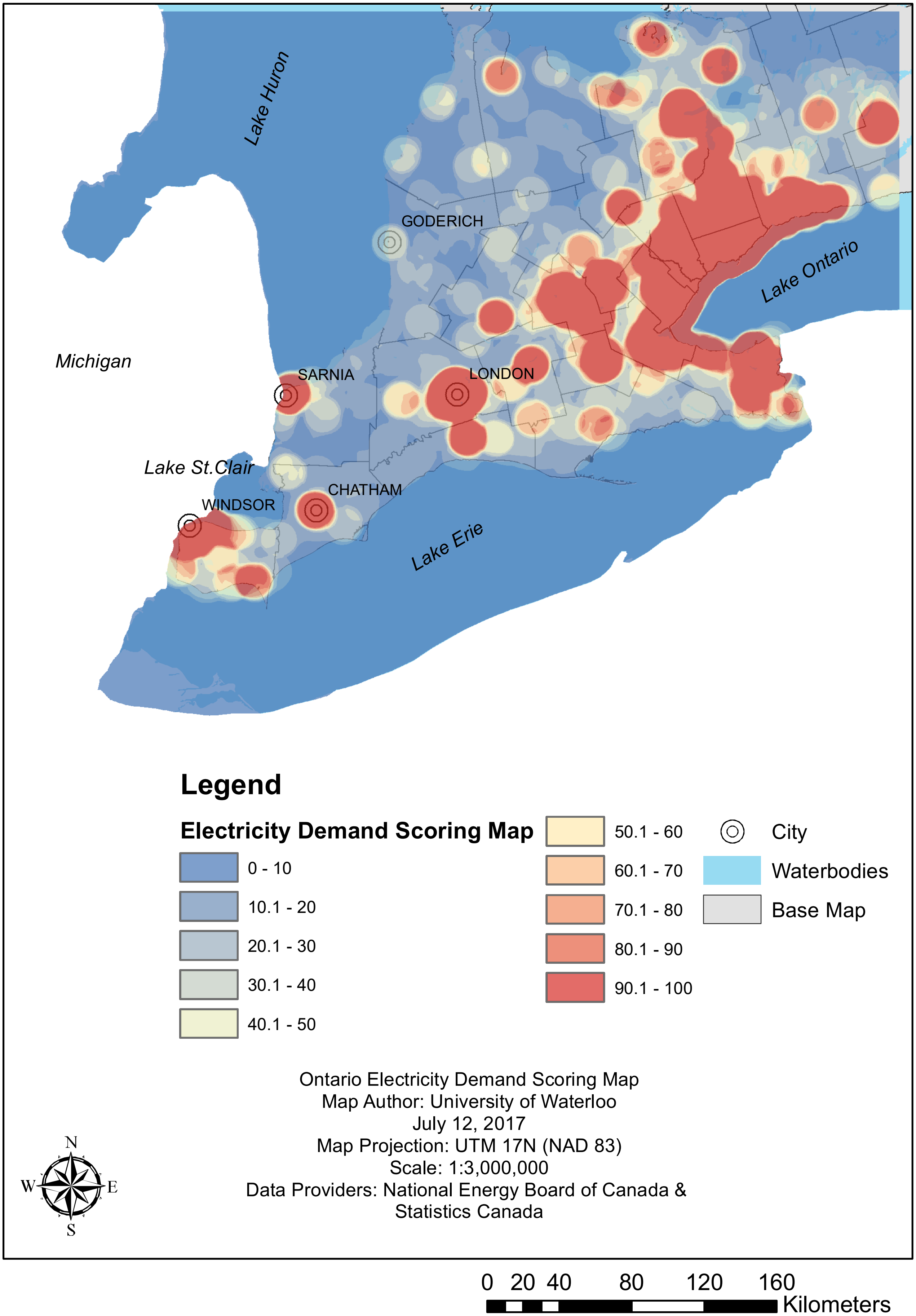


Ontario Renewable Energy Potential Scoring Map

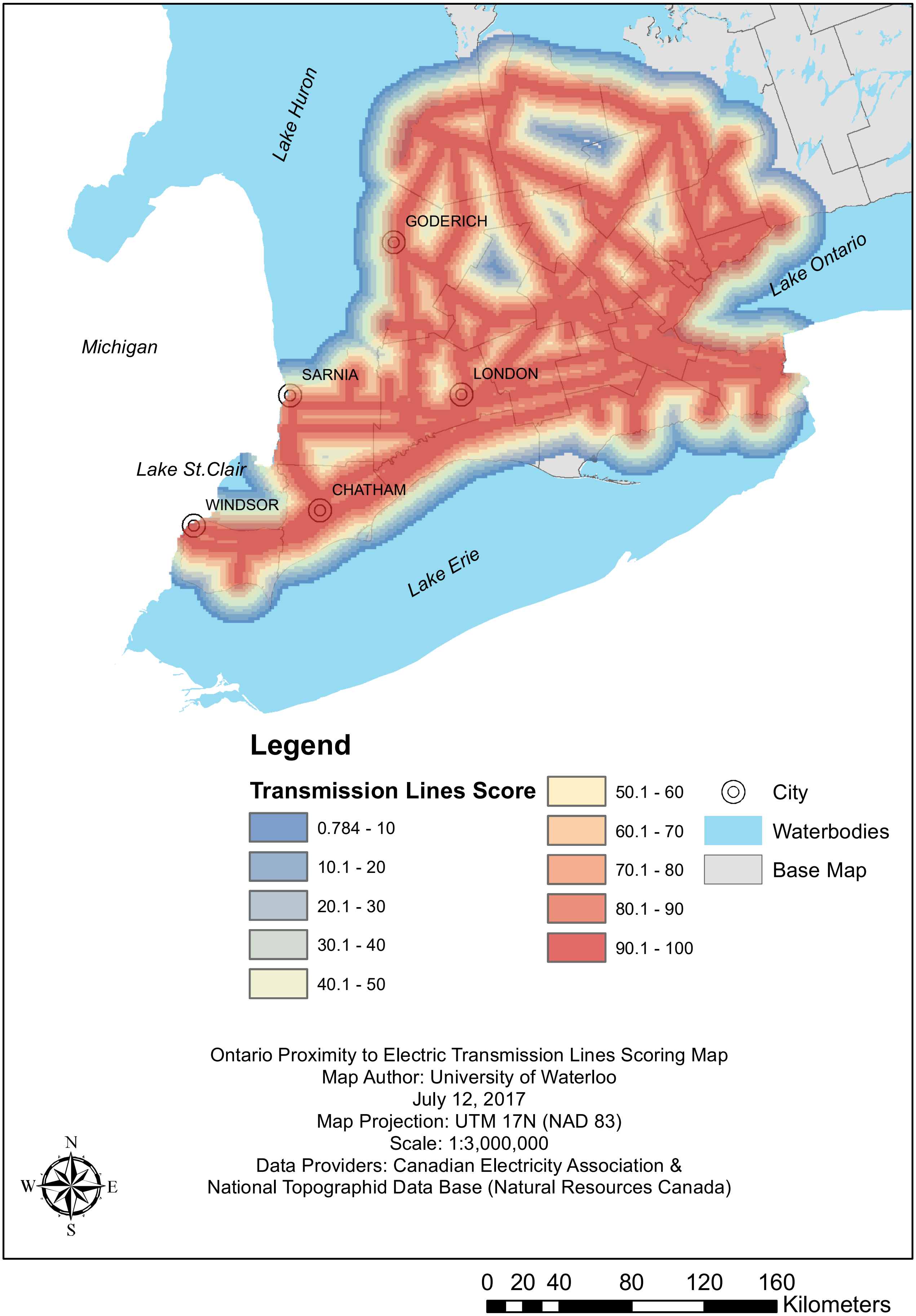


Ontario Renewable Energy Potential Scoring Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 17N (NAD 83)
Scale: 1:3,000,000
Data Providers: Natural Resources Canada & Environment and Climate Change Canada

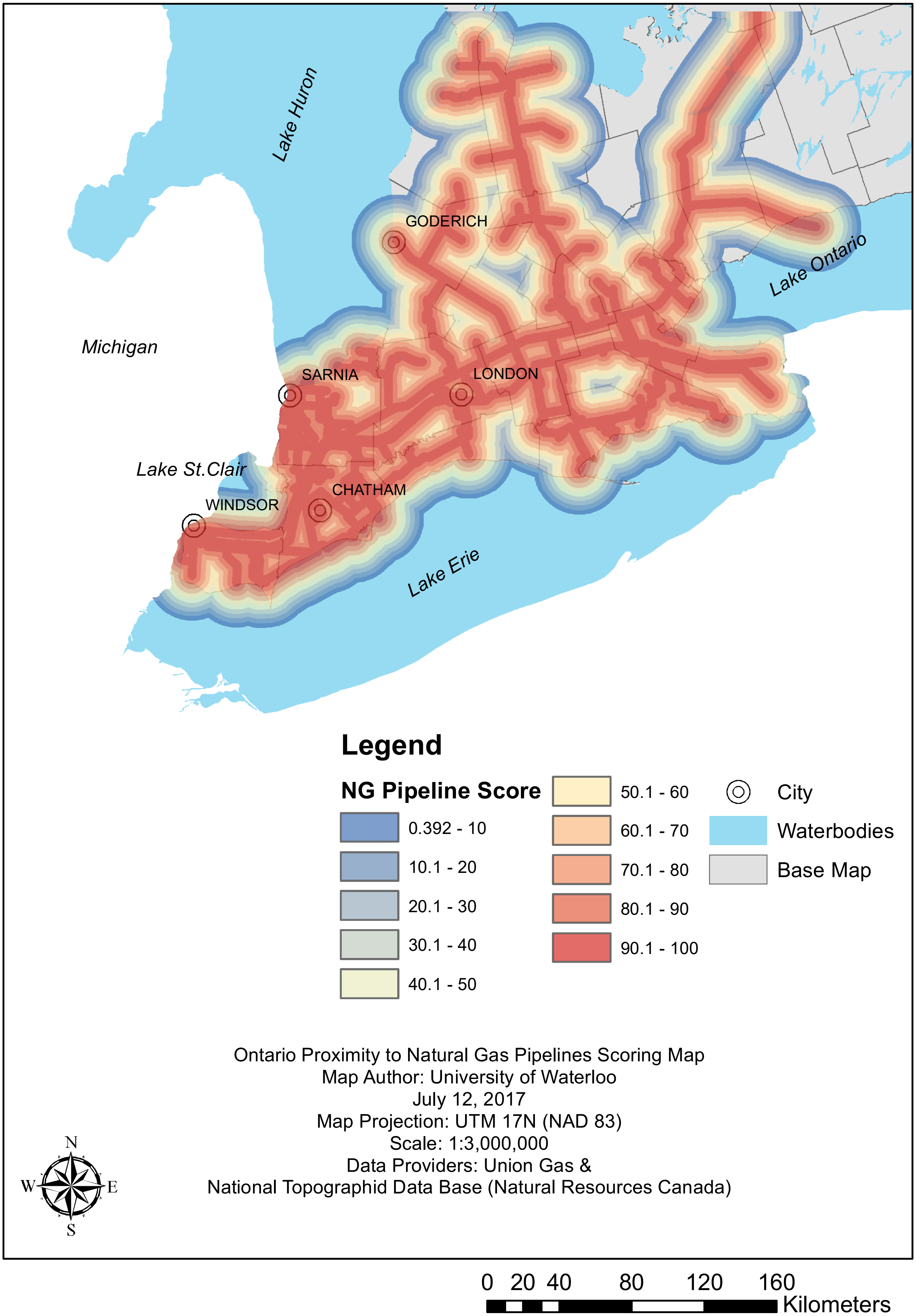
Ontario Electricity Demand Scoring Map



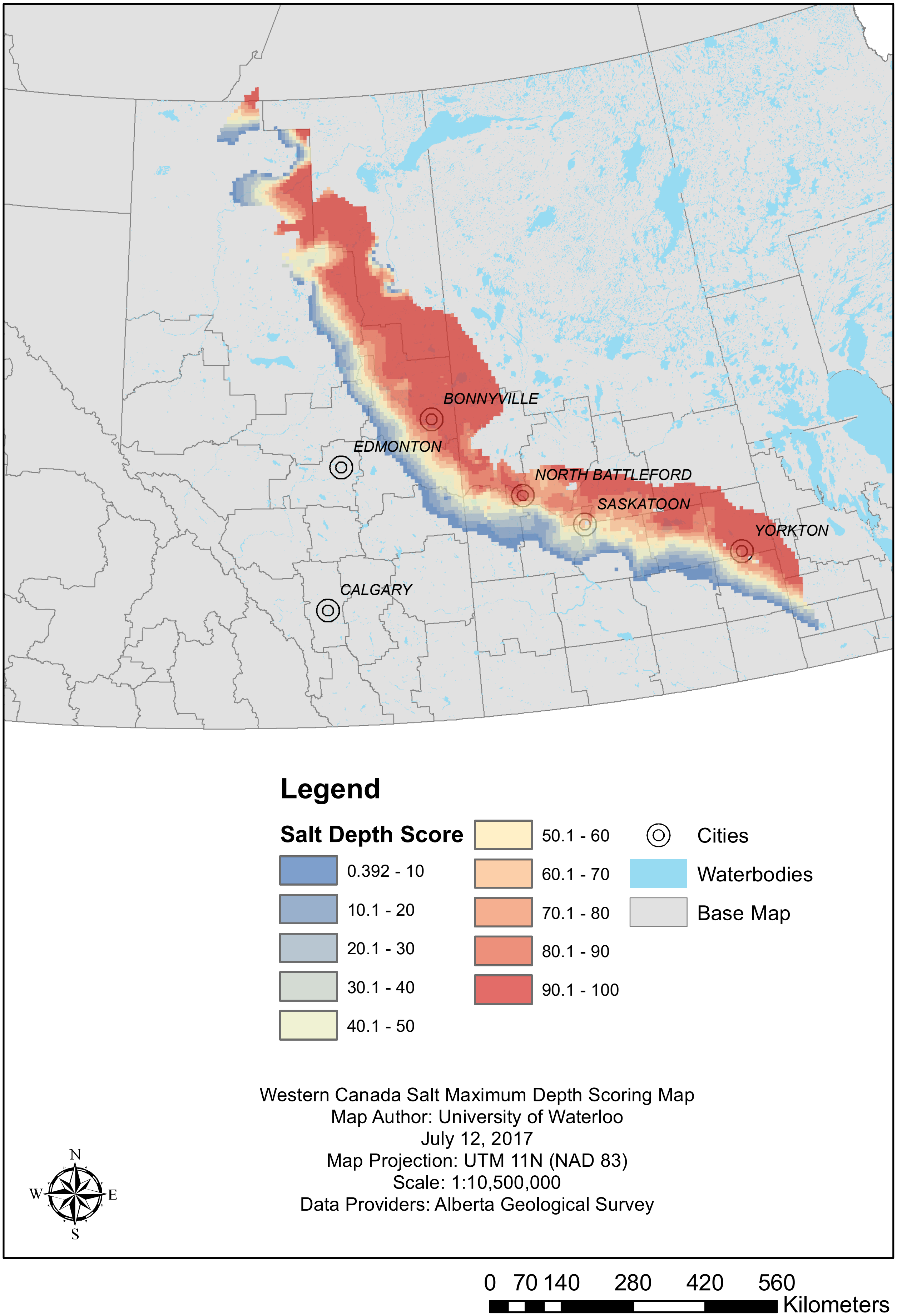
Ontario Proximity to Electric Transmission Lines Scoring Map



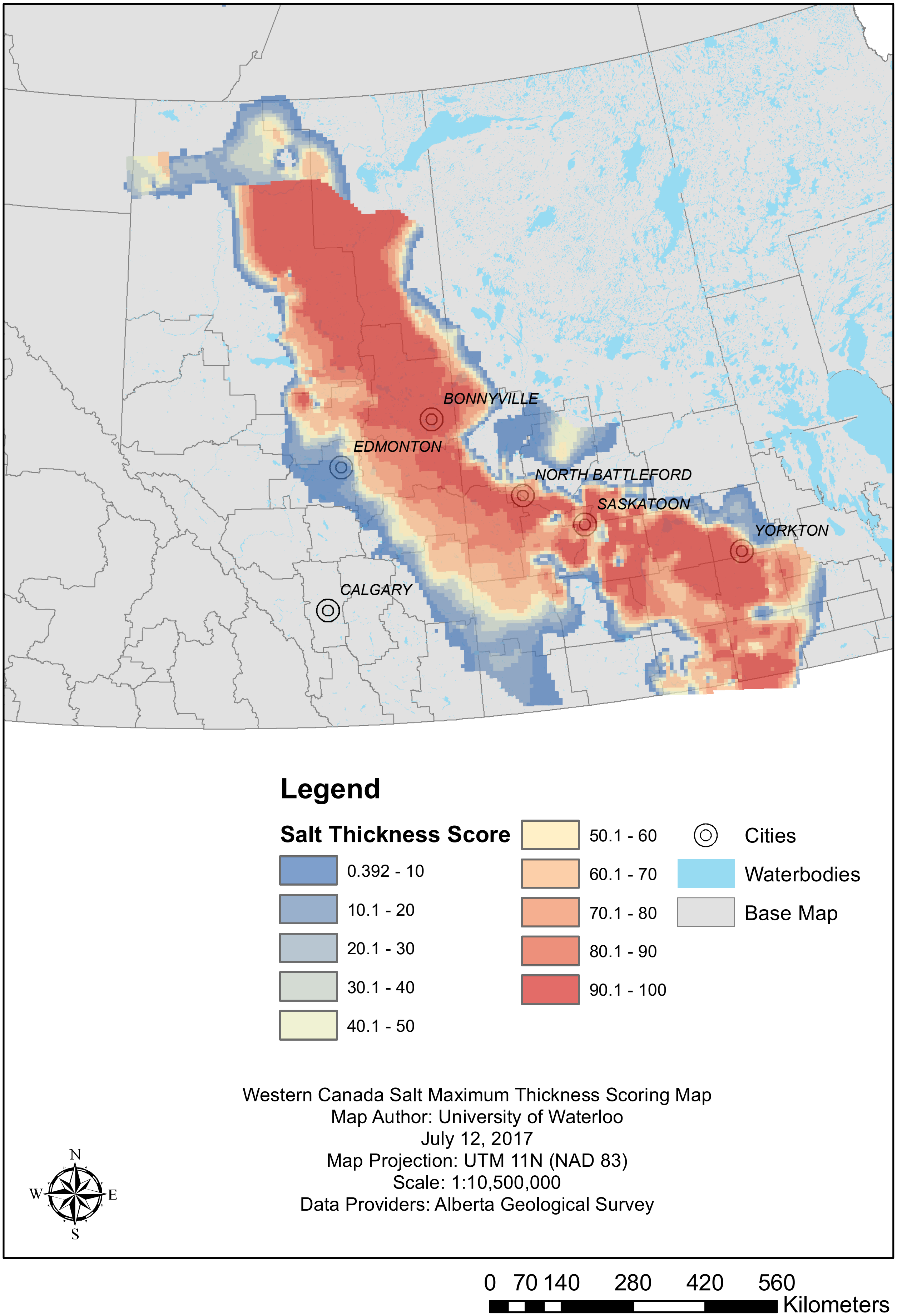
Ontario Proximity to Natural Gas Pipelines Scoring Map



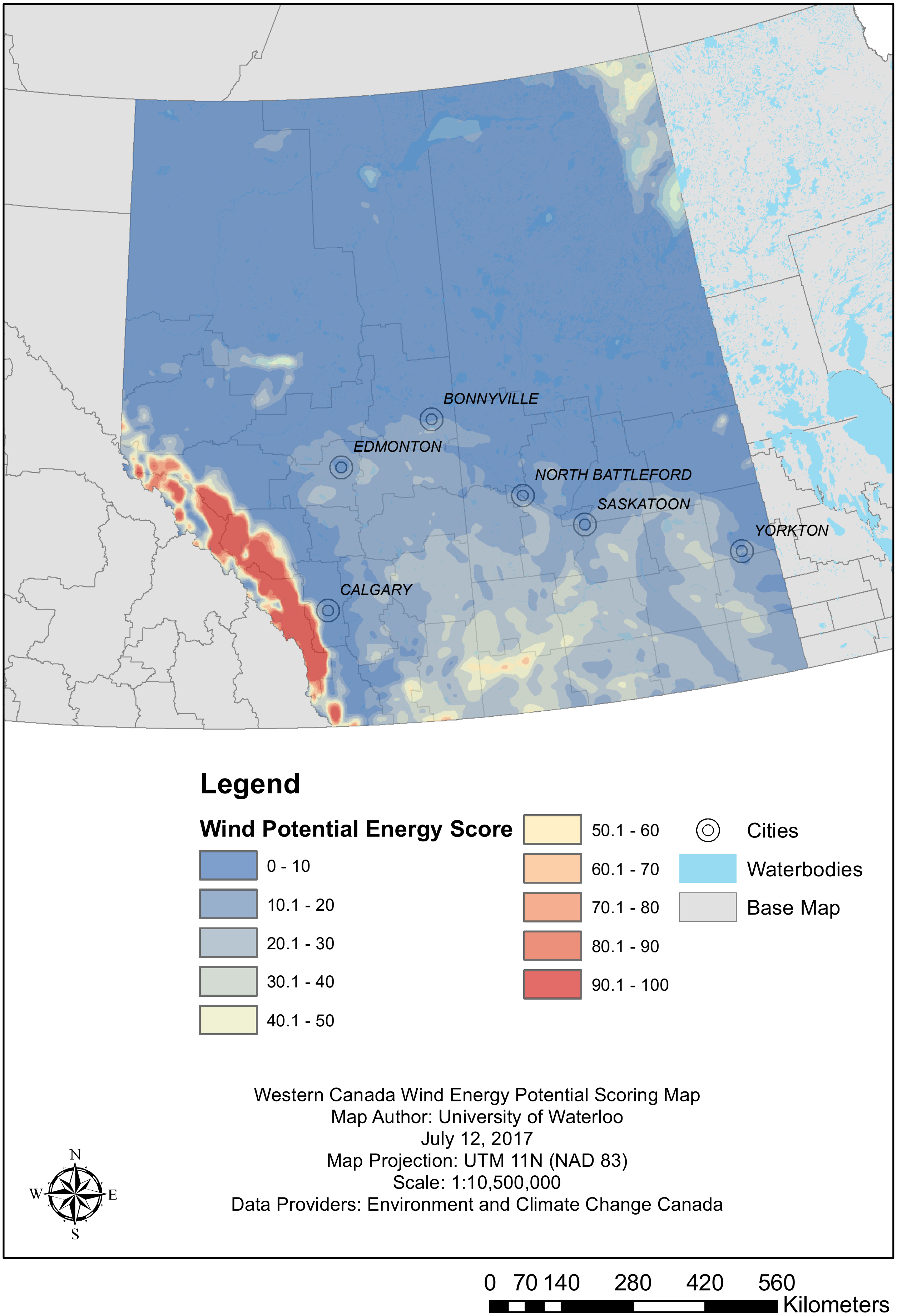
Western Canada Salt Maximum Depth Scoring Map



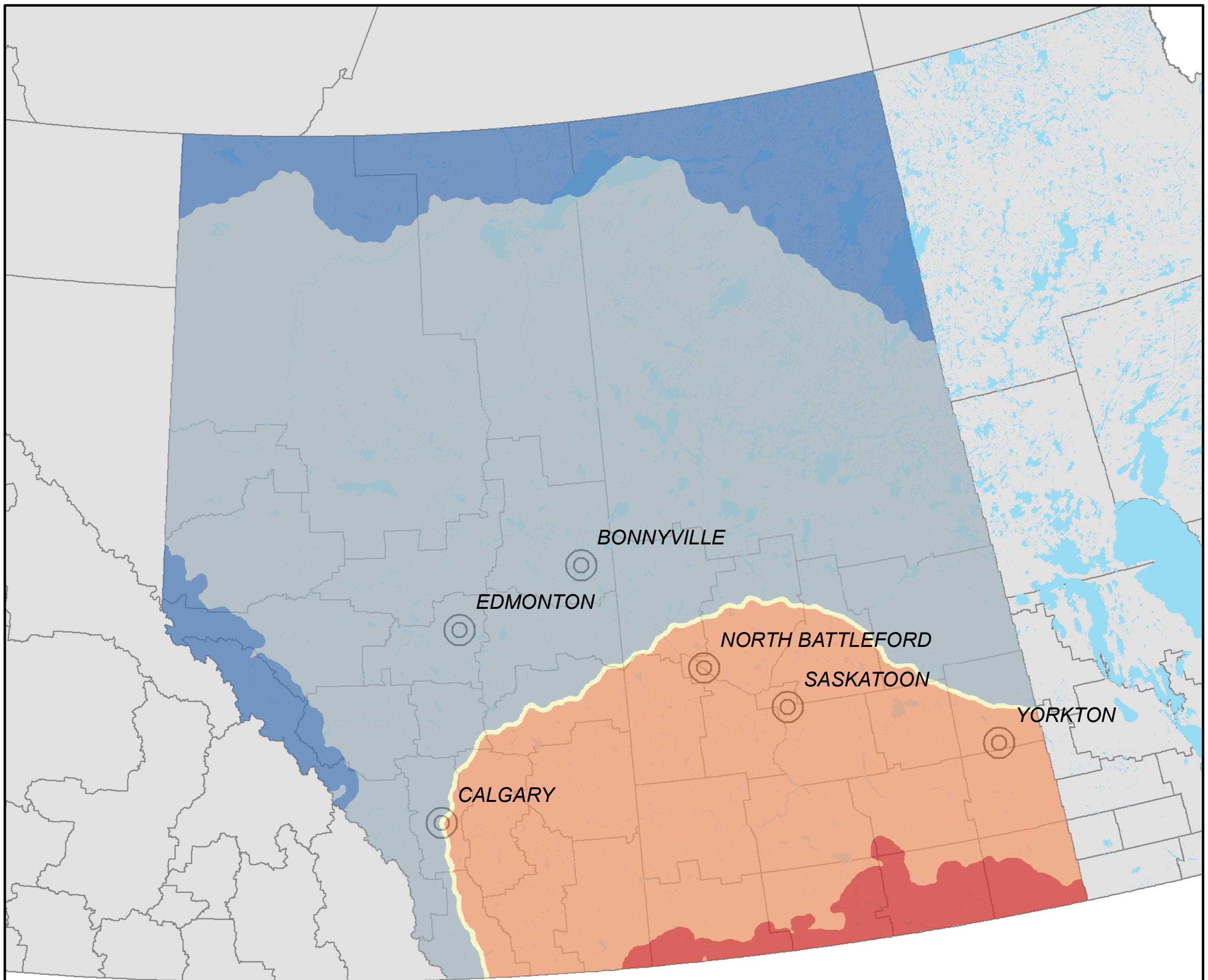
Western Canada Salt Maximum Thickness Scoring Map



Western Canada Wind Energy Potential Scoring Map



Western Canada Solar Energy Potential Scoring Map



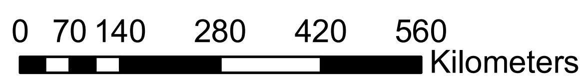
Legend

Solar Potential Energy Score

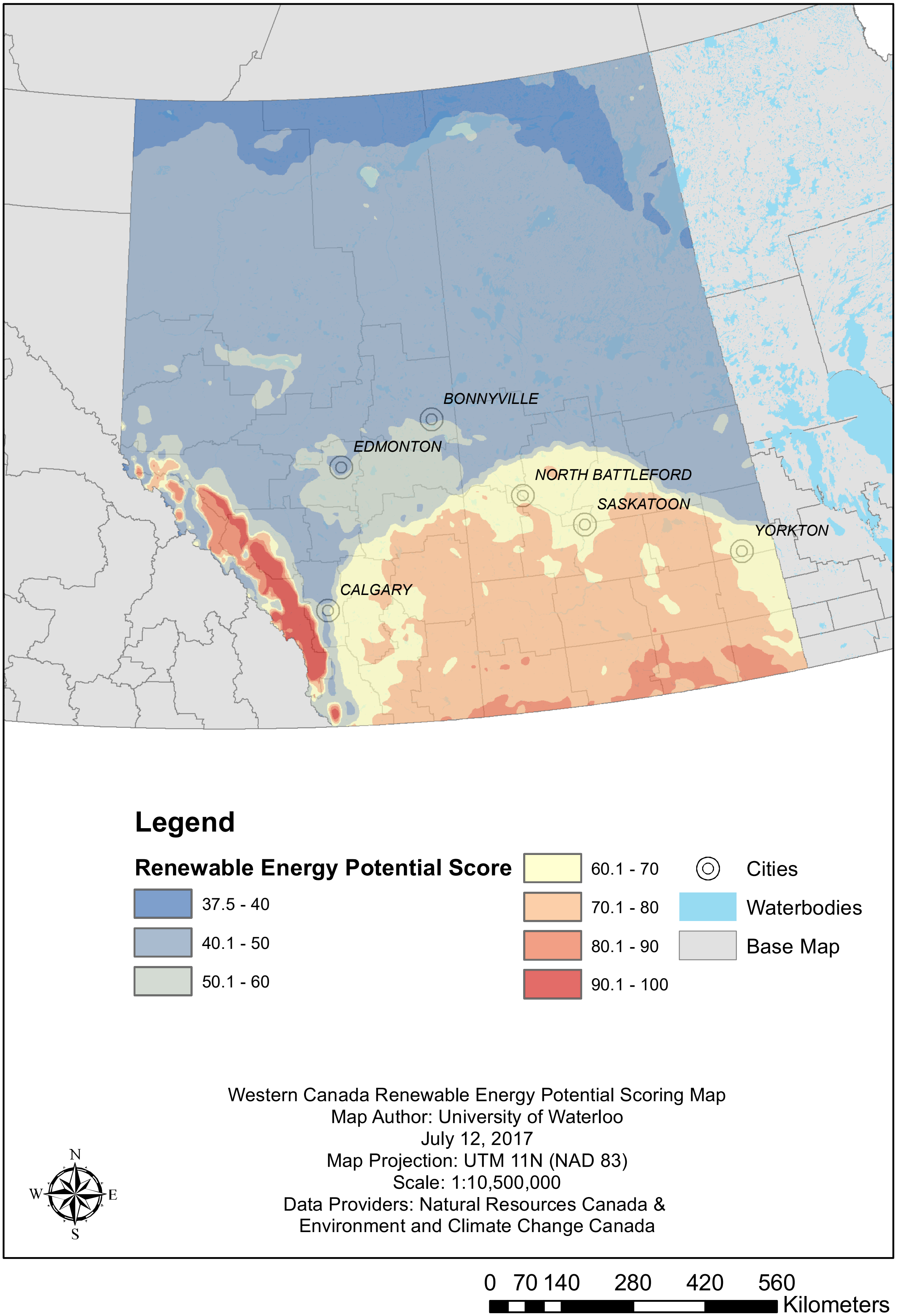
- 50 - 60
- 60.1 - 70
- 70.1 - 80
- 80.1 - 90
- 90.1 - 100

- Cities
- Waterbodies
- Base Map

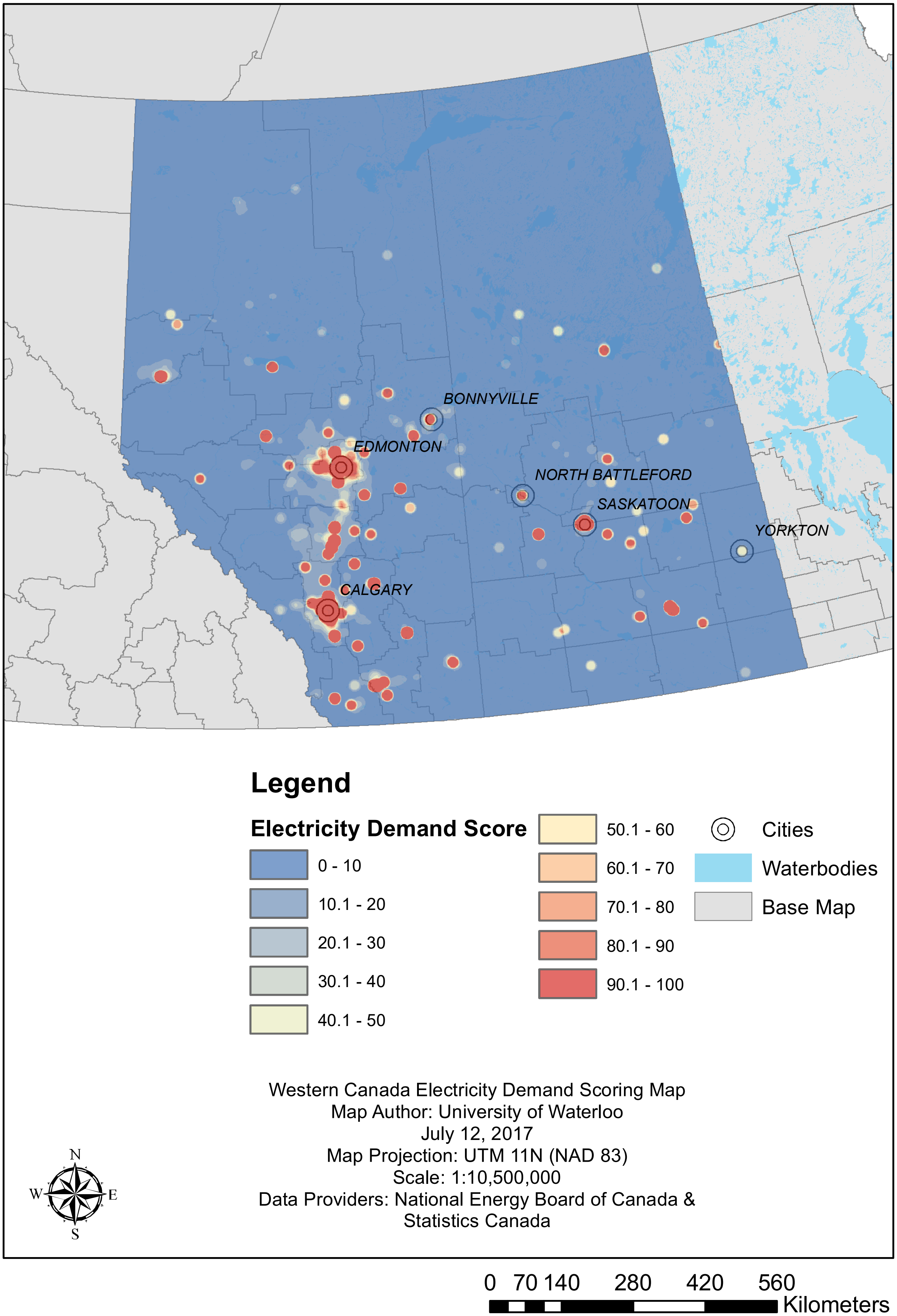
Western Canada Solar Energy Potential Scoring Map
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000
Data Providers: Natural Resources Canada



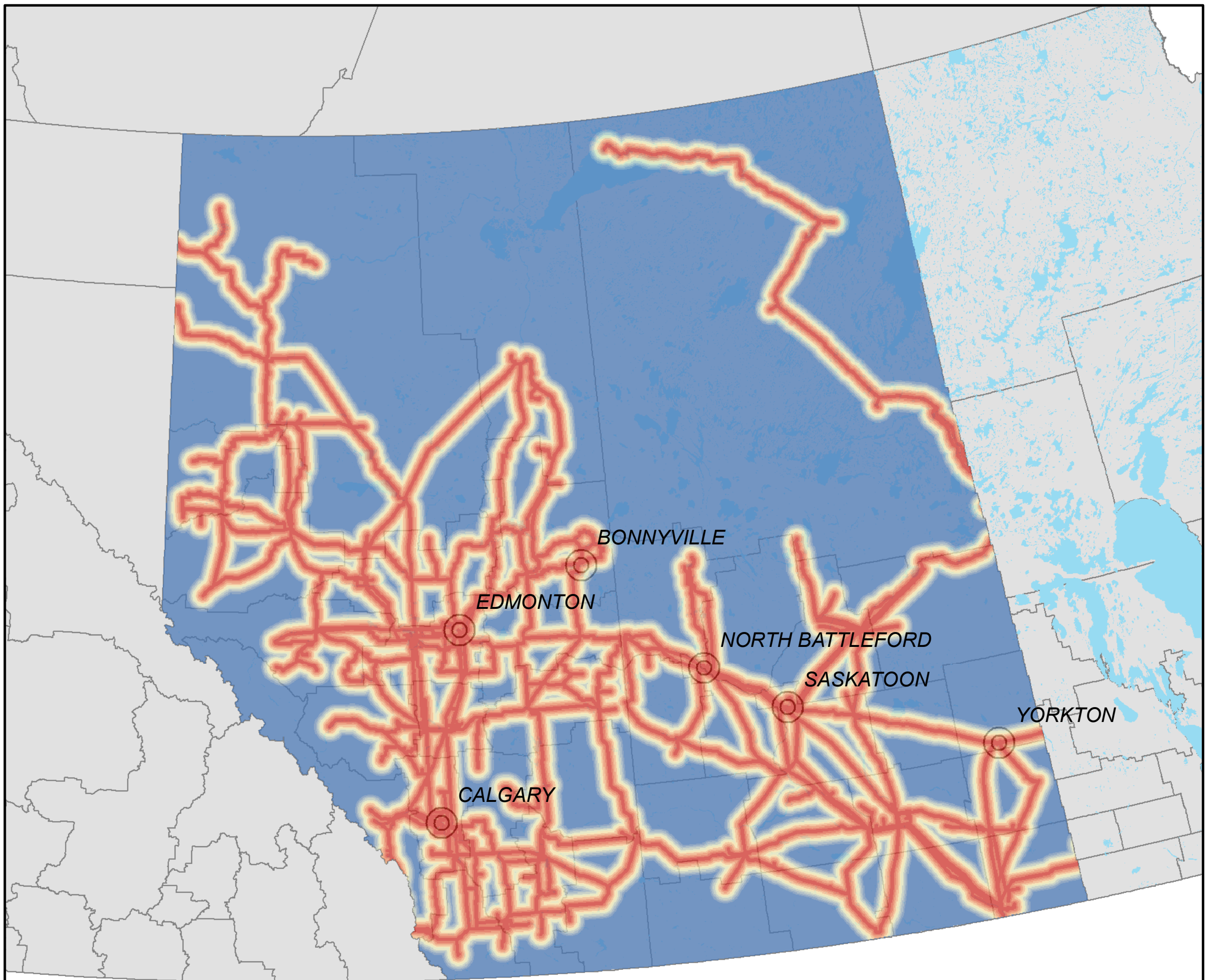
Western Canada Renewable Energy Potential Scoring Map



Western Canada Electricity Demand Scoring Map



Western Canada
Proximity to Electric Transmission Lines Scoring Map



Legend

Transmission Line 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

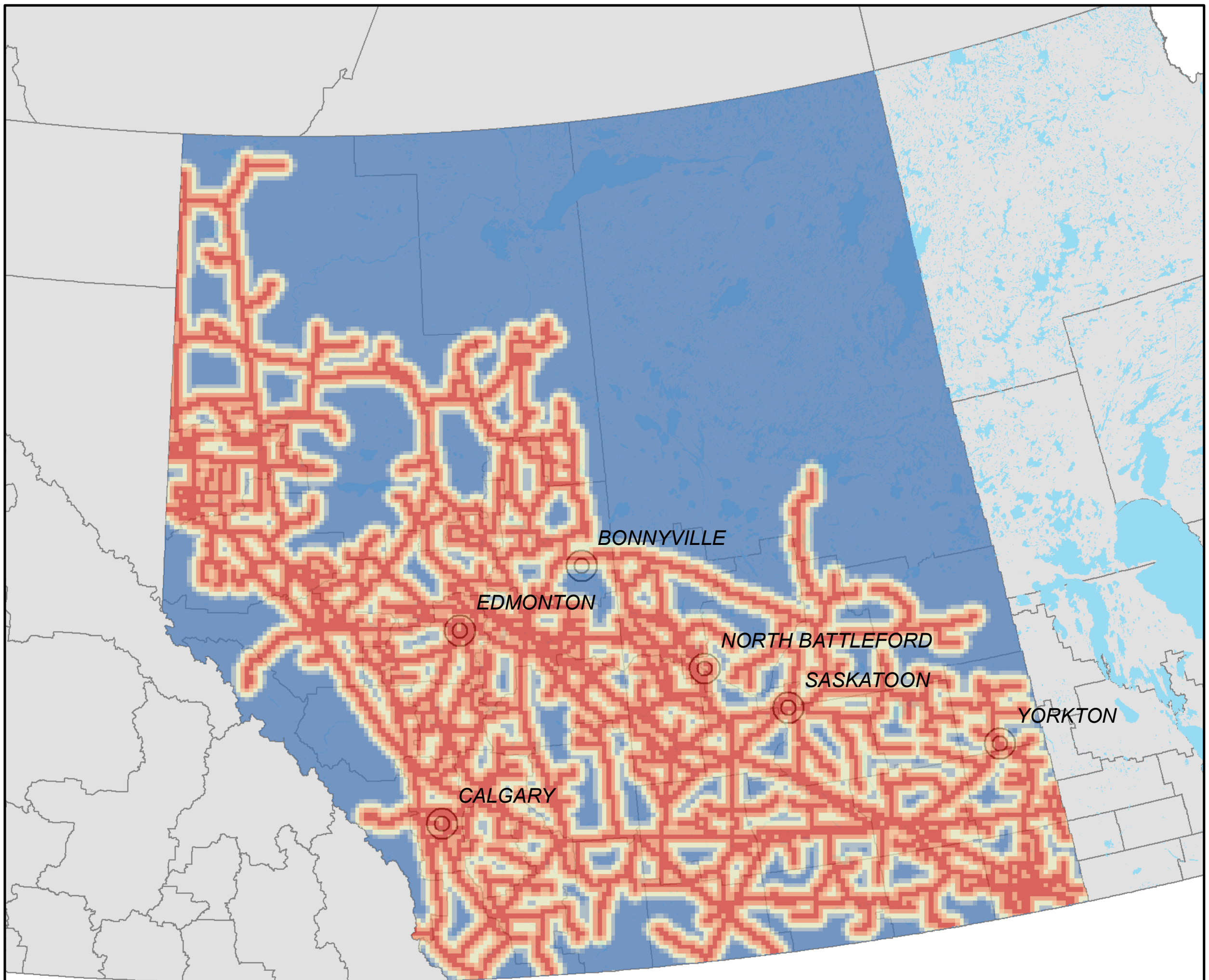
- Cities
- Waterbodies
- Base Map

Western Canada Proximity to Electric Transmission Lines Scoring 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 Scoring Map



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

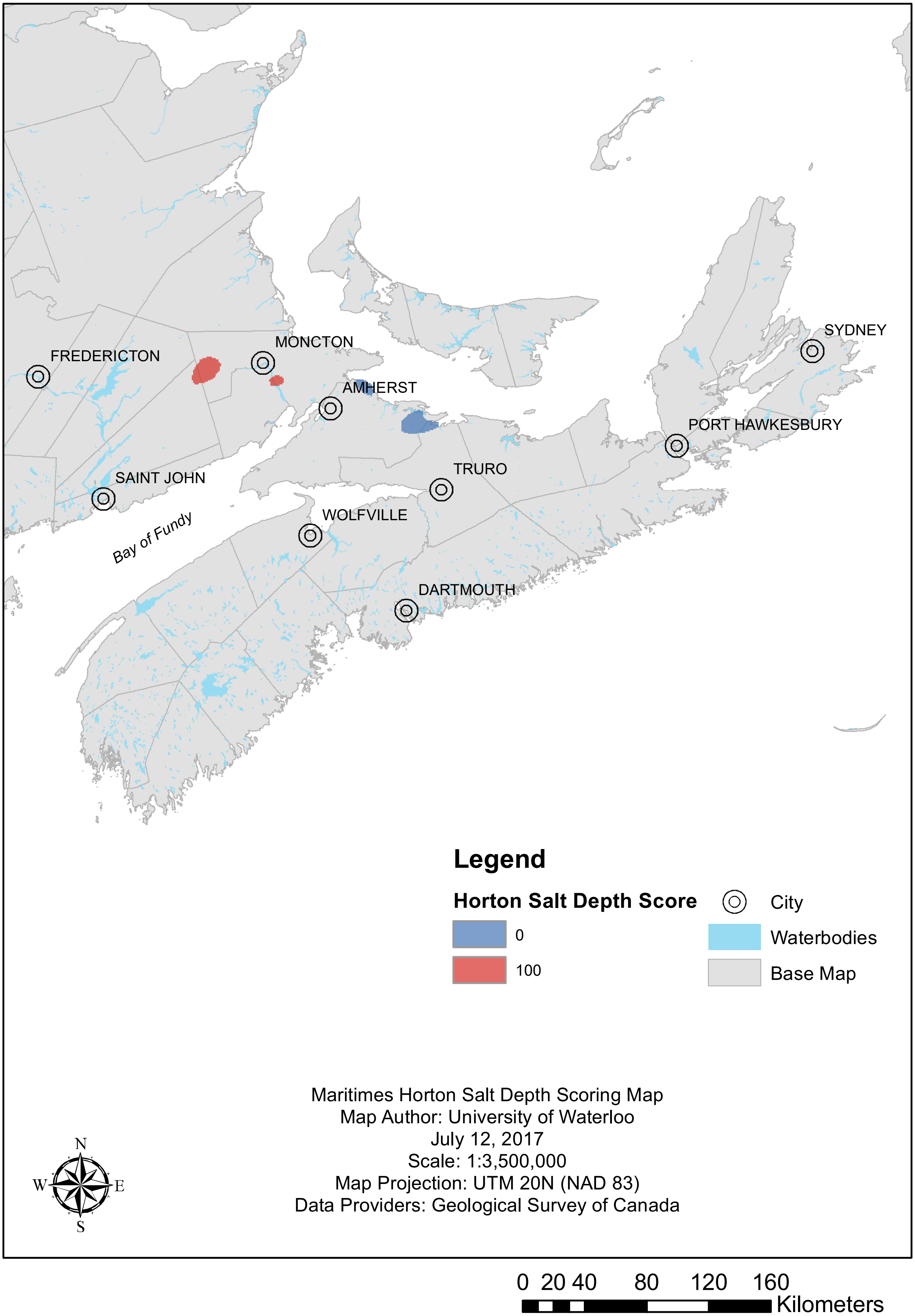
- Cities
- Waterbodies
- Base Map

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

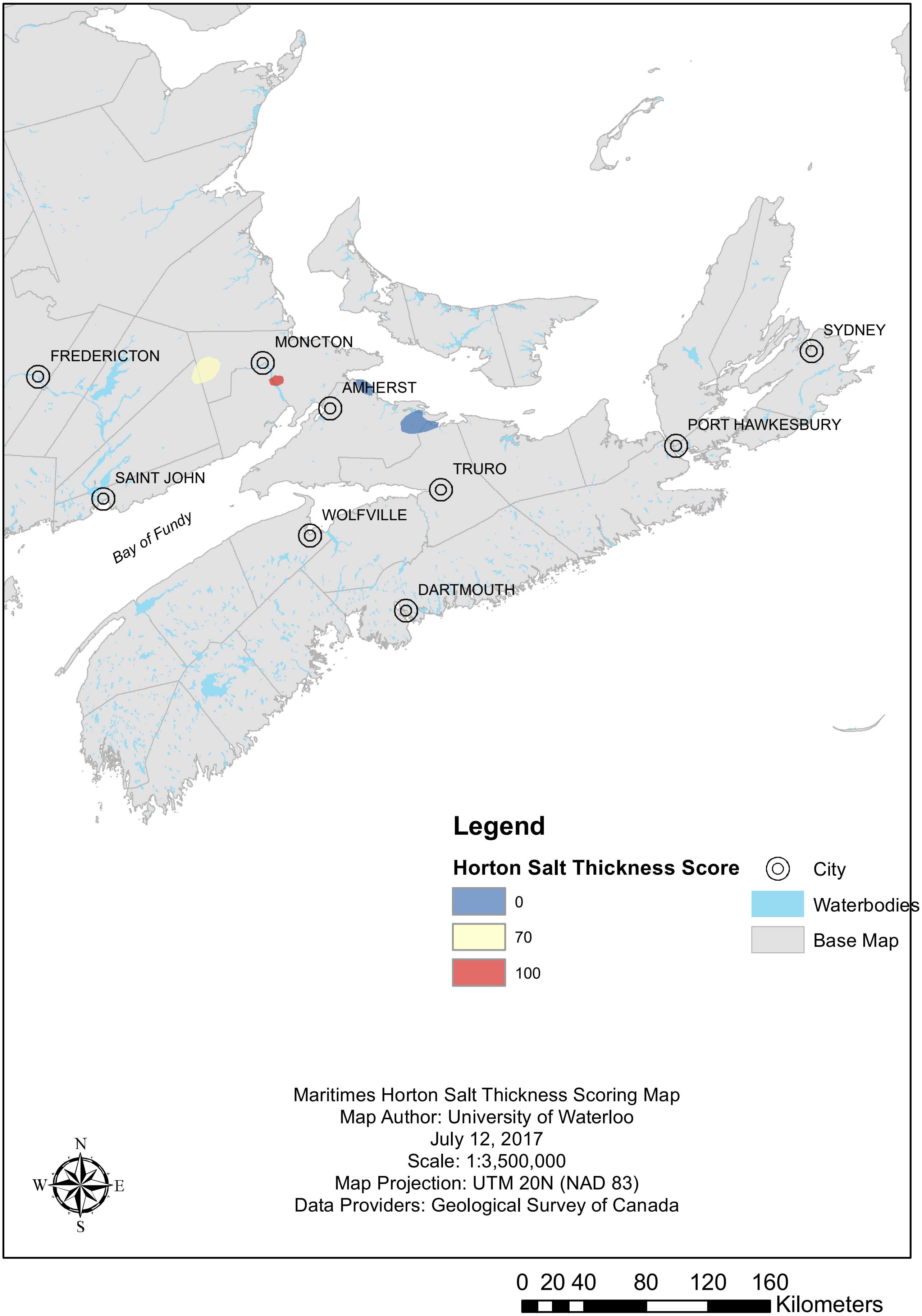
N
W E
S

0 70 140 280 420 560
Kilometers

Maritimes Horton Salt Depth Scoring Map

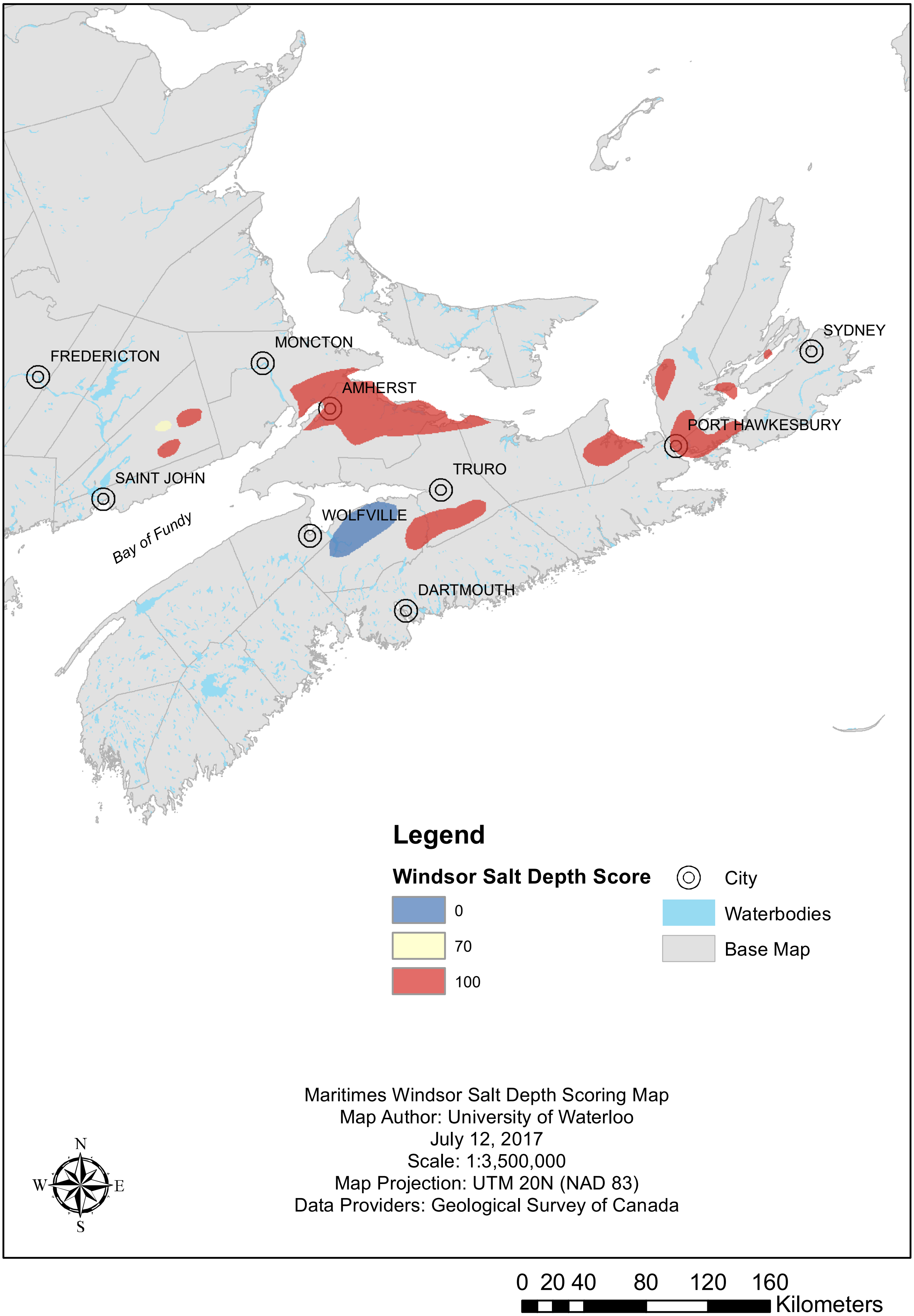


Maritimes Horton Salt Thickness Scoring Map

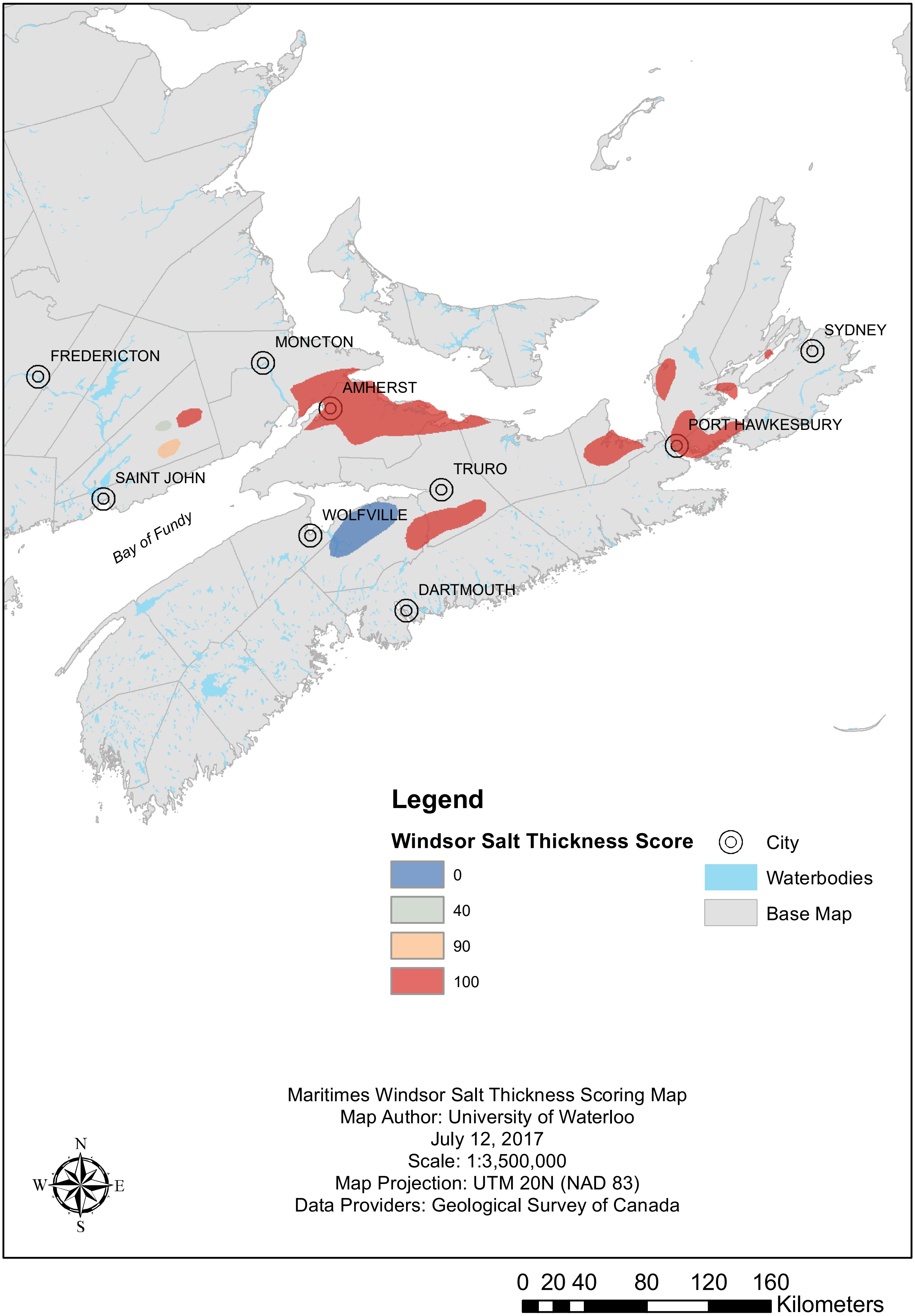


Maritimes Horton Salt Thickness Scoring Map
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)
Data Providers: Geological Survey of Canada

Maritimes Windsor Salt Depth Scoring Map

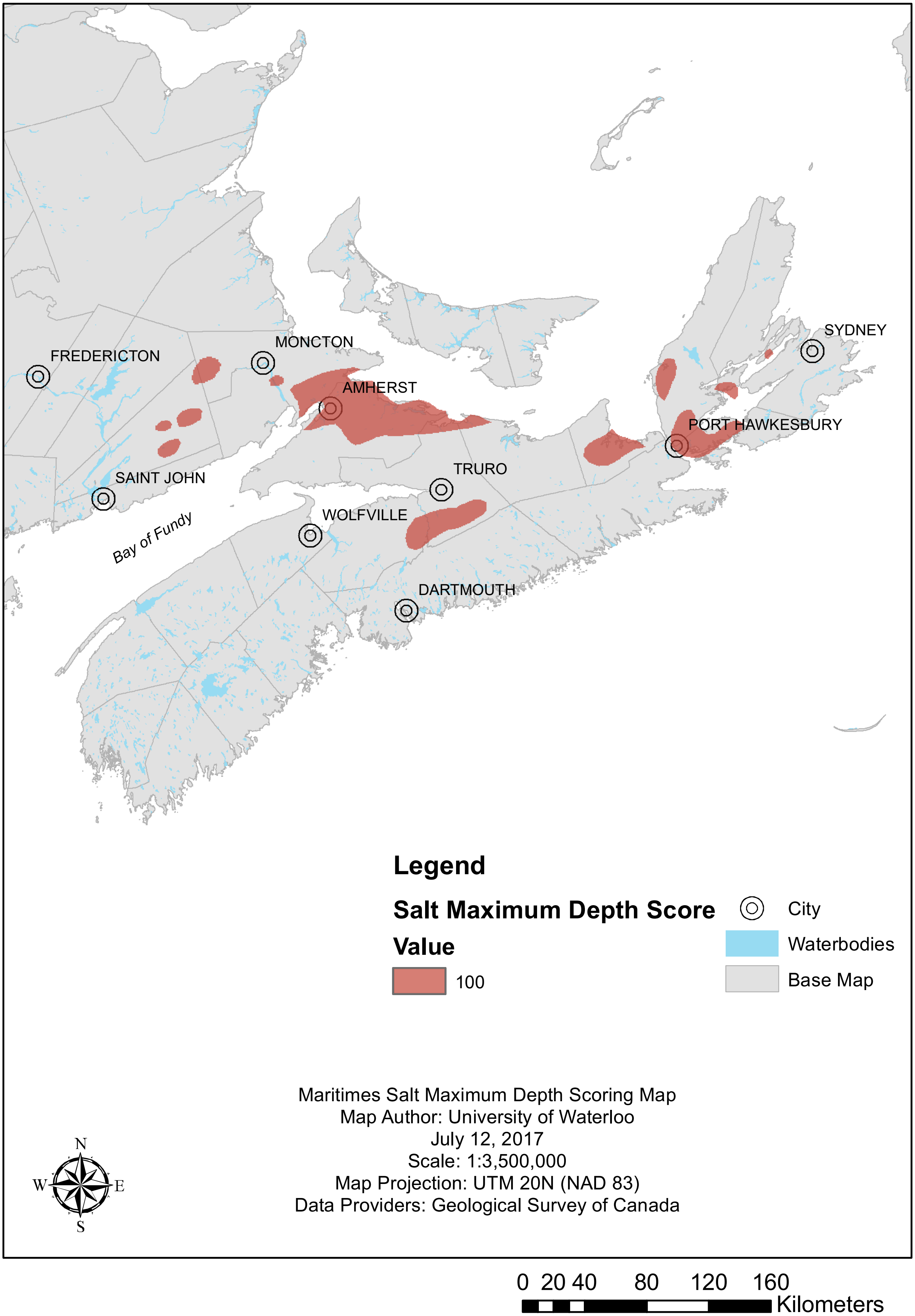


Maritimes Windsor Salt Thickness Scoring Map

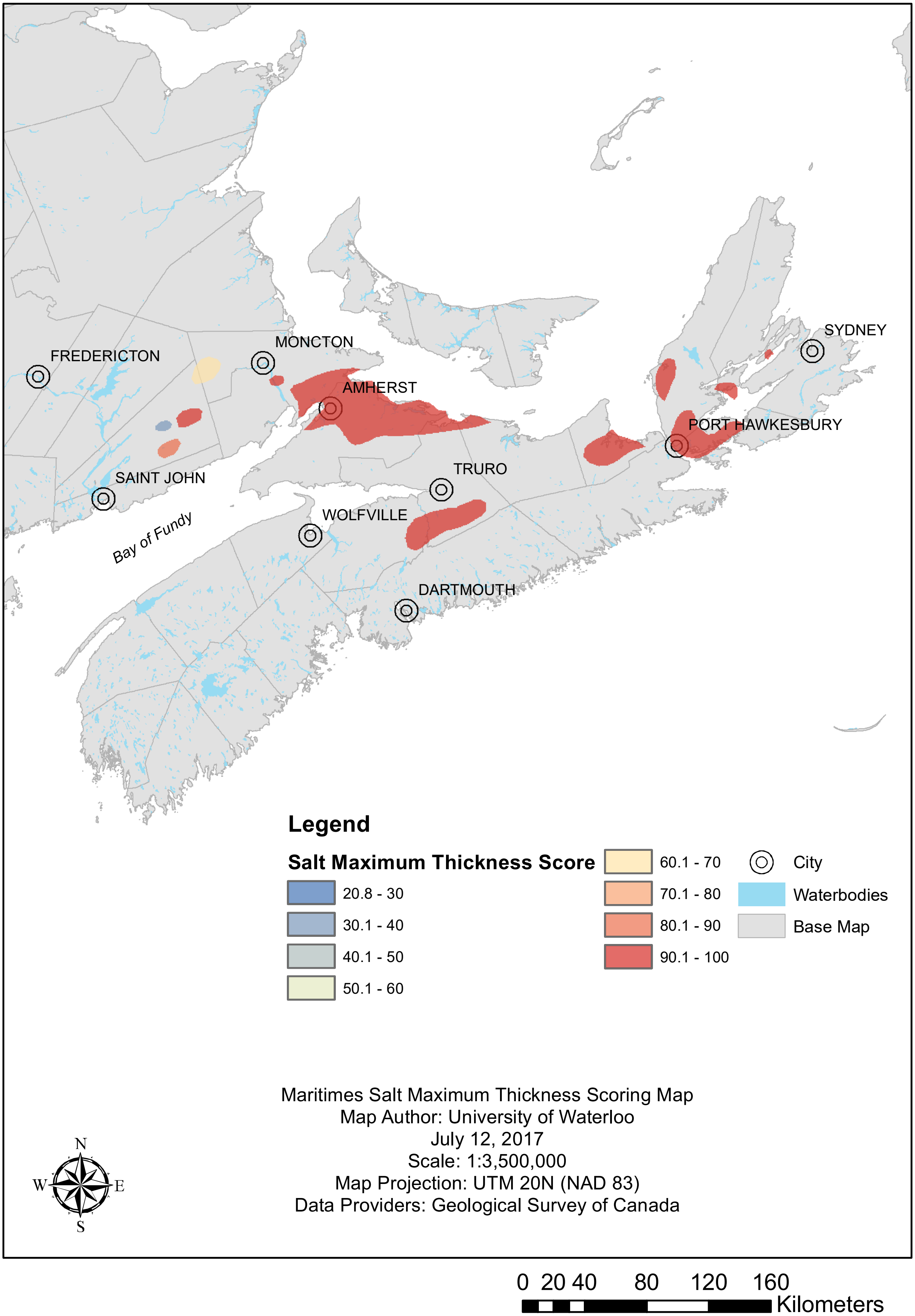


Maritimes Windsor Salt Thickness Scoring Map
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)
Data Providers: Geological Survey of Canada

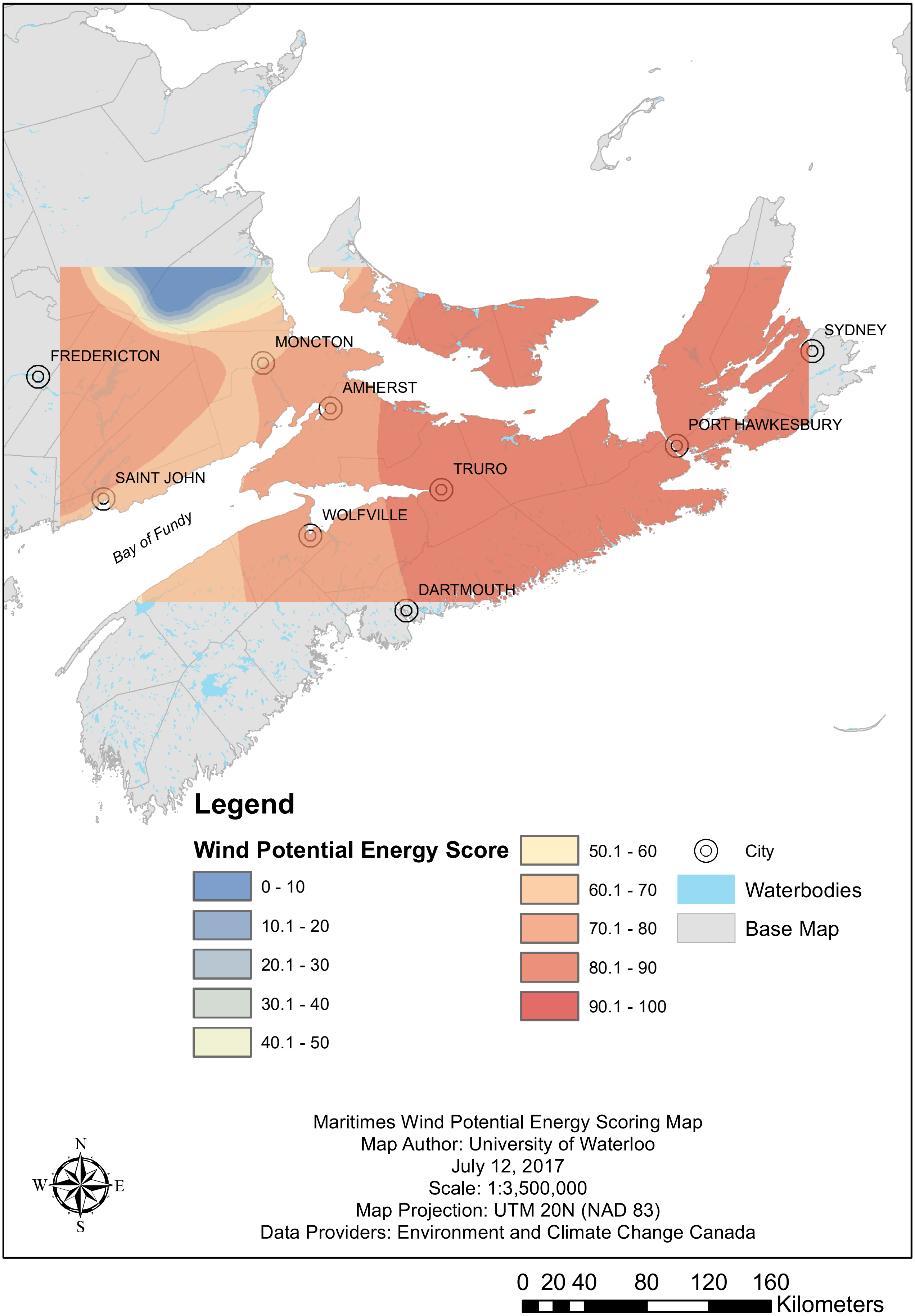
Maritimes Salt Maximum Depth Scoring Map



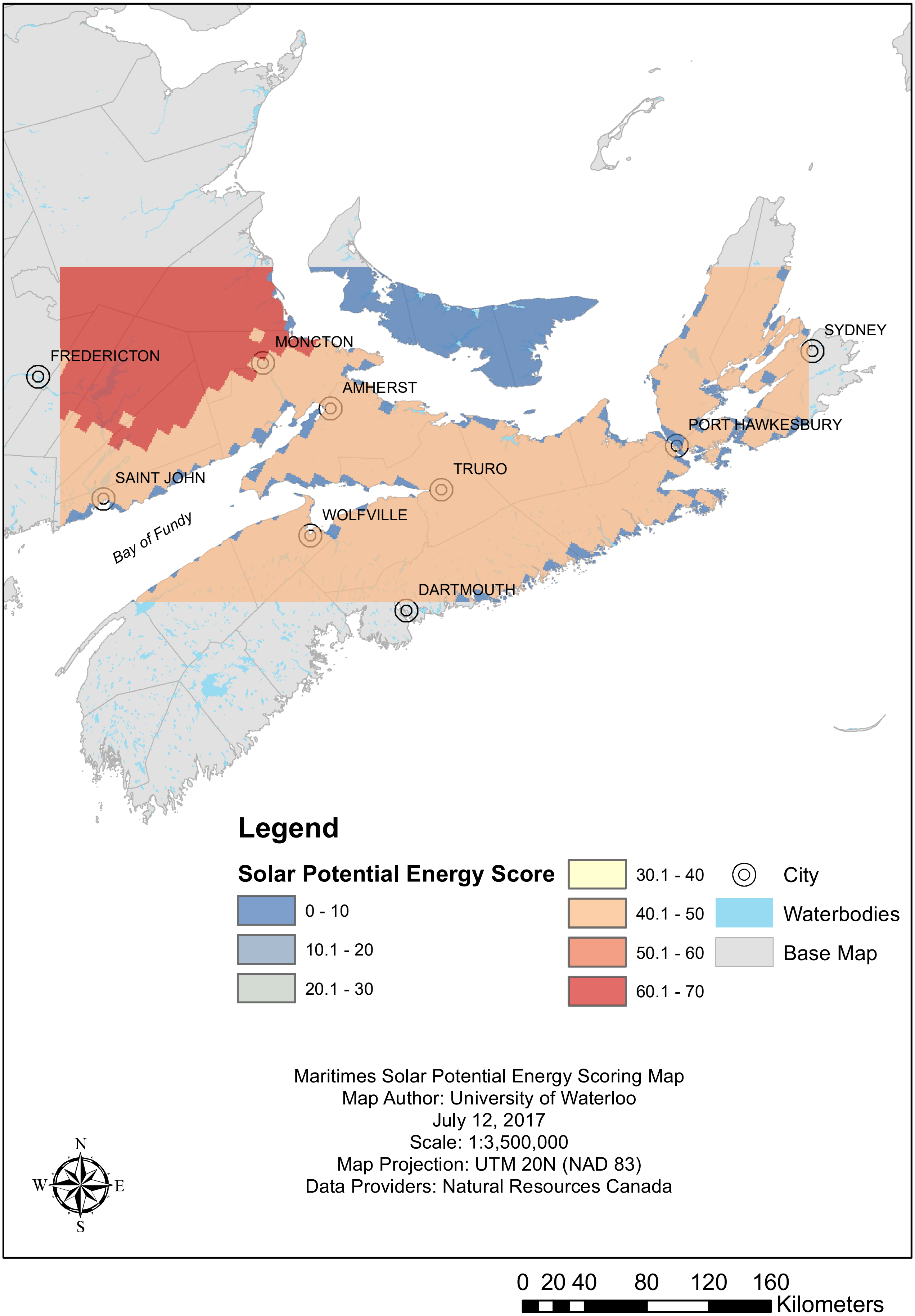
Maritimes Salt Maximum Thickness Scoring Map



Maritimes Wind Potential Energy Scoring Map

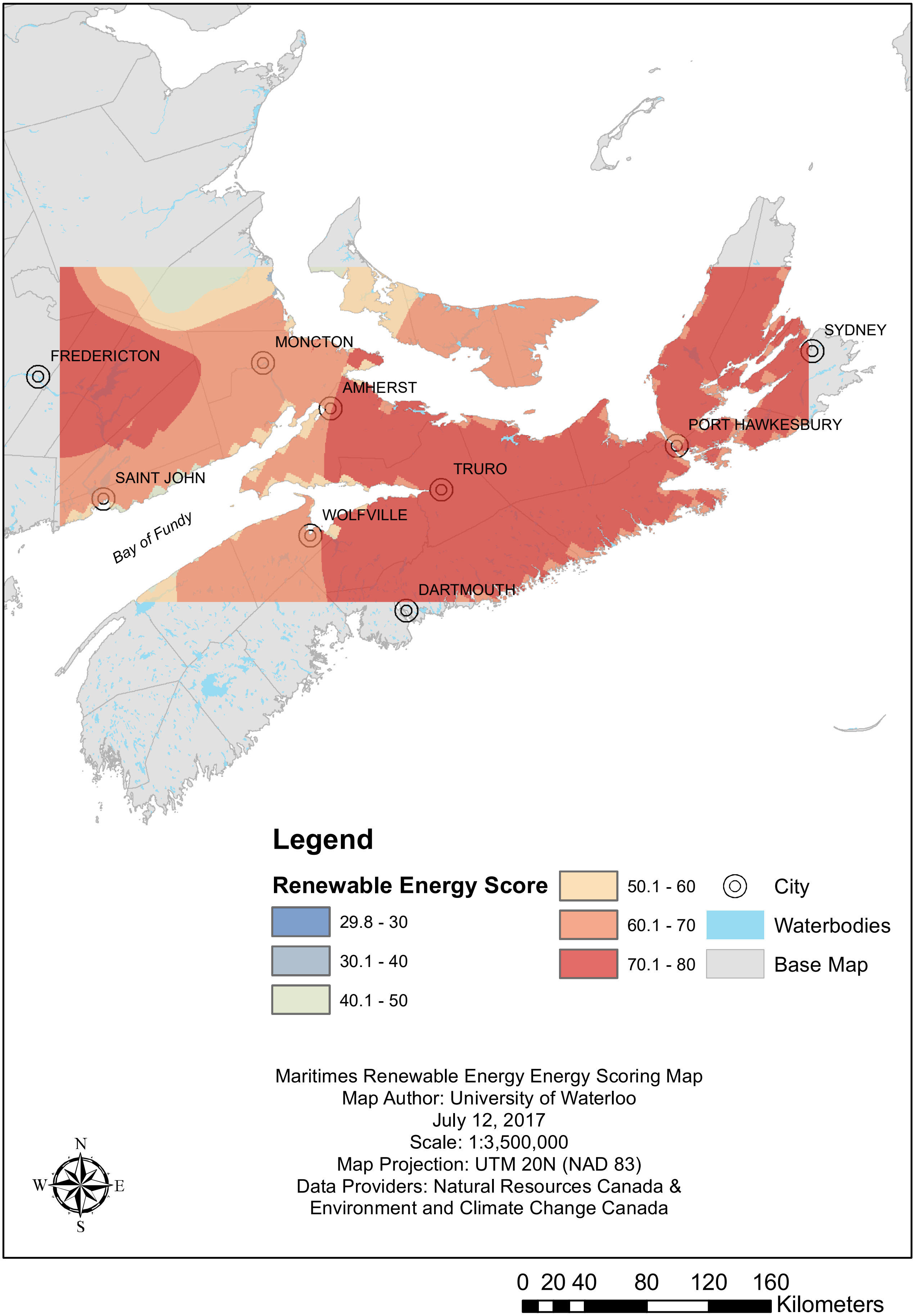


Maritimes Solar Potential Energy Scoring Map

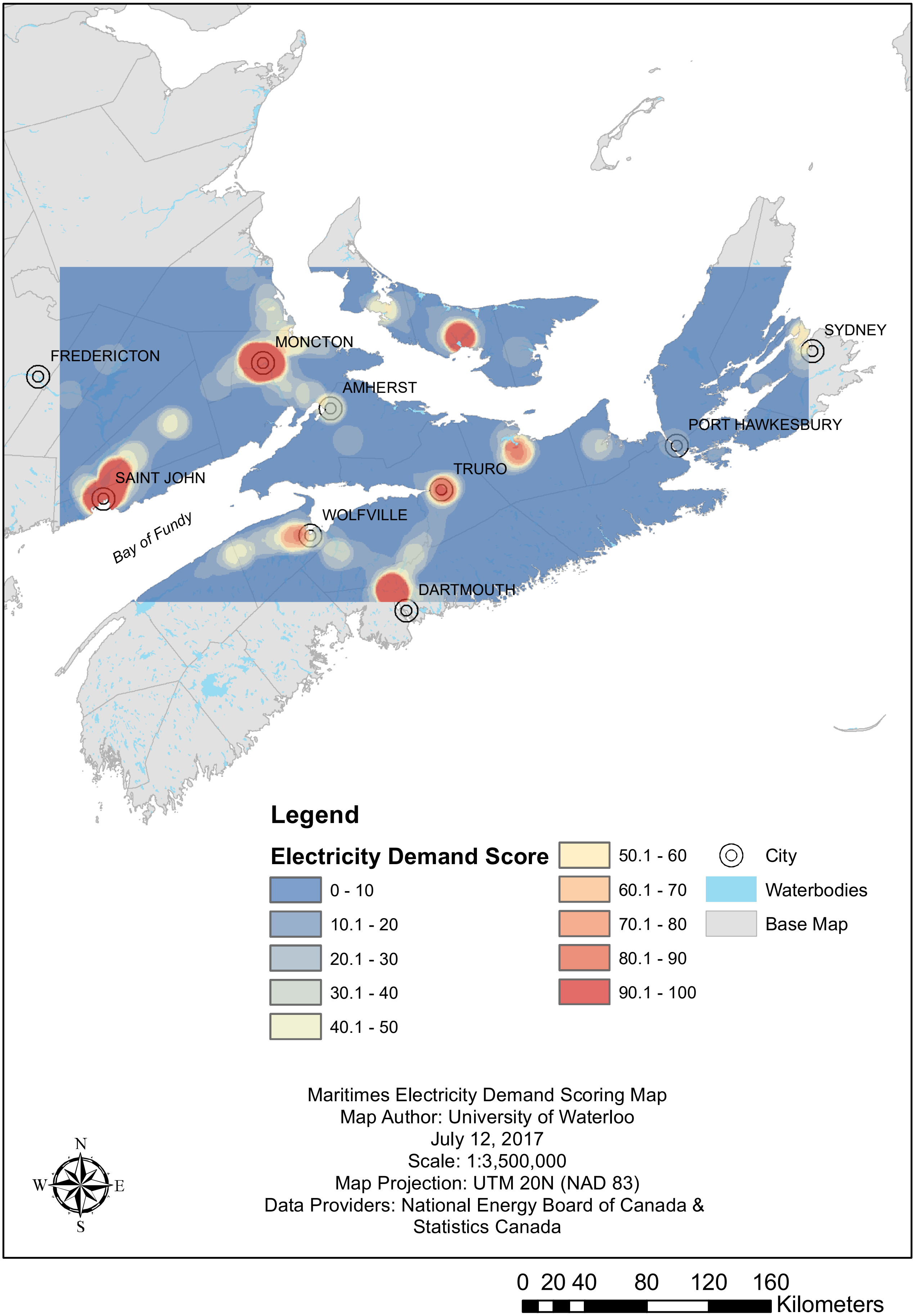


Maritimes Solar Potential Energy Scoring Map
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)
Data Providers: Natural Resources Canada

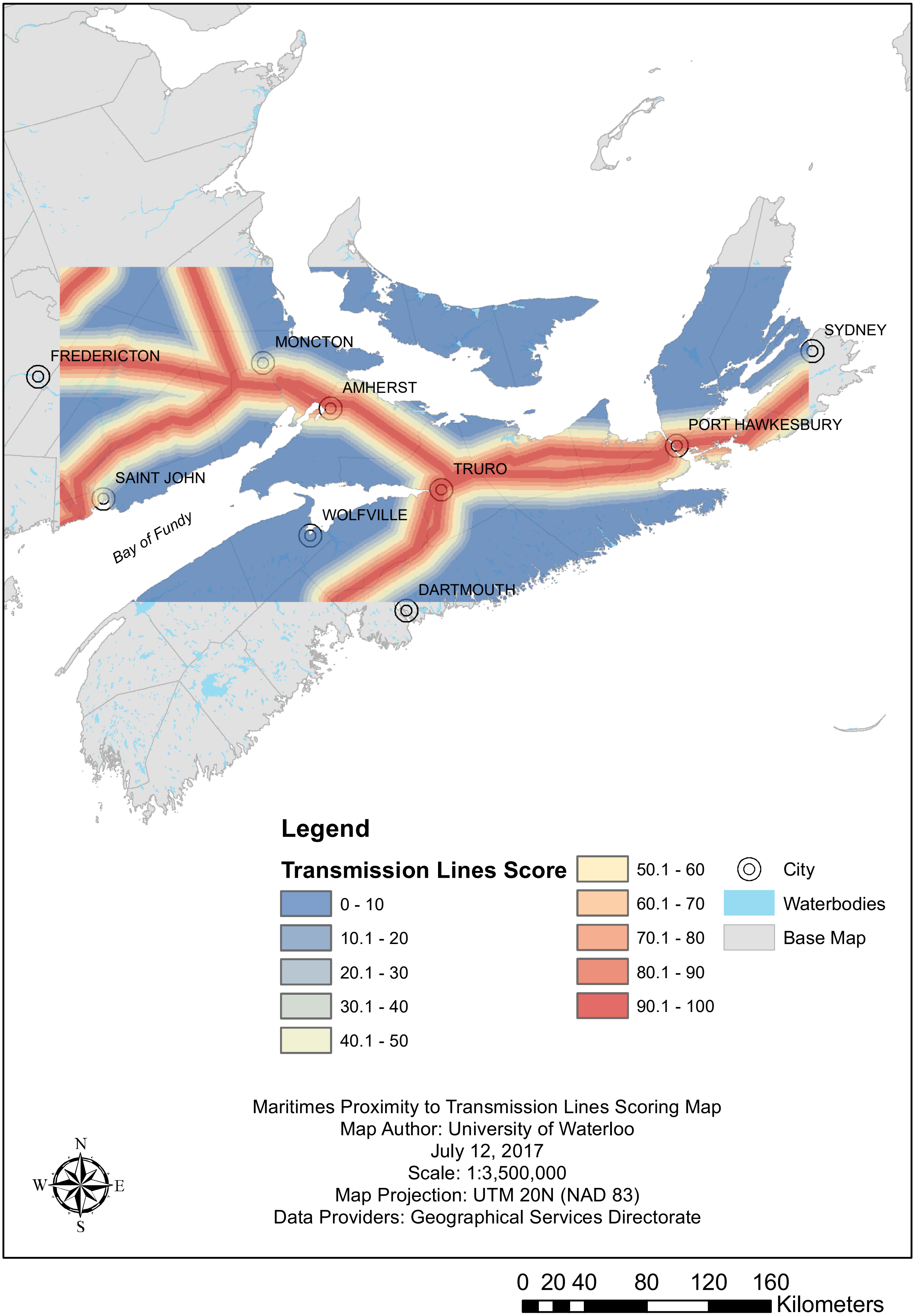
Maritimes Renewable Energy Scoring Map



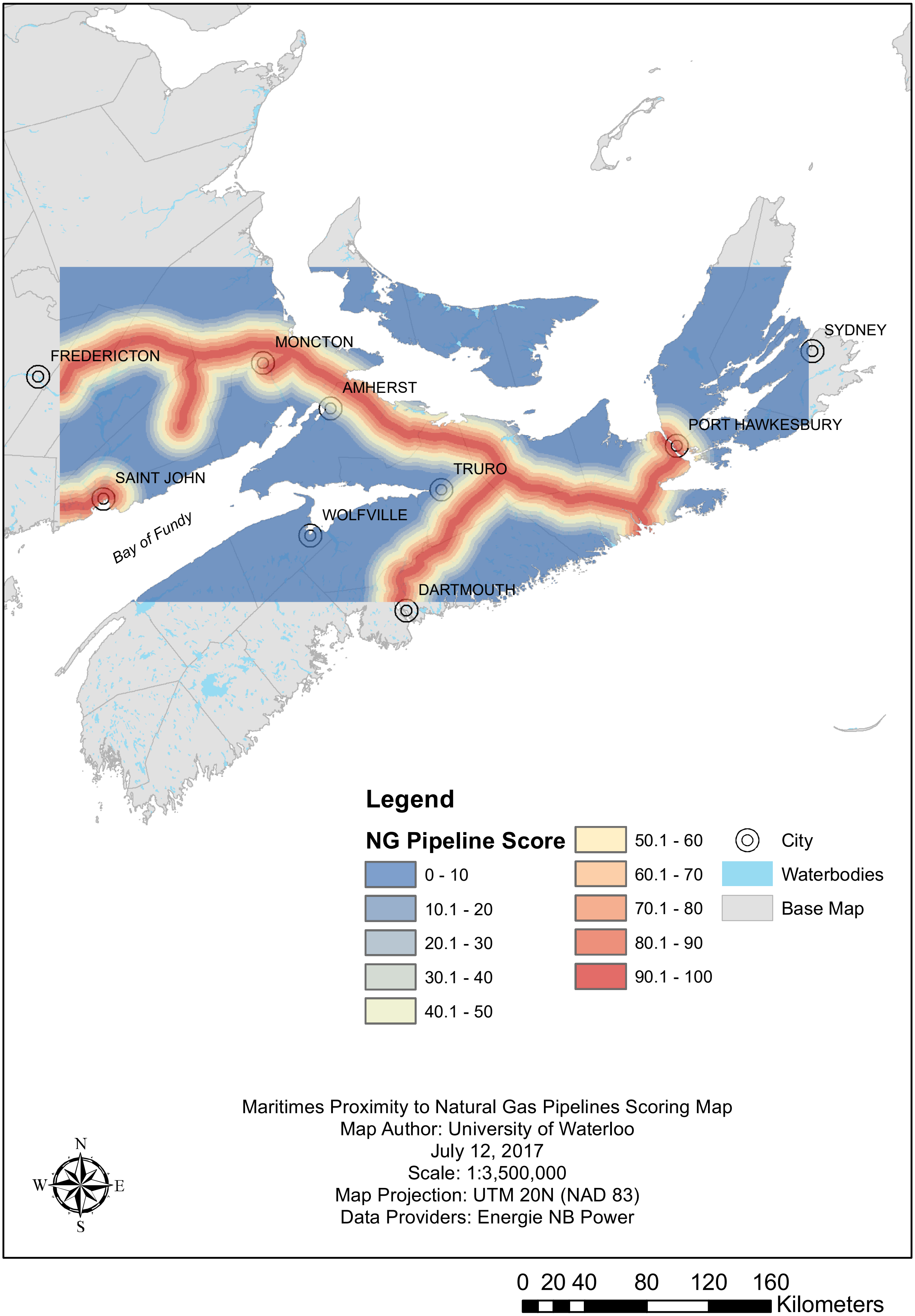
Maritimes Electricity Demand Scoring Map



Maritimes Proximity to Transmission Lines Scoring Map

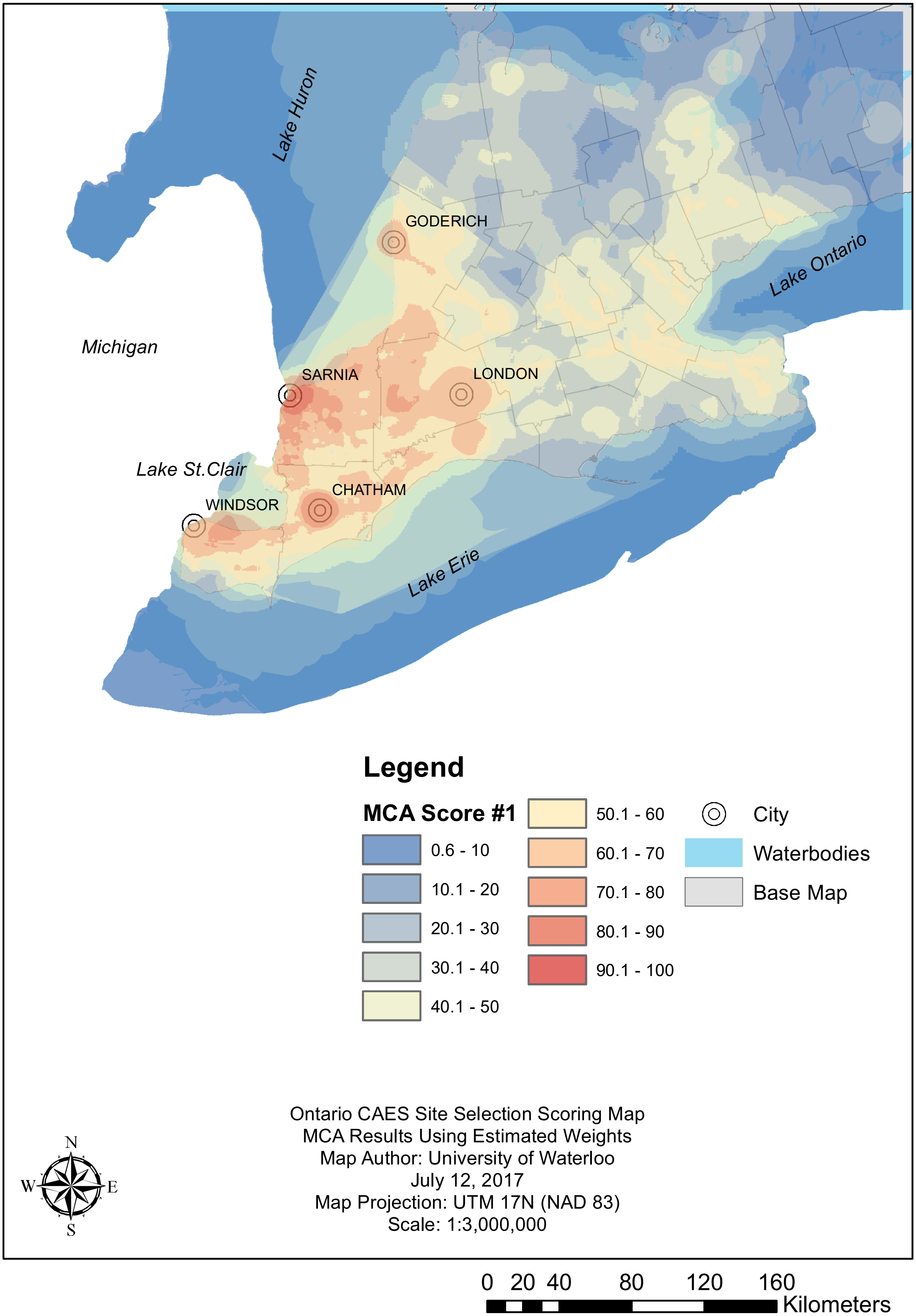


Maritimes Proximity to Natural Gas Pipelines Scoring Map

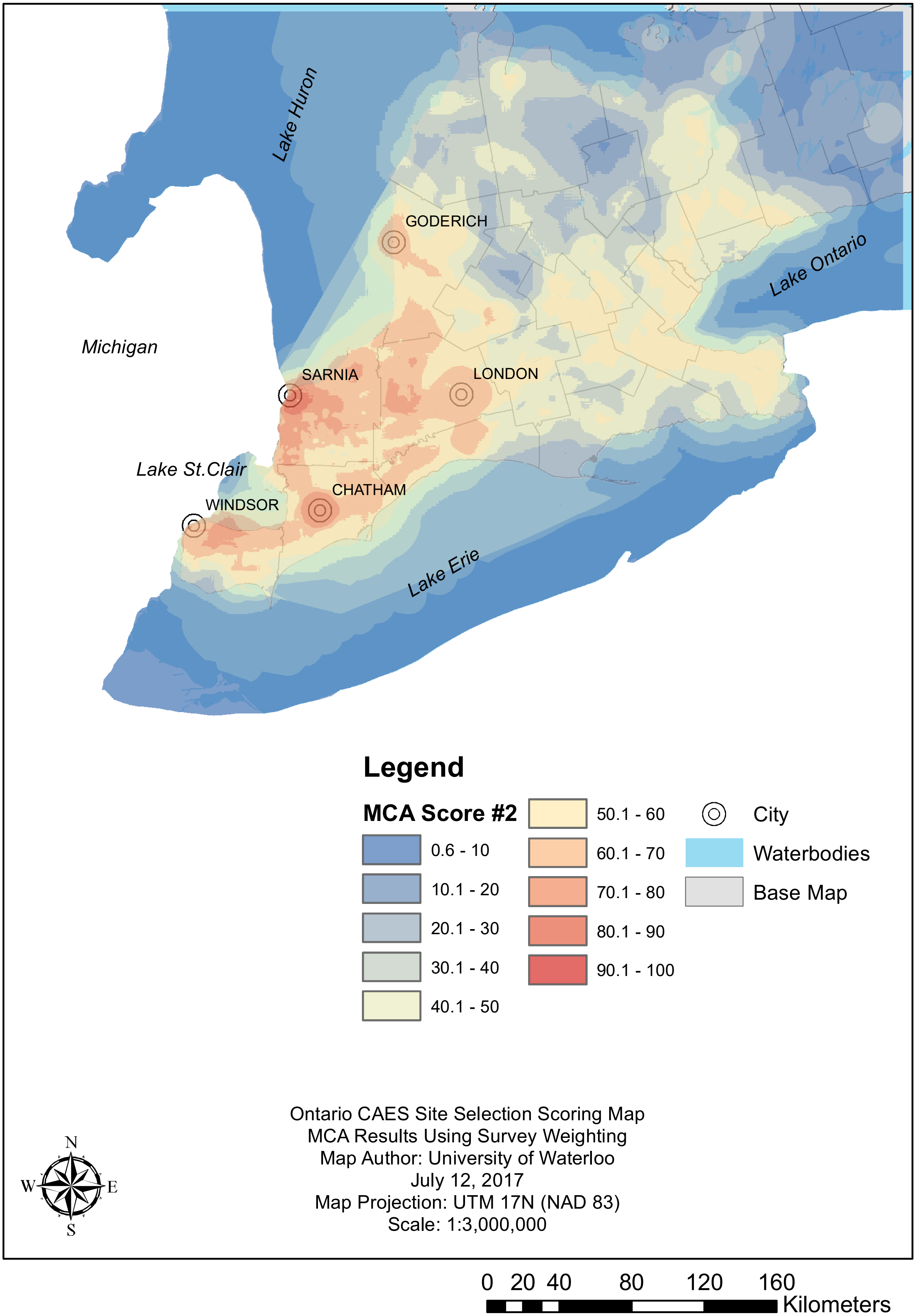


Appendix C: Multi-Criteria Analysis Results Maps

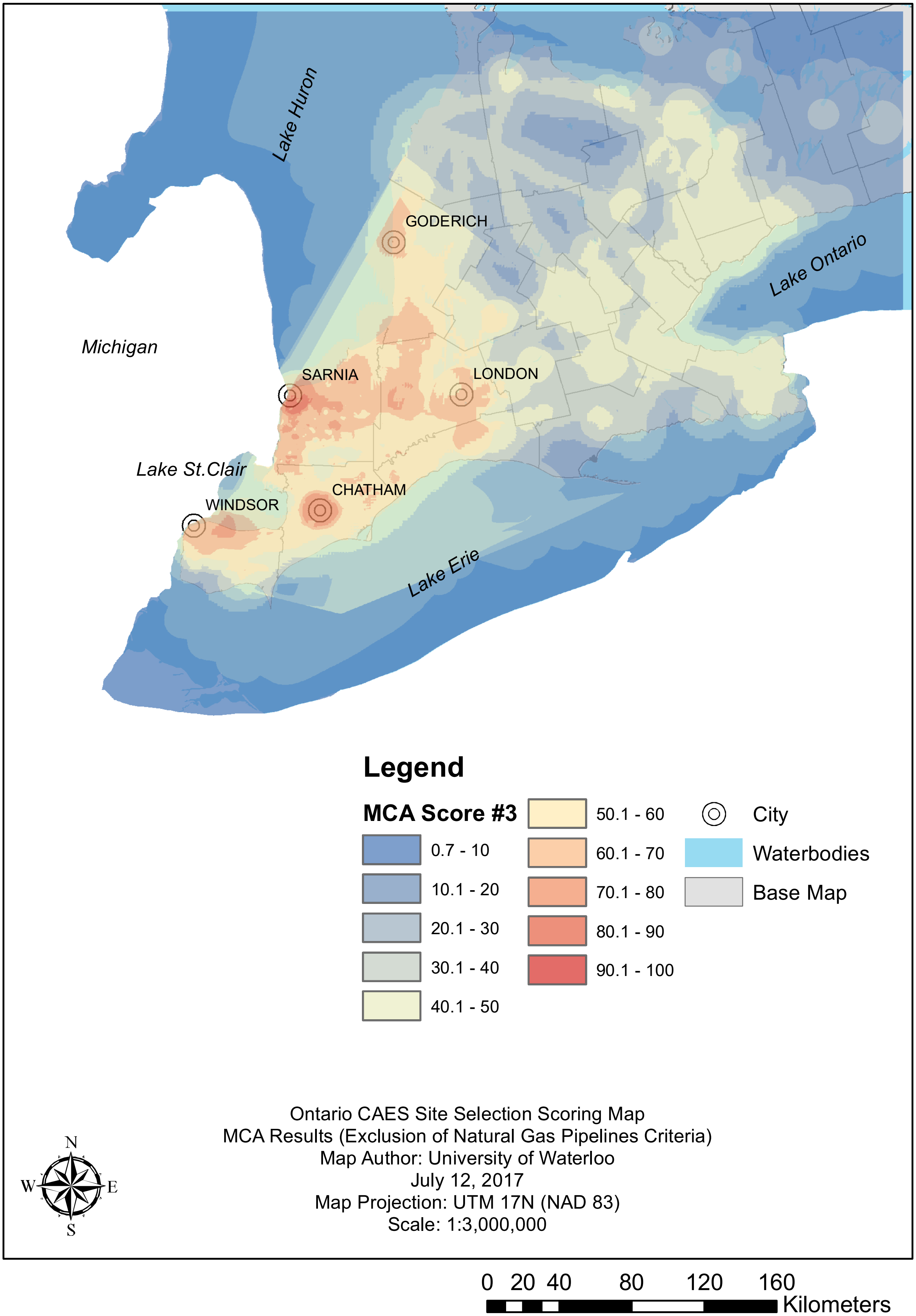
Ontario MCA Results - Estimated Weights



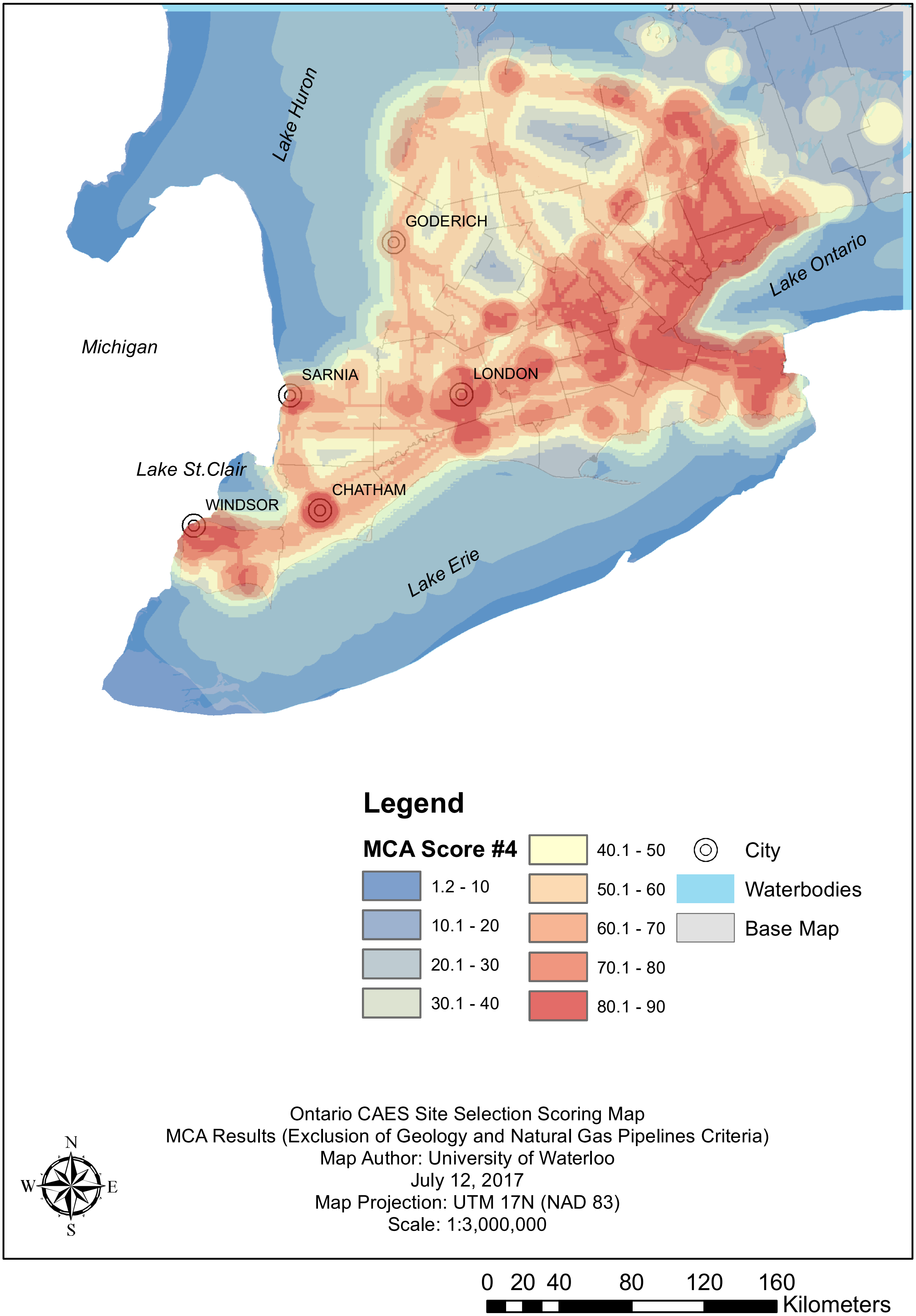
Ontario MCA Results - Survey Weighting



Ontario MCA Results
Exclusion of Natural Gas Pipelines Criteria

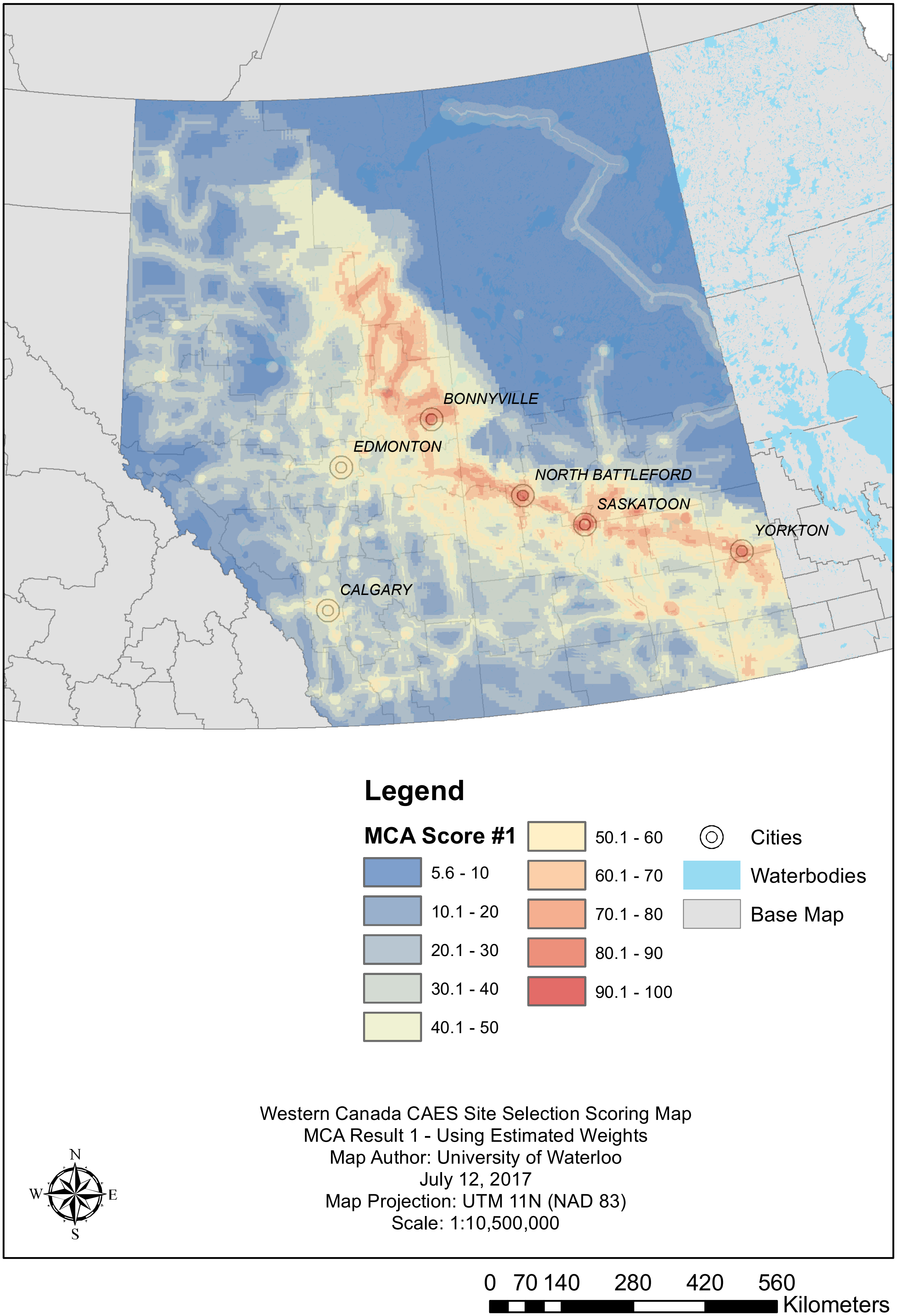


Ontario MCA Results
Exclusion of Geology and Natural Gas Pipelines Criteria

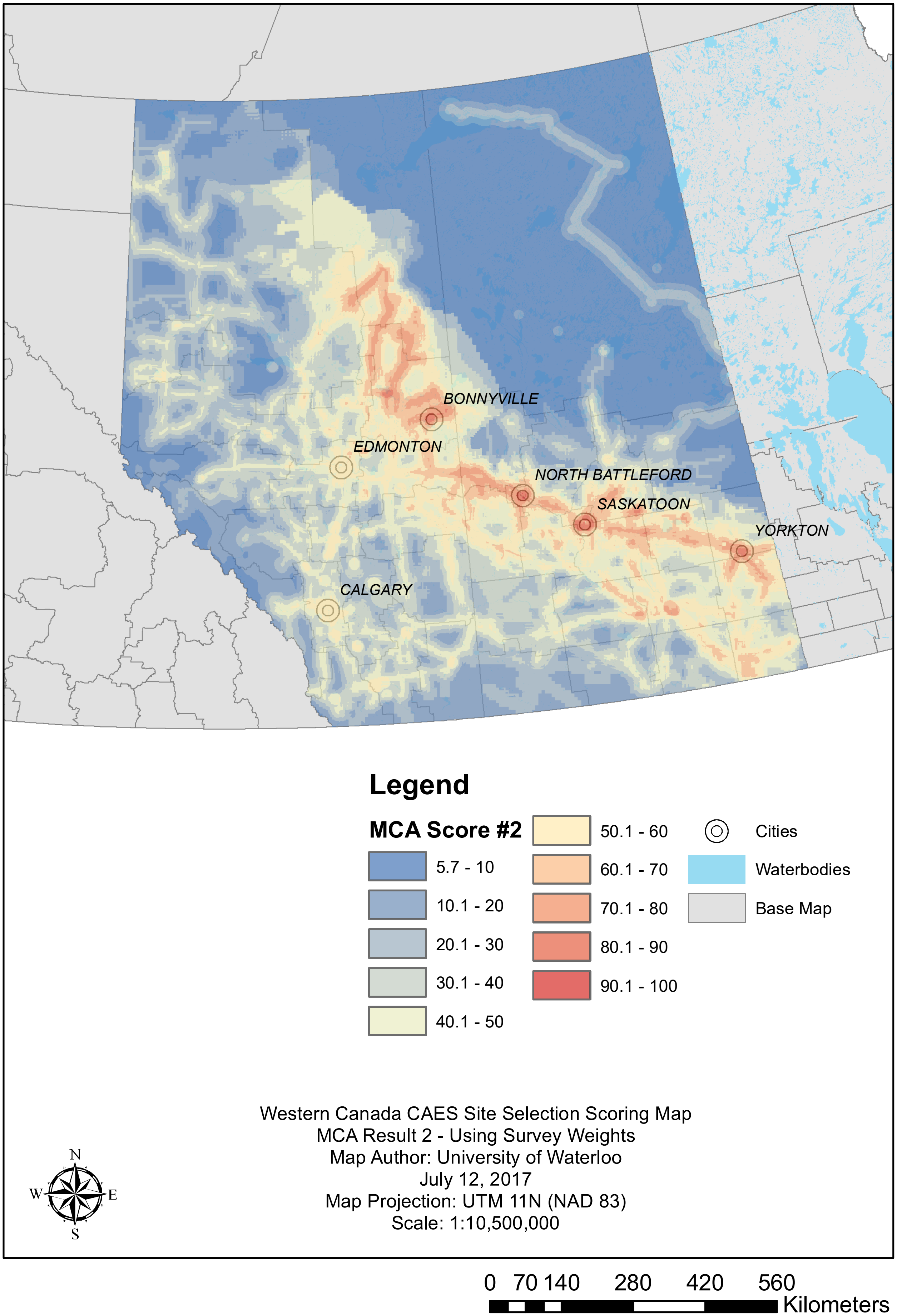


Ontario CAES Site Selection Scoring Map
MCA Results (Exclusion of Geology and Natural Gas Pipelines Criteria)
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 17N (NAD 83)
Scale: 1:3,000,000

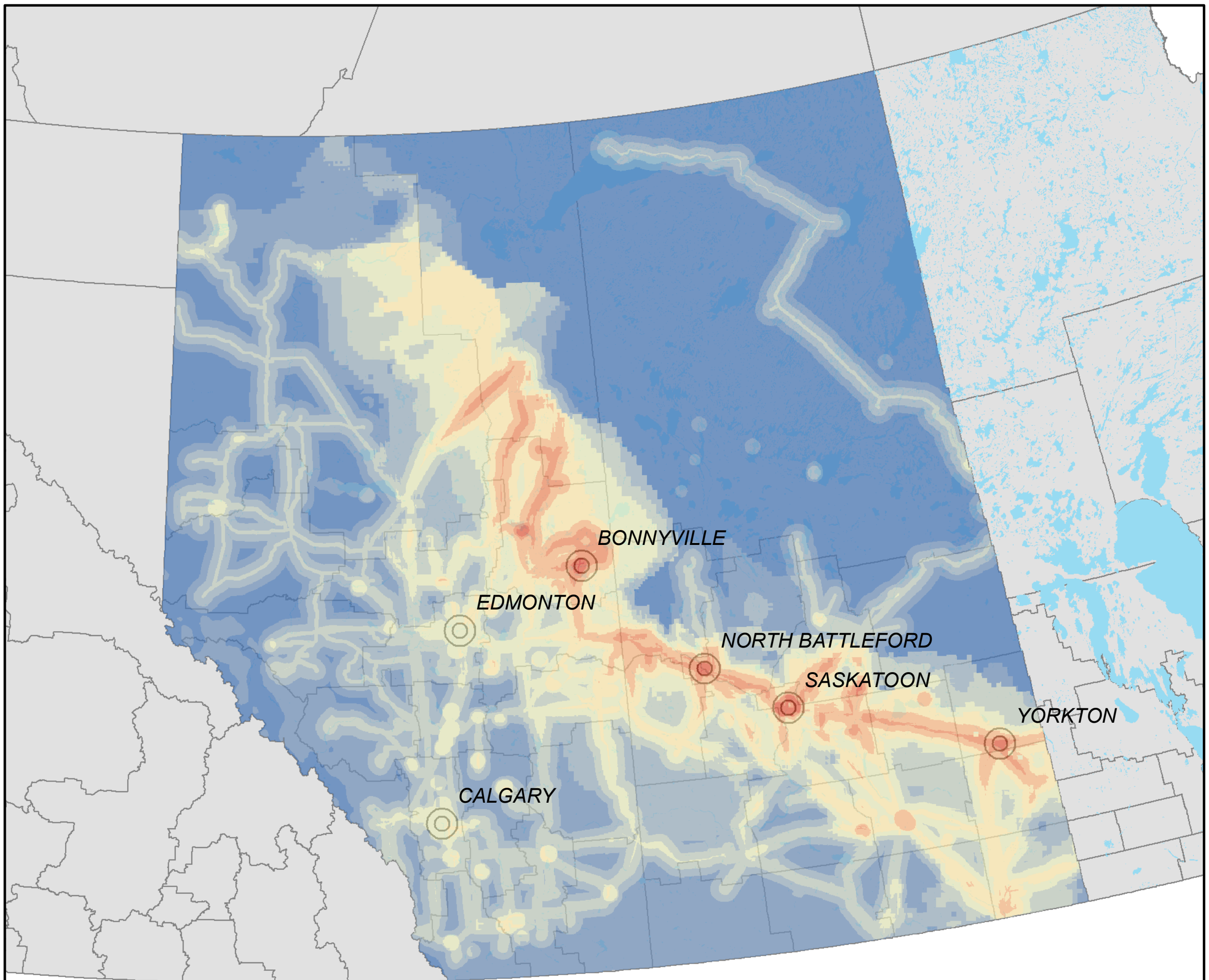
Western Canada MCA Result - Estimated Weights



Western Canada MCA Result - Survey Weights



Western Canada MCA Results
Exclusion of Natural Gas Pipeline Criteria



Legend

MCA Score #3

- 6.7 - 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

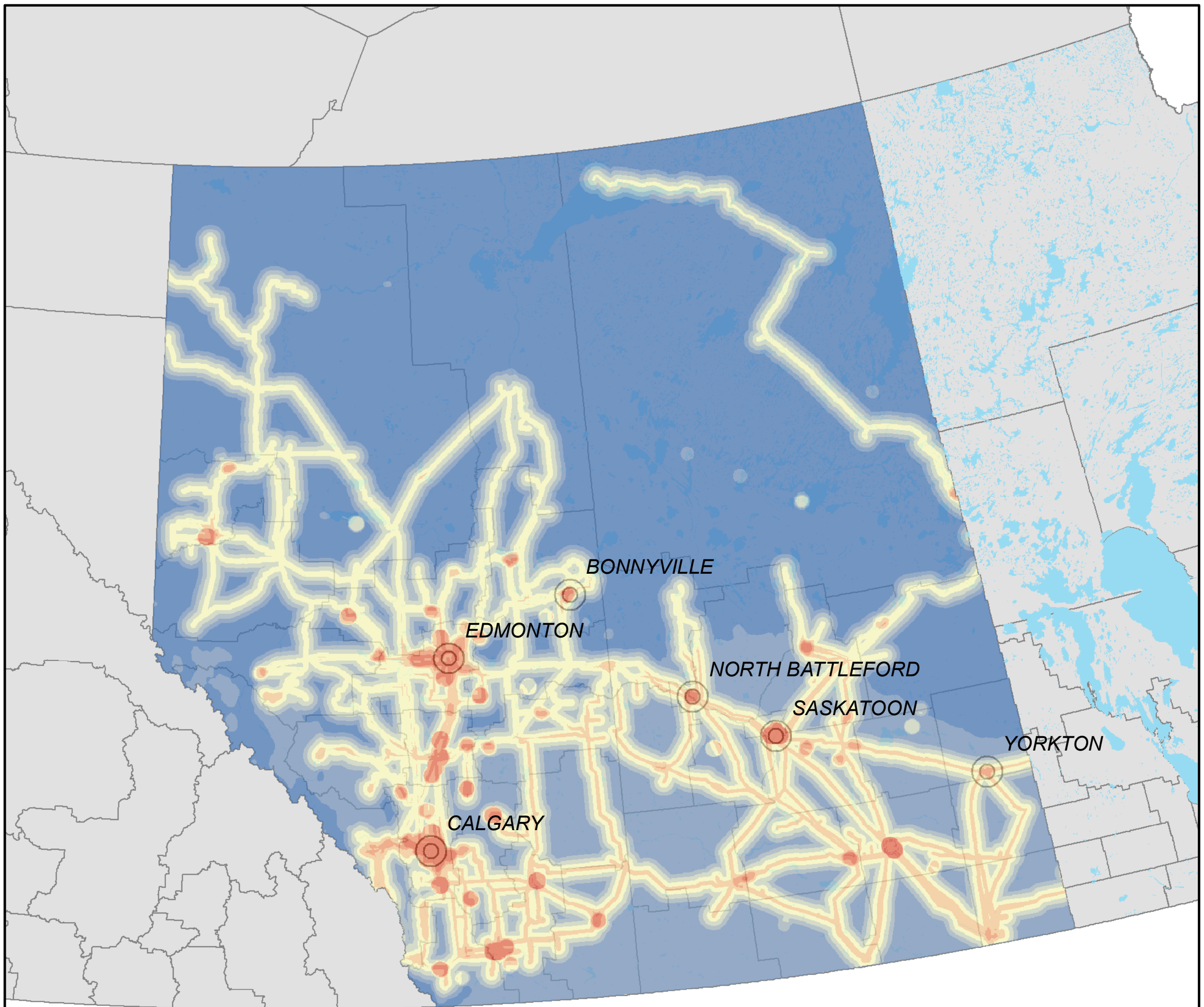
- Cities
- Waterbodies
- Base Map

Western Canada CAES Site Selection Scoring Map
MCA Result 3 (Exclusion of Natural Gas Pipeline Criteria)
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000

N W E S

0 70 140 280 420 560 Kilometers

Western Canada MCA Results
Exclusion of Geology and Natural Gas Pipeline Criteria



Legend

MCA Score #4

11.7 - 20	50.1 - 60
20.1 - 30	60.1 - 70
30.1 - 40	70.1 - 80
40.1 - 50	80.1 - 90
	90.1 - 100

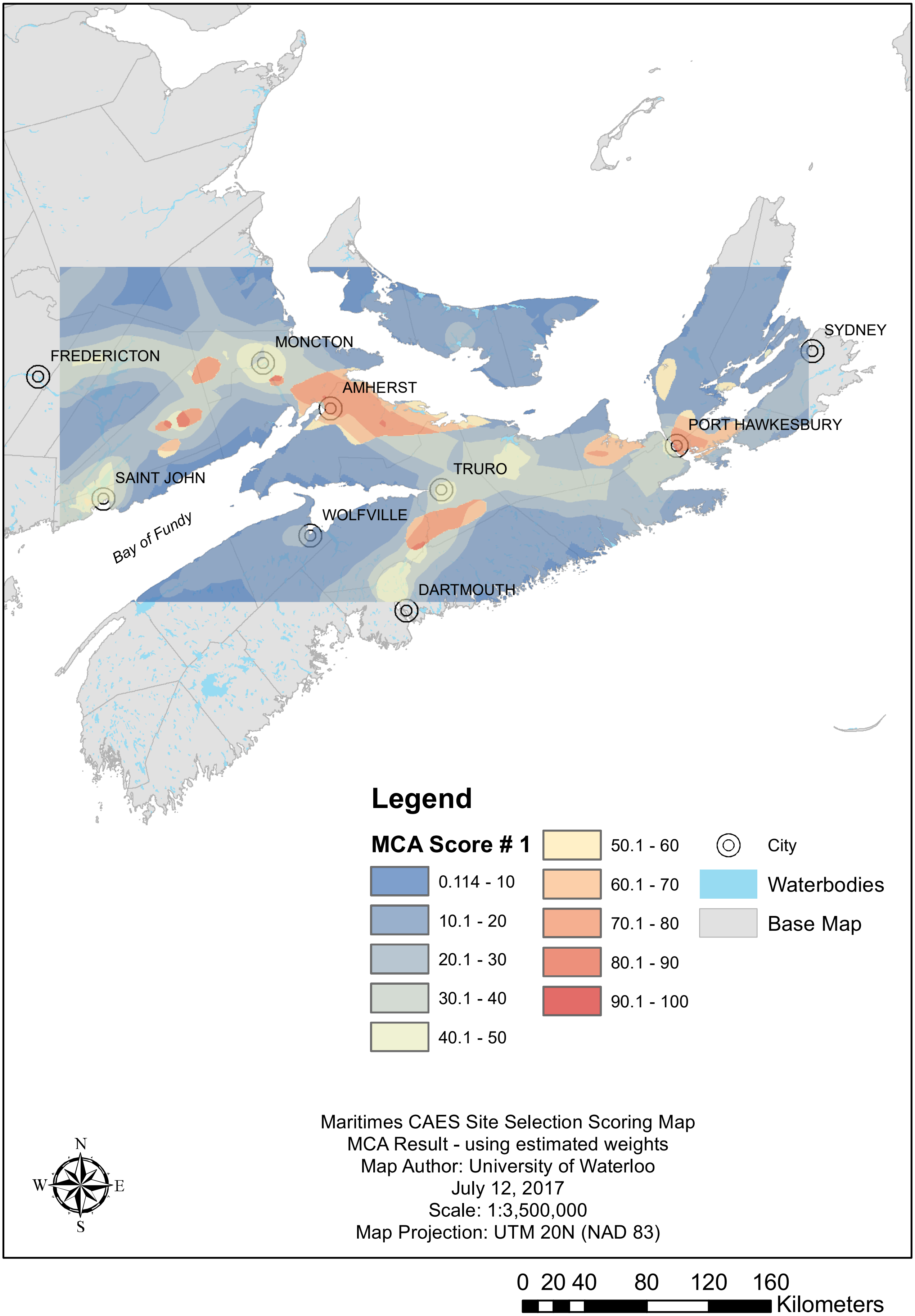
Cities
Waterbodies
Base Map

Western Canada CAES Site Selection Scoring Map
MCA Result #4 (Exclusion of Geology and Natural Gas Pipeline Criteria)
Map Author: University of Waterloo
July 12, 2017
Map Projection: UTM 11N (NAD 83)
Scale: 1:10,500,000

N W E S

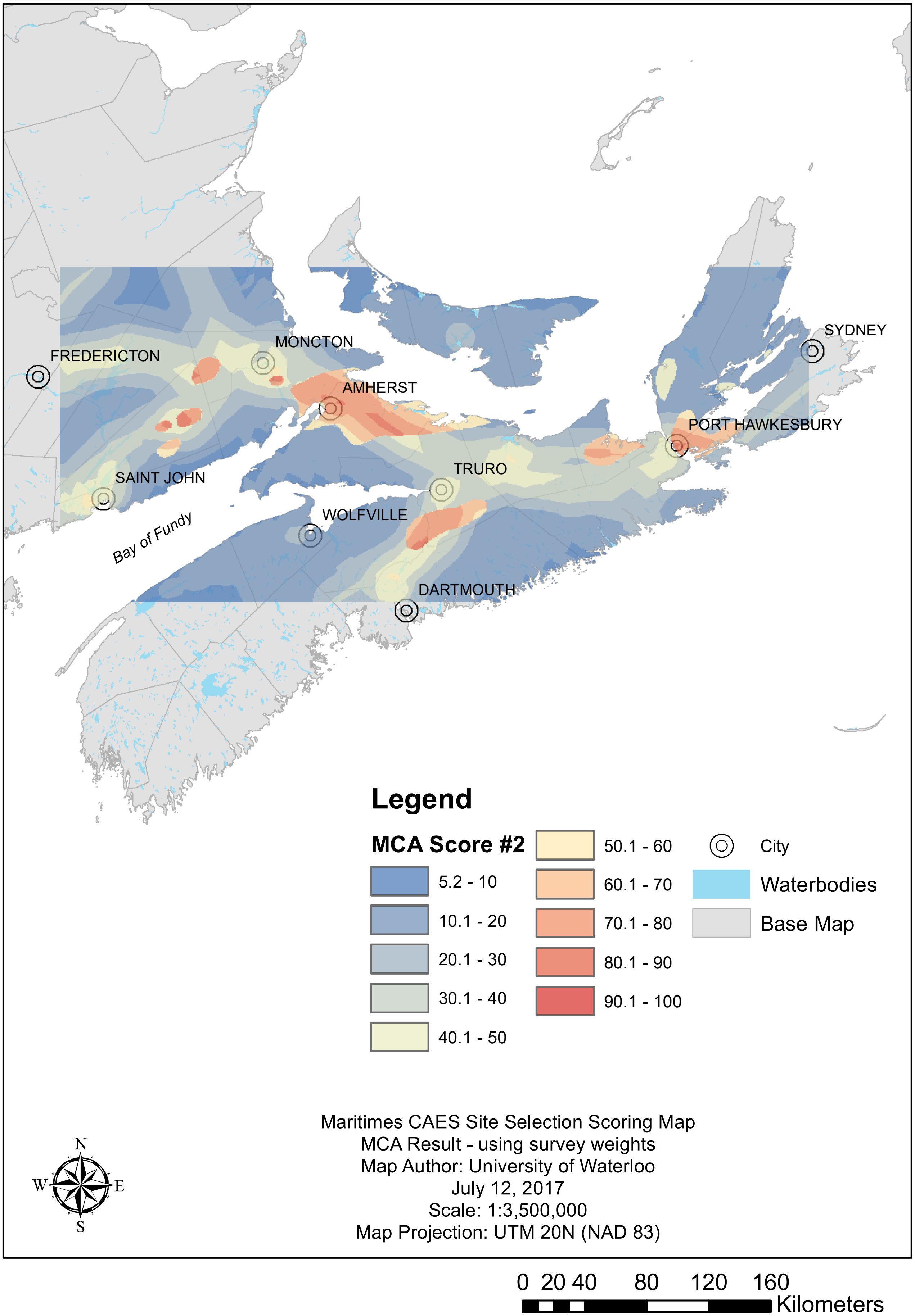
0 70 140 280 420 560 Kilometers

Maritimes MCA Result - Estimated Weights

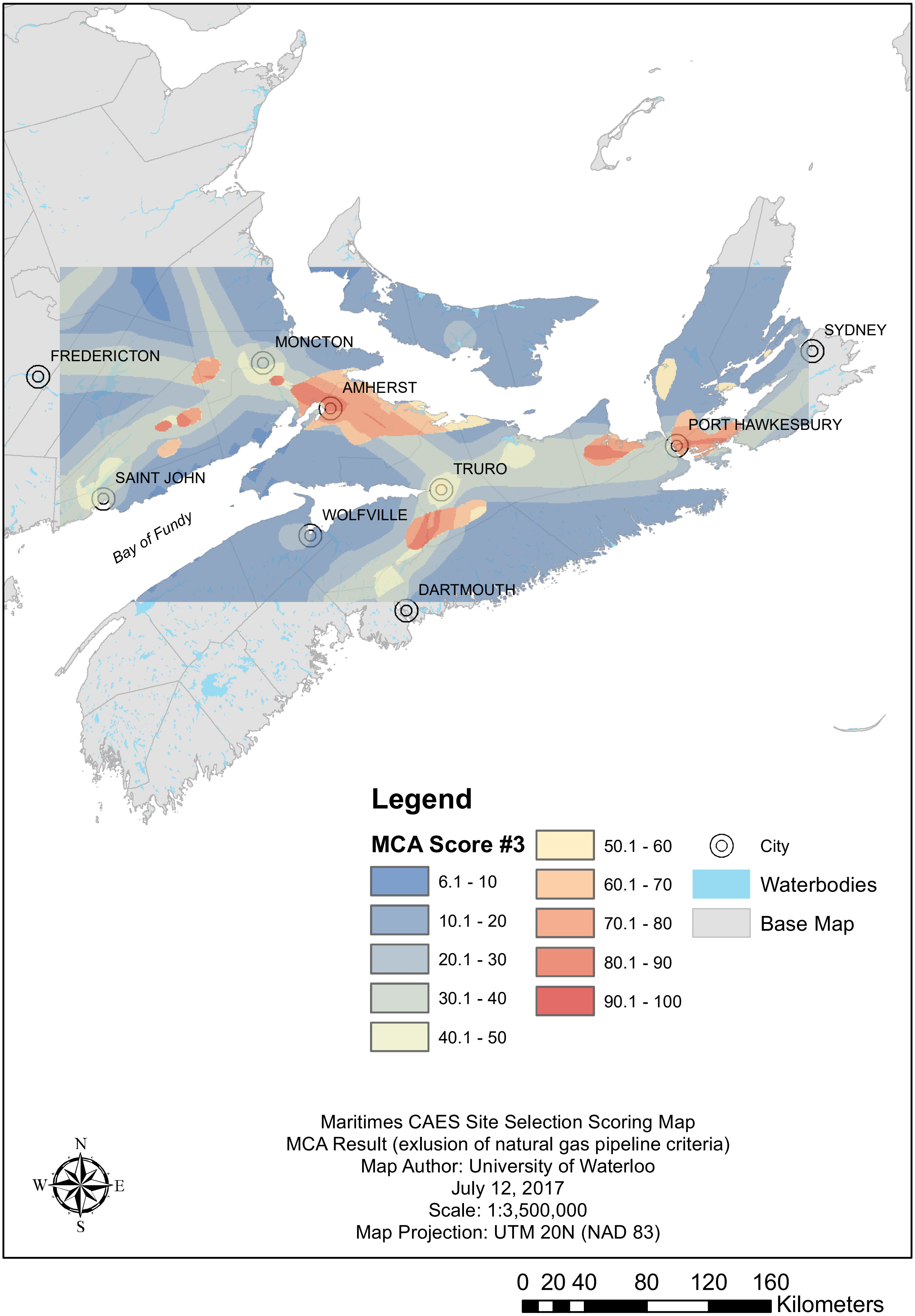


Maritimes CAES Site Selection Scoring Map
MCA Result - using estimated weights
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)

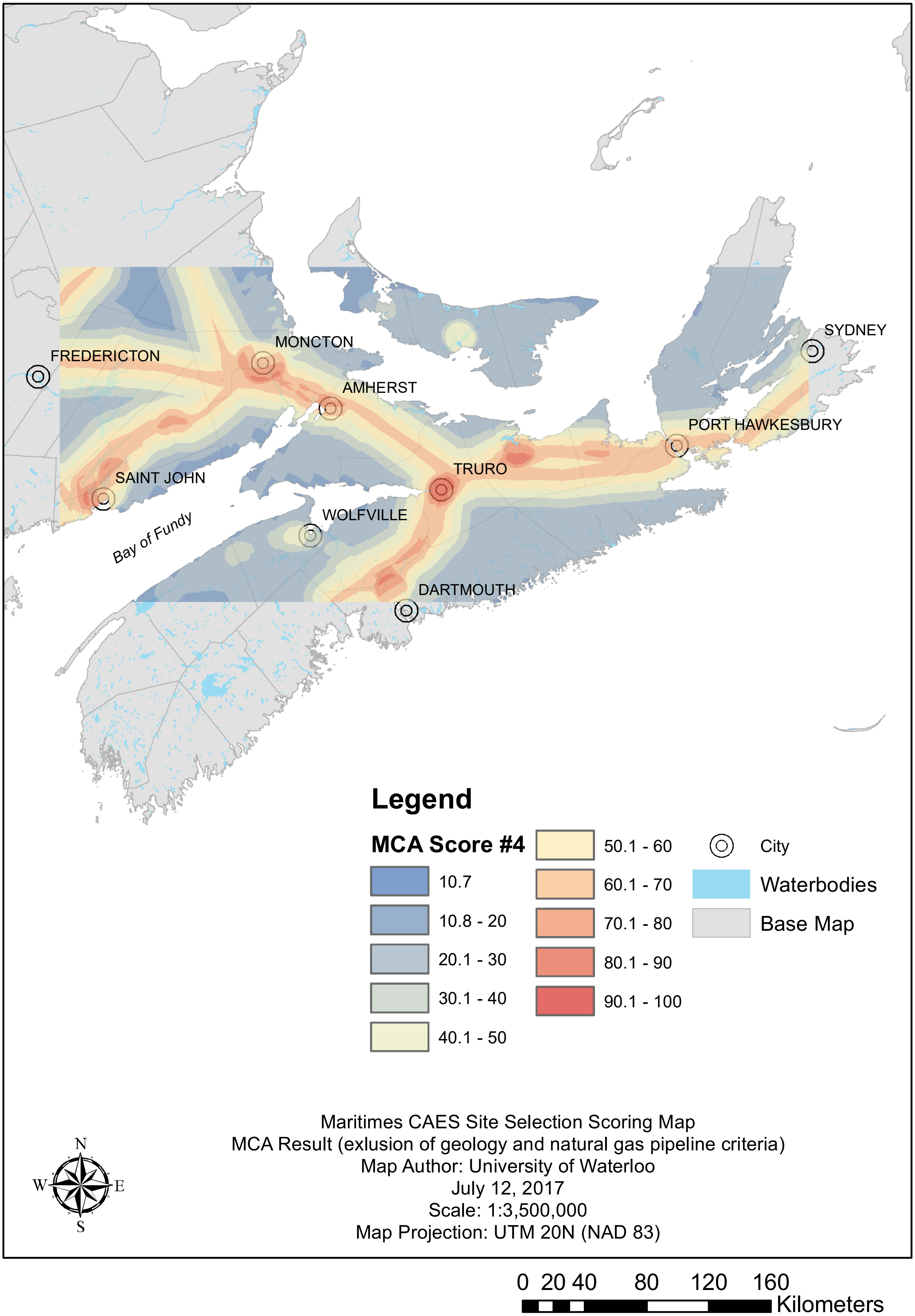
Maritimes MCA Result - Survey Weights



Maritimes MCA Result
Exlusion of Natural Gas Pipeline Criteria



Maritimes MCA Result
Exlusion of Geology and Natural Gas Pipeline Criteria



Maritimes CAES Site Selection Scoring Map
MCA Result (exlusion of geology and natural gas pipeline criteria)
Map Author: University of Waterloo
July 12, 2017
Scale: 1:3,500,000
Map Projection: UTM 20N (NAD 83)

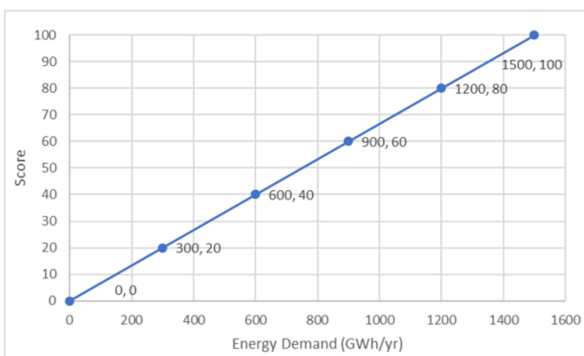
Appendix D: Informal CAES Criteria Weighting Survey

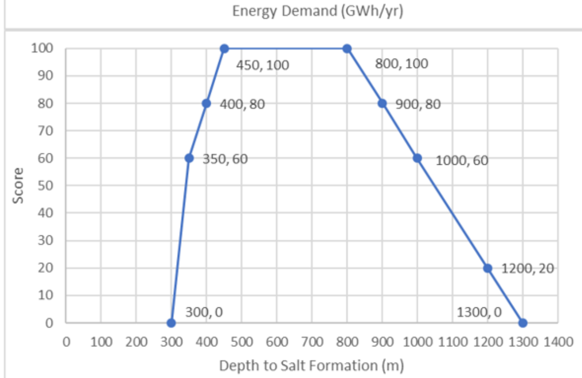
Compressed Air Energy Storage in Salt Caverns in Canada: Informal CAES Criteria Weighting Survey

Compressed Air Energy Storage in Salt Caverns in Canada: Informal CAES Criteria Weighting Survey The University of Waterloo is conducting a first-order spatial multi-criterion analysis (MCA) to assess the technical feasibility and potential of CAES in salt caverns across Canada. This study addresses the potential of CAES for supporting intermittent renewable power generation, allowing increased renewable energy penetration on the electric grid. Although CAES also plays an important grid role with second-by-second load balancing and ancillary services, for this survey we restrict the analysis to CAES use in renewables integration. A MCA generally requires quantitative input and the application of professional judgement. Our judgement was needed for three major steps in the MCA: criteria selection, criteria scoring, and criteria importance weighting. We hope to collect input from other professionals who are knowledgeable in various aspects of CAES. Specifically, we seek an informal consensus on what values should be adopted for the criteria importance weighting factors. Although it is not critical that respondents understand the methodology used in this study, a brief explanation of the process is described below to give the respondent more context. The MCA used in this study is a weighted linear additive system: the final score of an alternative, a location in this study, is equal to the summation of all the criteria multiplied by their respective weights:

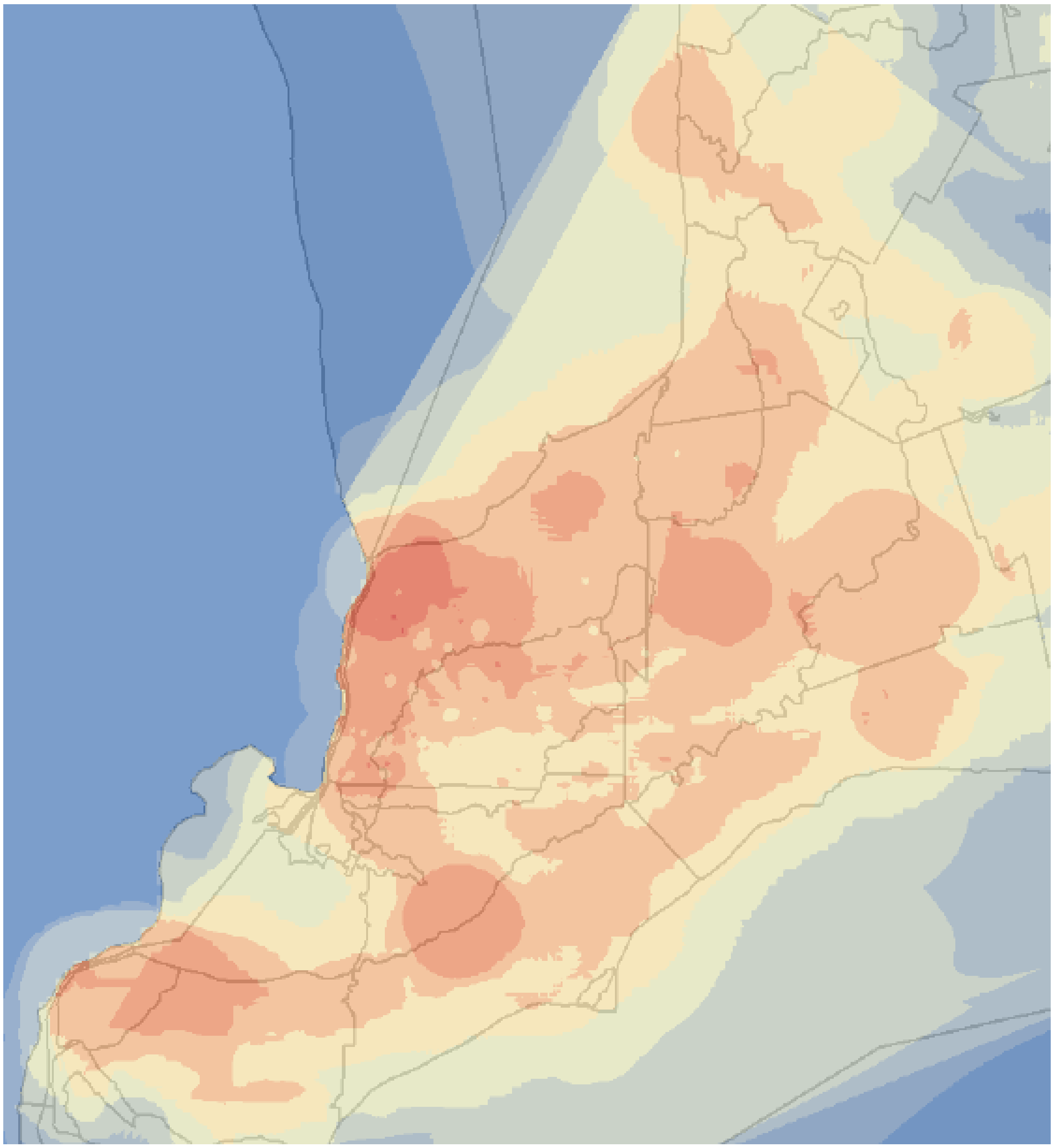
$$A_m = C_{1,m} * W_1 + C_{2,m} * W_2 + \cdots + C_{n,m} * W_n$$

Am is any possible or alternative location, $C_{1,m}$ is the score of criterion 1 for location 'm', W_1 is the weighting of criterion 1, and by extension $C_{n,m}$ is the score of criterion 'n' for location 'm', W_n is the weighting of criterion 'n.' Scores are determined by scoring systems for each criterion that convert a given value for the metric into a score on a scale of 0-100. Two examples of scoring systems are shown below.





The process starts with a metric determined from GIS maps, for example, depth to salt formation in metres. This becomes a score based on the author's experience of what is a good value and what is a bad value in the Canadian context. Finally, the product-sum of all criteria and their weights is calculated to determine an individual site score. As this is a spatially continuous GIS analysis, each pixel on the GIS maps are scored, and the results are shown as a colour plot. Some preliminary results are shown below: blue is low CAES potential, red is high CAES potential.



To more clearly understand the approach, the following reference may help:

Nadeem, M. and Dusseault M.B. 2007. Geological engineering criteria for deep waste disposal. Environmental Geosciences 14(2), 61-77.

For an introduction to Energy Storage methods, this reference is useful:

Ibrahim, H., Ilinca, A. and Perron, J. 2008. Energy storage systems – Characteristics and comparisons. Renewable and Sustainable Energy Reviews 12, 1221-1250.

Privacy Assurance

You will not be identified in the report or elsewhere for your participation unless you so wish; then your name will be listed in the acknowledgements. We will remove any identification and affiliation and delete the emails and files immediately after we incorporate the results; your opinions will not be identifiable. This is an informal survey of experts freely volunteering their opinion; no respondent is responsible or accountable for any opinions or assessments. Thank you for your participation, your input is valuable to us in developing a robust site selection approach to CAES for renewables integration!

Maurice B Dusseault, PEng, PhD

Professor of Geological Engineering, University of Waterloo

Fraser Lord, EIT, BASc

MASc Candidate, Civil and Environmental Engineering, University of Waterloo

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Name:

Main business affiliation:

- ❍ Industry (1)
- ❍ Government (2)
- ❍ Academic (3)
- ❍ Consultant (4)
- ❍ NGO (5)
- ❍ Other (6) ____________________

Area(s) of Expertise (relating to CAES – e.g. geomechanics, power engineering, grid management, renewable energy, geosciences, etc.):

Would you like recognition for your contribution in the acknowledgements?

- ❍ No (1)
- ❍ Yes, please indicate what name/entity you would like to be acknowledged (ex. enter your name and titles or enter your company name) (2) ____________________

When considering potential CAES sites, how would you rate the importance of these criteria in your process for selecting a site? A summary of the criteria can be found below. Numeric scale is from 0-100 where 0 is not important and 100 is highly important.

	Irrelevant (0) (1)	Unimportant (20) (2)	Secondary (40) (3)	Considerable (60) (4)	Primary (80) (5)	Pivotal (100) (6)
Depth of salt (1)	❍	❍	❍	❍	❍	❍
Salt thickness (2)	❍	❍	❍	❍	❍	❍
Local renewable energy potential (3)	❍	❍	❍	❍	❍	❍
Local energy demand (4)	❍	❍	❍	❍	❍	❍
Proximity to electric transmission lines (5)	❍	❍	❍	❍	❍	❍
Proximity to natural gas transmission lines (6)	❍	❍	❍	❍	❍	❍

Summary of Criteria

- Depth of salt: depth from ground surface to the top of the salt formation in question. The MCA process automatically evaluates all available salt formations for a location and selects the one with the highest total geologic score.
- Salt thickness: thickness of salt formation in question. This criterion is also considered in selecting the best formation.
- Local renewable energy potential: uses the higher score between two separate metrics: solar energy potential and wind energy potential.
    - Solar energy potential: average energy potential of solar within a 10 km radius, measured in annual average MJ/day/m^2panel area.
    - Wind energy potential: average energy potential of wind within a 10 km radius, measured in annual average W/m^2 propeller swept area.
- Local energy demand: total energy use within a 10 km radius, calculated by multiplying local population by the respective per capita energy use for each province.
- Proximity to electric transmission lines: distance to the closest electric power line which is 115 kV or larger.
- Proximity to natural gas transmission lines: distance to the closest natural gas transmission pipeline.

Part of an expert opinion solicitation is to ask the experts to self-rank in terms of their skill level for the particular metric. This allows us to weight the responses and thereby arrive at a more realistic consensus for the importance ranking of the site selection metrics. What confidence do you place in your choice of each criterion importance weighting?

Here, larger numbers represent a greater uncertainty in your answers. The word association in the columns is to help in gauging your confidence and translating it to a numeric value.

	Guessing (±50) (1)	"Ball-park" (±35) (2)	Uncertain (±25) (3)	Mixed (±15) (4)	Confident (±10) (5)	Positive (±5) (6)
Depth of salt (1)	❍	❍	❍	❍	❍	❍
Salt thickness (2)	❍	❍	❍	❍	❍	❍
Local renewable energy potential (3)	❍	❍	❍	❍	❍	❍
Local energy demand (4)	❍	❍	❍	❍	❍	❍
Proximity to electric transmission lines (5)	❍	❍	❍	❍	❍	❍
Proximity to natural gas transmission lines (6)	❍	❍	❍	❍	❍	❍

The list of criteria is not comprehensive, we selected the ones we judged to be of "first-order importance". In your opinion, are there important criteria missing from the list? Note that we focus on CAES use in renewables integration. You may suggest criteria that fall outside of this scope but please identify them as such to reduce the chance of us misinterpreting your suggestions. For example, a grid-scale CAES facility (>100 MW) provides load balancing, power ramping services, peak shaving, and some other useful roles, but we are limiting our survey to the integration of renewables only.

Do you have any concerns that you may be misunderstanding or responding inappropriately to a question? The purpose of this question is to help us understand your answers and to distinguish between uncertainty around the question and uncertainty in the value of your answers. We will answer any email queries you may have (fdlord@uwaterloo.ca). Comments: