Geographical Considerations for Site Selection of Small Modular Reactors in Saskatchewan

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By

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Raid Hassan Almalki, candidate for the degree of Master of Science in Geography, has presented a thesis titled, *Geographical Considerations for Site Selection of Small Modular Reactors in Saskatchewan*, in an oral examination held on April 30, 2018. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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ABSTRACT

Saskatchewan is one of Canada’s highest emitters of greenhouse gases, largely due to burning lignite coal to generate electricity. It is also the world’s second largest producer of uranium. Small Modular Reactors (SMR) are the next generation of electrical power, producing less than 300 megawatts (MW) and featuring a basic design that offers enhanced safety benefits on health and the environment than traditional reactors. The purpose of this research is to establish a process of geographical considerations for site selections of SMRs in Saskatchewan. Locating a SMR site is a two stage process: (i) identifying candidate site locations purely based on available geographical, economic, and logistical data – an objective process; and (ii) refining the locations based on public perception, social convention and political will – a subjective process. This study is on the objective part: the geographical considerations for site selection of SMRs in Saskatchewan.

Study areas were subjected to a multi-criteria decision analysis based on specific criteria selected from different Canadian federal regulation documents. Criteria weights were assigned using Analytical Hierarchy Process methods, with results from two different types of criteria weights applied for demonstration purposes. Three distinct cases of criteria fuzzy standardization were conducted to assign the suitable geographical distance values of all the criteria. Spatial decision-making models were implemented in a geographic information system to identify candidate sites. Geographical maps constructed from the findings, show the suitable sites for SMRs, ranging from very suitable to unsuitable based on the geographical analysis for the study area.
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<thead>
<tr>
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<th>Full Form</th>
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<tbody>
<tr>
<td>AHP</td>
<td>Analytical Hierarchy Process</td>
</tr>
<tr>
<td>CNSC</td>
<td>Canadian Nuclear Safety Commissions</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CI</td>
<td>Consistency Index</td>
</tr>
<tr>
<td>CR</td>
<td>Consistency Ratio</td>
</tr>
<tr>
<td>CLI</td>
<td>Canada Land Inventory</td>
</tr>
<tr>
<td>EPZ</td>
<td>Emergency Planning Zone</td>
</tr>
<tr>
<td>FNR</td>
<td>Fast Neutron Reactors</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>HTGR</td>
<td>High Temperature Gas-coolant Reactors</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>LWR</td>
<td>Light Water Reactor</td>
</tr>
<tr>
<td>MCDA</td>
<td>Multiple Criteria Decision Analysis</td>
</tr>
<tr>
<td>MMU</td>
<td>Minimum Mapping Unit</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>MWe</td>
<td>Megawatt electricity</td>
</tr>
<tr>
<td>RI</td>
<td>Random-Index</td>
</tr>
<tr>
<td>SMR</td>
<td>Small Modular Reactor</td>
</tr>
<tr>
<td>SSTRA</td>
<td>Site Selection Threat and Risk Assessment</td>
</tr>
<tr>
<td>SK</td>
<td>Saskatchewan</td>
</tr>
<tr>
<td>U</td>
<td>Uranium</td>
</tr>
<tr>
<td>WLC</td>
<td>Weighted Linear Combination</td>
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1. INTRODUCTION, THESIS OBJECTIVES, AND BACKGROUND

1.1. Introduction

As the global population increases currently from 7.3 billion to around 8.5 billion by 2030, so too does the demand for global energy. The International Energy Agency estimates a 53% increase in global energy consumption by 2030 (Idris and Latif 2012). To meet the demand, more energy producers need to be built. If these producers generate electricity by conventional coal- or gas-fired means, the raised amount of carbon dioxide (CO₂) emissions produced will have increasingly negative consequences on the environment by raising the temperature throughout the earth.

Currently, fossil fuels (gas, coal, and oil) are the greatest energy source for electricity generation, producing up to 82% of the global supply and hydro the lowest energy source for electricity generation (Figure 1) (World Energy Council 2013).

![World Energy Resources in 2011](image_url)

Figure 1: World Energy Resources in 2011 (World Energy Council 2013).
The effect on climate of increasing amounts of atmospheric CO₂ is of widespread concern, influencing decisions about how electricity should be generated. Worldwide releases of CO₂ from burning fossil fuels total about 30 billion tonnes per year, with about 40% stemming from coal and about 43% from oil (Tarlton 2012). Every 1000 MW power station running on black coal produces CO₂ emissions of about 7 million tonnes per year; if brown coal is used, the amount increases to about 9 million tonnes (Tarlton 2012).

In Saskatchewan, electricity is generated from a variety of sources. The provincial utility, SaskPower, operates five gas-powered stations, three coal-fired stations, seven hydroelectric stations and two wind facilities (SaskPower 2014). The generating capacity from these facilities is 3,338 MW, with an additional 843 MW available through long-term power purchase agreements (SaskPower 2014). SaskPower's total available capacity is marginally above the province's record system peak load of 3,628 MW in 2014 (SaskPower 2014).

About 40% of Saskatchewan's electricity is produced by five natural gas stations and 34% by three coal-fired power plants (SaskPower 2016-17). In 2012, these stations released 15.7 million tonnes of CO₂ into the atmosphere, accounting for about 21% of the province's total greenhouse gas emissions (Figure 2) (Environment Canada 2014).

Saskatchewan is the leading coal producer in Canada, with annual production of about 10 million tonnes of thermal coal, or lignite. Also, Saskatchewan is the leading uranium producer in Canada and accounts for over 16% of the world’s primary uranium production, second only to Kazakhstan (Saskatchewan Ministry of the Economy 2015). This gives rise to the opportunity for the province to produce its electricity through nuclear fission rather than by burning fossil fuels (Saskatchewan Ministry of the Economy 2015).
Clean energy is environmentally friendly, with little or no emissions. Nuclear power generation can make a significant contribution to decreasing dangerous greenhouse gas emissions. In addition to being a low-emission technology, nuclear generation uses fuel produced from an ore mined in Saskatchewan. Unlike solar and wind energy, which are irregular and sometimes intermittent power sources, nuclear power provides a consistent baseload power supply. Also, the impact of solar and wind energy on the environment by using more land areas. Thus, that will hamper other land uses purposes, including livestock grazing and agriculture.

![Distribution of Saskatchewan GHG Emissions by Major Sector, 2012](image)

*Figure 2: Distribution of Saskatchewan GHG Emissions by Major Sector 2012 (Environment Canada 2014)*

The electricity generated by nuclear energy has the potential to minimize environmental impact, as compared to other sources of energy. In a nuclear power plant, the nuclear fission of uranium in the reactor vessel does not produce CO₂ (Hsu, Wu and Jui 2014). While some greenhouse gases may be released as by-products of uranium mining and transportation of the core
uranium to the nuclear plant, these emissions are insignificant in comparison to the amounts released by coal-fired generating stations (Hsu, Wu and Jui 2014).

The use of nuclear fission for electrical power generation was established during the 1950s. Since then, the generating capacity of reactor units has increased from 60 MWe to more than 1600 MWe (World Nuclear Association 2017). Historically, nuclear power plants have been massive infrastructure projects, supplemented with significant fuel cycle operations and subsequent generation of radioactive waste. This has led to the consideration of smaller power plants. The shift towards developing smaller power plants is being driven by the higher operational costs and higher potential of accidents and greater risks associated with conventional reactors, and the increasing need to generate electricity for grid and off grid areas that require less than 4 MWe (World Nuclear Association 2017). Small unit power plants can be built as individual structures or as modules to increase capacity, as required. The small unit offers flexible investment as compared to traditional reactors that are challenging to finance. Smaller units can be built below the ground, a safety improvement over the larger above-ground nuclear plants. As well, designing smaller plants in factories and shipping them to the site is more cost effective than larger plants built on-site (World Nuclear Association 2017).

Small modular reactors (SMRs) are the next generation of nuclear power plants. SMRs typically produce less than 300 MWe (Lyons 2012). Their basic design offers enhanced safety benefits, such as the potential to reserve a smaller emergency exclusion zone and the potential for siting the reactor beneath grade (Lyons 2012). Economically, they benefit from reduced economic dangers and the flexibility to add units as power demands increase (Lyons 2012). They also have the potential to meet localized demands reliably, without loss from long and vulnerable
transmission lines (Stewart 2017). It is possible, therefore, that Saskatchewan might consider power generated by SMR as a feasible alternative to fossil fuels within the foreseeable future.

Currently, over 850 nuclear reactors operate worldwide, with use ranging from producing isotopes for medicine and industry (240 small reactors in 56 countries), to powering ships and submarines (180 small reactors), to generating energy (433 large reactors in 30 countries) (Tarlton 2012). The International Atomic Energy Agency (IAEA) estimates that around 96 SMRs will be operated worldwide by 2030 (Canadian Nuclear Association 2013).

SMRs are capable of supplying power from different applications such as smaller electrical grids or remote, off-grid areas. Designers point out that SMRs will be able to supply service regions where larger nuclear power plants cannot do so (Canadian Nuclear Safety Commission 2016).

Alternative uses of SMRs are being considered beyond generating electricity. These include supplying steam for industrial applications and district heating systems, and producing value-added products, such as hydrogen fuel or desalinated drinking water (Canadian Nuclear Safety Commission 2016).

The latest nuclear power generation technologies, which include SMRs and advanced reactors, vary significantly from traditional nuclear power plants in their size, design features and cooling types (Canadian Nuclear Safety Commission 2016). Because SMRs have fewer risks than the big nuclear plants, they have the potential of more suitable sites. In particular, their site locations could potentially be different from past nuclear power plant projects. For example, they could be located:

- On small electrical grids where the power must remain below specified standards; for example, 300 megawatts of electricity (MWe) per each facility to sustain grid stability (Canadian Nuclear Safety Commission 2016).
• At edge-of-grid or off-grid locations in the range of 2 to 30 MWe to supply small amounts of power or where energy production is expensive and dependent on fossil fuels (Canadian Nuclear Safety Commission 2016).

• In areas where old coal power plants are being retired.

In addition, SMRs can be more cost effective, operate more safely, and have greater public acceptance. For example, since SMRs can be manufactured in different factories and then shipped to their destinations for final assembly, they can be more cost effective than traditional nuclear power plants. The smaller footprints of SMRs open up more potential suitable sites. Moreover, big nuclear power plants could be sited away from populated areas, increasing their production, maintenance, and transmission costs, whereas SMRs can be situated quite close to the places where their power is needed.

SMRs offer safety improvements over larger nuclear plants. For example, some studies recommend that SMRs are built below the ground, increasing safety and security (Rodman 2015). Additionally, SMRs can be sited in more earthquake-prone areas- since ground movement protection is more easily built in the SMR design.

In some locations, public perception towards nuclear power tends to be more negative than positive. Ironically, this is particularly so in the U.S. and France, where significant proportions of the national energy supply are nuclear-sourced (Nuclear Energy Agency 2010). Opinion polls reveal that public support of the nuclear power has decreased since the 2011 Fukushima crisis (Gerry and Keith 2015). The public opposes nuclear power for many reasons; the most prevalent reason lies in the fact that people perceive it as dangerous technology. The nuclear industry has responded by implementing a wide range of image-building initiatives, in an effort to alter the public’s perception of generating electricity using nuclear reactors. These include information
events, cost-benefit analyses, risk mitigation strategies, as well as attempts to present nuclear power as the best solution to contemporary climate issues (Bond 1973). Nuclear energy is currently considered as a major source for generating electricity. As global climates continue to change, the low-carbon footprint of a nuclear power plant makes it an increasingly attractive option to traditional power generation from fossil fuels. The advent of small modular reactors presents interesting opportunities for the power production in the near future.

Most SMR site-selection assumptions are derived through various approaches drawing from past operating experiences in conjunction with current technologies. Such approaches and processes may have an impact on how the nuclear power plant will operate under both normal operation and accident conditions. Raising regulatory questions and concerns of uncertainties during the site licensing process increases the need for greater data and risk assessments to ensure safety, security, health, and the environment (Canadian Nuclear Safety Commission 2016). Mitigating risk is the goal.

1.2. Thesis Objectives

This research will look into identifying suitable sites for SMR across Saskatchewan; focusing on the geographical factors. The primarily goals are: to explore how geographical siting activities fit into infrastructure development phases and identifies the geographical factors likely to be used to define appropriate sites, based on safety, health, environmental and social parameters. The data used to inform the site selection procedure, strategies for implementing the siting process, and the methods for assessing the various siting factors, are identified and described.
1.3. Background

SMRs are one of the new technologies of nuclear fission reactor types, which are smaller than traditional reactors, and there are a few prior siting studies to use as models. The primary SMR technologies under development are:

1.3.1. Light water reactors (LWRs):

LWRs, which are moderated and cooled using ordinary water and are distinguished by having the lowest technological risk of the current SMR designs (World Nuclear Association 2017). They are similar to most operating power and naval reactors today. LWRs have a fuel cycle of less than six years in duration and typically use U-235 fuel. Regulatory obstacles are the lowest of any small reactors because they are the most congruent with the present regulatory structure (World Nuclear Association 2017).

1.3.2. Fast neutron reactors (FNRs):

FNRs are smaller and simpler than LWRs, with longer term operation before refueling. However, a new safety case must be established for them due to higher enrichment more than 20%, others; less than 5%. FNRs have a better fuel performance with a longer refueling interval, up to 30 years (World Nuclear Association 2017).

1.3.3. High temperature gas-coolant reactors (HTGRs):

HTGRs can generate electricity, provide heat for the industrial and transport sectors, and produce hydrogen for the long term (Golder Associates 2016). The technology of HTGRs is based on using coated fuels with layers of pyrolytic carbon and silicon carbide and helium as a coolant, allowing higher outlet temperatures for different applications such as process heat and hydrogen production, hence higher thermal efficiency (Golder Associates 2016).

1.3.4. SMR Siting
Several studies have focused on siting SMRs for specific power generation technology applications, using appropriate criteria to screen sites and employing a geographic information system (GIS) corresponding to the environmental applications identified. A report from the Oak Ridge National Laboratory proposes some SMR criteria for site selection: slope, seismic activity, proximity to cooling water sources, population density, proximity to hazard facilities, avoidance of protected lands and floodplains, susceptibility to landslide hazards, and attractive criteria such as proximity to transportation resources, cooling water, and transmission lines (Randall, Olufemi and Willis 2012).

The Idaho National Laboratory recommends that site selection needs to take hazard avoidance into account. Their criteria include population density, available water resources, seismic activity, proximity to hazard areas such as airports and industrial activities, avoidance of protected lands and flood plains, susceptibility to landslides, and other factors can impact constructability and operations (Idaho National Laboratory 2013).

A report prepared by Golder Associates divided siting criteria into three parts (Golder Associates 2016):

1. Constrained areas including flooding zone, wetlands, tsunami inundation, parks, volcanic hazards, and landslides.

Attractive areas: transmission lines, railroads, highways, and existing power plants.
2. SCOPE OF STUDY, RESEARCH GOALS, AND APPROACH AND METHODS.

2.1. Scope of Study

This study focuses on the Canadian Province of Saskatchewan (Figure 3). Saskatchewan has an area of 652,330 square kilometers, with about one-eighth covered with water (Lewry 2016). The southern part of the province, where population density is highest, is rolling prairie, interspersed with valleys eroded by meltwaters from the last glacial era (Lewry 2016). The highest elevation in the Cypress Hills, sitting at 1460 meters above sea level (The Canadian Encyclopedia 2017). The province has three major river systems all emptying into Hudson Bay: the North and South Saskatchewan Rivers, the Churchill River, and the Assiniboine River. The central and northern parts of the province are not heavily populated (The Canadian Encyclopedia 2017). The soils around the southern part are predominantly chernozems and conducive to agriculture, while in the north, the climate and poor soil development prohibits large scale agriculture (The Canadian Encyclopedia 2017). Fishing production is more notable in the north; in the south, individual farmers raise fish for their own use (The Canadian Encyclopedia 2017).

Saskatchewan was chosen as this study’s locale because it has the unique distinction as one of Canada's highest greenhouse gas emitters in 2015 (Environment and Climate Change Canada 2017), arising from the burning of lignite coal, and having the second-largest uranium reserves in the world (Saskatchewan Ministry of the Economy 2015). Saskatchewan has the potential to be one of Canada's lowest greenhouse gas emitters if power generation is switched to nuclear.
2.2. Research Goals

Locating a SMR site is a two stage process: (i) identifying candidate site locations purely based on available geographical, economic, and logistical data – an objective process; and (ii) refining the locations based on public perception, social convention and political will – a subjective process. This study’s purpose is on the objective part: the geographical considerations for site selection of SMRs in Saskatchewan.

Figure 3: SMR siting study in Saskatchewan Canada
The purpose is to develop an objective and reproducible process for optimum site selection for small modular nuclear reactors and to identify the most important spatial geographic factors in finding suitable sites for SMRs.

This purpose is focused around two key questions:

1. What are the important geographical objective criteria to consider when siting a modular nuclear reactor?

2. By what methods should these criteria be combined to find suitable locations?

The site suitability analysis is based on objective geographical factors. Our siting criteria do not include factors such as: energy supply and demand, SMR competition with other power generation technologies, public perception, cost and cultural resource issues. These factors need to be considered by the Saskatchewan governing bodies.

Further, in order to create a functional analysis for this study, the relative importance of the various siting criteria had to be estimated. The estimates used here were based on information found in the literature, shared knowledge, and in some cases data characteristics. It is acknowledged, however, that the estimates may benefit from additional fine-tuning with input from domain experts. Even so, such expert knowledge is somewhat subjective and different experts may provide different recommendations. It is also noted that SMR technologies are new: expert knowledge of some siting aspects does not yet exist.
2.3. **Approach and Methods**

The purpose of this thesis is focused on the determination of candidate sites for small modular reactors in Saskatchewan. Conceptually, this process can be considered in four stages: (i) identifying the criteria crucial for site selection; (ii) assigning weights to the selected criteria to reflect their relative importance, (iii) evaluating the methods by which the criteria are combined in a geospatial analysis and (iv) spatial interpretation of the results. Details about each of these stages are provided below. Procedurally, Figure 4 illustrates how the siting process can be implement in a GIS.
Figure 4: Flowchart showing the methods in using GIS.

1. **Input**
2. **Data processing and conversion**
3. **Evaluation criteria data \( (x_i) \)**
4. **Weighted criteria using pairwise comparison \( (w_i) \)**
5. **Screen the area using Evolution criteria \( (\sum w_i x_i) \)**
6. **Candidate sites**
7. **Candidate areas with restriction criteria \( (\sum wixi \cdot \prod cj) \)**
8. **Restriction criteria data \( (cj) \)**
9. **Output**
10. **Suitable sites**
3. RESULTS

3.1. Identifying the criteria for site selection


The potential criteria included: population distribution and density, surface water, land uses, protected lands, airports, earthquakes and surface-faulting hazards, electricity infrastructure, existing power plants, flooding, wetlands, transportation, groundwater, fisheries areas, volcanoes, forest fires, tornadoes, mines, agricultural areas, and slope.

Some of these criteria were not used in this study because some they were not applicable in the Saskatchewan environment. Criteria that weren't used included earthquakes, mines, existing power plants, fisheries areas, forest fires, grass fires, volcanoes, and climatic factors. These are all important factors, but some they have more impact on the construction of a reactor at a particular site, than on the overall selection of that site. For example, the forest fire criterion was not included in this study because the use of fire buffers could mitigate the impact of forest fires on reactor operation (National Agroforestry Center 2008). The volcanoes criterion was not used since active volcanism is absent in Saskatchewan (Natural Resources Canada 2017).

Locating an SMR at a uranium mine or an existing power plant may well be cost effective because the reactor can take advantage of the infrastructure already in place there. Predetermining
the location of an SMR in this way negates the need for a province-wide siting analysis, such as the present study, so these locations were excluded from this analysis.

3.1.1. Identification of Restrictions and Evaluation Criteria

The selected criteria are refined by determining which identify site restrictions and which are more useful for inter-site comparison evaluations. Site restriction criteria limit (exclude) possible alternatives based on Boolean relations (true/false). The evaluation criteria can be quantified according to the degree of suitability for all feasible alternatives (Gigovic, et al. 2016). Determining the differences between the criteria was adopted according to the study goals and the CNSC regulations.

After reviewing the CNSC environmental and public safety regulations, nine restriction criteria and five evaluation criteria were adopted to find the suitable sites for SMRs. These were selected because of their relevance to smaller reactors and their applicability in the Saskatchewan environment. These restriction and evaluation criteria are described in Tables 1 and 2, respectively.

As illustrated in Figure 5, the geographic distances for the siting criteria exclusion zones used in this study were standardized to three fuzzy cases:

- Open
- Normal
- Restrictive

The Normal case criteria maps and accompanying details appear in the Results section, under the Evaluation and Restriction criteria maps subsection. The other cases criteria maps are presented in the Appendix. The final suitability maps, which capture the various results for all the cases, are in the Results section, under SMR Siting Suitability.
The spatial distances between a reactor location and its various restriction and evaluation criteria features are important geographical measurements for SMR siting. Currently, no legislative or regulatory requirements exist for measuring the distance between SMRs and the siting criteria; neither are restrictions in place on minimum distances between SMRs and siting criteria. Therefore, the geographical measurements, or the criteria standardizations values from the siting criteria, are fuzzy and may vary between government parties and vendors. The variations stem from the stakeholders’ perspectives and knowledge of the interaction between siting SMRs with the other siting criteria.

To better understand the effects of such variations SMR siting studies should focus on different cases, such as the Open case, that considers placing the reactor near to the siting criteria, in contrast to the Restrictive case that calls for more distance between the SMR and siting criteria. For example, the Open case may determine 2 km as the spatial distance between the SMR’s placement and land uses criterion; alternatively, the Restrictive case may decide that 10 km is preferable as the spatial distance. Thus, drawing from the previous examples, different cases, including the Normal case that is between the Open and Restrictive cases, are presented in Figure 5. Measurements, for demonstration purposes, are included, in an effort to address the vested interests of government parties and vendors.
Figure 5: Comparison of siting cases for sitting SMR
Table 1: Restriction criteria for site selection of SMR in SK (after CNSC 2008).

<table>
<thead>
<tr>
<th>Restriction Criteria</th>
<th>Description</th>
<th>Exclusion zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protected areas</td>
<td>Protected lands include national monuments, national forests, wilderness areas, wildlife refuges, wild and scenic rivers, provincial parks and county parks. These lands are excluded based on their public nature and safeguarding of wildlife species, wildlife habitats and unique or ecologically sensitive areas.</td>
<td>&lt; 3 km</td>
</tr>
<tr>
<td>Land uses</td>
<td>Regional sensitive land use (e.g., hospitals, residences, state, federal, and local parks, local culturally sensitive lands, and sensitive viewsheds) must be determined.</td>
<td>&lt; 2 km</td>
</tr>
<tr>
<td>Flooding areas</td>
<td>Site assessment must consider surface water hydrology and instrumentally recorded hydrological data, such as water levels and flow rates. Thus, lands that have flood potential are excluded.</td>
<td>&lt; 1 km</td>
</tr>
<tr>
<td>Airports</td>
<td>Lands located in proximity to airports are avoided based on their potential hazards. The exclusion is for both commercial and non-commercial Service Airports.</td>
<td>&lt; 2 km</td>
</tr>
<tr>
<td>Population density</td>
<td>Land with a population density greater than 200 people per square km (500 persons per square mile) is excluded (Idaho National Laboratory 2013).</td>
<td>&lt; 3 km</td>
</tr>
<tr>
<td>Wetlands</td>
<td>Wetland areas that have a quantity of organic matter must be protected. All wetlands are excluded without any buffer zone.</td>
<td>Excluded</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Groundwater is taken into consideration through hydrogeological investigation, based on data modeling. The impact of siting the SMRs on the groundwater flow system and contamination requires assessment. The more depth of groundwater the more preferable, because water reduces strength of soil materials. After evaluating the groundwater criteria, land with groundwater level close to the surface are excluded.</td>
<td>Evaluated</td>
</tr>
<tr>
<td>Agriculture</td>
<td>These lands are Evaluated based on their public nature. The agriculture classified into different classes based on ISO 19131 Canada Land Inventory (CLI). Thus, All the agriculture lands or the lands that are suitable for agriculture must be evaluated. Those with agricultural potential must be avoided.</td>
<td>Evaluated</td>
</tr>
<tr>
<td>slope</td>
<td>The lands with greater than 15% (~8°) is excluded for the Normal case (Golder Associates 2016).</td>
<td>&lt; 10 %</td>
</tr>
</tbody>
</table>
Table 2: Evaluation criteria for site selection of SMR in SK (after CNSC 2008).

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populated areas</td>
<td>SMRs need to be located relatively close to major population or customer bases. Placing them in very close proximity to populations is avoided, predominately as a safety measure. Highly populated areas will not be considered. Thus, Populated areas must be evaluated.</td>
</tr>
<tr>
<td>Railways</td>
<td>One of the advantage of SMR is the ability to manufacture and then ship it to the site. Therefore, railways are required for siting SMRs as rail transport is the key means of equipment transport.</td>
</tr>
<tr>
<td>Transmission lines</td>
<td>Practical and strategic connections to the transmission grid to supply electricity to areas of demand. The ability of the grid system to accept power in-feed at a site location, without requiring costly and time-consuming reinforcement, is critical. Due to high capital and low running costs, nuclear reactors should be sited to work as a base load plant; the network infrastructure should enable continuous operation at full power (IAEA 2012). Also, remote locations off-grid are considered in this study. Thus, the transmission line criterion must be evaluated based on the distance of how SMR need to be close to a transmission line.</td>
</tr>
<tr>
<td>Roads</td>
<td>SMR can be manufactured and then shipped it to the site. So, roads to transport SMR equipment and to afford site access, are required for siting SMRs.</td>
</tr>
<tr>
<td>Surface water</td>
<td>Surface water refers to the major water source – lakes and rivers – found in a specific area. Surface water must be determined to avoid any potential impact of the reactors’ operation and contaminant potential must be determined to be considered in SMRs operations and cooling.</td>
</tr>
</tbody>
</table>

3.1.2. Data finding, processing, and conversion

After the criteria are determined, matching datasets were found. Since geospatial datasets are created by different agencies for specific purposes, their combination is frequently not directly possible. Thus, various data formatting processes and conversions are put into place in preparation for weighting and combining. The processing and conversion steps in Figure 6 may include scaling, resolution adjustment, coordinate system reprojection, map extent selecting, querying, buffering, and transforming data between vector to raster data structures. Such data preparations are important to minimize errors that may accumulate through the siting process.
The datasets used in this study come from various federal and provincial government sources and are described in Table 3.
<table>
<thead>
<tr>
<th>Name</th>
<th>Source</th>
<th>Date</th>
<th>Projection</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface water</td>
<td>DMTI</td>
<td>2013</td>
<td>GCS_WGS_1984</td>
<td>Major lakes and rivers in Saskatchewan.</td>
</tr>
<tr>
<td>Land use</td>
<td>GeoGratis</td>
<td>2016</td>
<td>GCS_North_American_1983_CSRS</td>
<td>The featured entities are: dam, liquid storage facility (basin, swimming pool…), Tank, Building, Landmark Feature (cross, radar, crane, fort…), Chimney, cell tower, Waste, Leisure Area, Residential Area, Commercial, and Institutional Area and Ritual Cultural Area (shrine, cemetery…).</td>
</tr>
<tr>
<td>Populated areas and density</td>
<td>Statistics Canada</td>
<td>2015, 2016</td>
<td>PCS_Lambert_Conformal_Conic</td>
<td>The file boundary was for 2015 and the census subdivision table was joined with the file boundary.</td>
</tr>
<tr>
<td>Slope</td>
<td>Earth Explorer</td>
<td>2010</td>
<td>GCS_WGS_1984</td>
<td>Global Multi-resolution Terrain Elevation Data with resolution of 7.5 arc-seconds (about 250 meters).</td>
</tr>
<tr>
<td>Airport</td>
<td>Our-airport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity infrastructure</td>
<td>SaskPower</td>
<td>2010</td>
<td></td>
<td>Major transmission lines in Saskatchewan</td>
</tr>
<tr>
<td>Wetland</td>
<td>Commission for Environmental Cooperation</td>
<td>2010</td>
<td>GCS_WGS_1984</td>
<td></td>
</tr>
<tr>
<td>Protectors areas</td>
<td>Environment Canada</td>
<td>2008</td>
<td>GCS_WGS_1984</td>
<td>Includes wildlife species, wildlife habitats and unique or ecologically sensitive areas, national parks, Canada terrestrial and marine protected areas</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><a href="http://geogratis.gc.ca/api/en/nrcan-rncan/esssst/08e80876-a3a6-5aba-9e94-4ff82337cc64.html">http://geogratis.gc.ca/api/en/nrcan-rncan/esssst/08e80876-a3a6-5aba-9e94-4ff82337cc64.html</a></td>
</tr>
<tr>
<td>Railways</td>
<td>DMTI</td>
<td>2013</td>
<td>NAD_1983_UTM_Zone_13N</td>
<td></td>
</tr>
<tr>
<td>Highways</td>
<td>Natural Resources Canada</td>
<td>2016</td>
<td>NAD_1983_UTM_Zone_13N</td>
<td></td>
</tr>
<tr>
<td>Agriculture</td>
<td>Agriculture &amp; Agri-Food Canada</td>
<td>1960-1980</td>
<td>GCS_Clarke_1866</td>
<td>The agriculture layer was classified into 5 categories based on ISO 19131 Canada Land Inventory (CLI) – Data Product Specification as showing in the following after this table, where Class 1 is prime agricultural farm land with no significant limitations. These areas are unsuitable for siting an SMR. Conversely, Class 5 agricultural land has severe limitations for food production and are high suitable for siting SMRs. Agricultural data are only available for the southern portions of the province because agriculture is restricted in the north due to climatic (i.e. short growing season) and petrologic (i.e. lack of soil) conditions. These northern areas were classified in this research as unsuitable for agriculture.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Groundwater Information Network</td>
<td>2014</td>
<td>WGS 84</td>
<td>Groundwater data were unavailable for the northern regions of the province dominated by igneous and metamorphic rocks of Precambrian origin. As indicated in Golder Associates (2014), Everitt et al. (1996) reported that in Manitoba's Lac du Bonnet Batholith, groundwater movement occurred down to about 200 m. It is expected that groundwater flow within Canadian Shield rocks in Saskatchewan will be similar to other locations in the Canadian Shield (Golder Associates 2014). Thus, Groundwater in the Canadian Shield is both scarce and deep.</td>
</tr>
</tbody>
</table>

The agriculture criterion was classified based on the ISO 19131 Canada Land Inventory (CLI) document as specified in Table 4.
Table 4: ISO 19131 Canada Land Inventory (CLI) – Data Product Specification (Agriculture and Agri-Food Canada n.d.)

<table>
<thead>
<tr>
<th>Name</th>
<th>Class_A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>The primary and/or dominant CLI class</td>
</tr>
<tr>
<td>Producer</td>
<td>Agriculture and Agri-Food Canada</td>
</tr>
<tr>
<td>Value Data Type</td>
<td>CHARACTER</td>
</tr>
<tr>
<td>Value Domain Type</td>
<td>1 (enumerated)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feature Attribute Value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Label 1</td>
<td>No Significant Limitations</td>
</tr>
<tr>
<td>Label 2</td>
<td>Moderate Limitations; moderate conservation practices required.</td>
</tr>
<tr>
<td>Label 3</td>
<td>Moderately Severe Limitations; range of crops restricted or special conservation practices required.</td>
</tr>
<tr>
<td>Label 4</td>
<td>Severe Limitations</td>
</tr>
<tr>
<td>Label 5</td>
<td>Forage Crops – Improvement practices feasible</td>
</tr>
<tr>
<td>Label 6</td>
<td>Forage Crops - Improvement practices not feasible</td>
</tr>
<tr>
<td>Label 7</td>
<td>No Capability for arable culture or permanent pasture</td>
</tr>
<tr>
<td>Label 0</td>
<td>Organic Soils</td>
</tr>
<tr>
<td>Label 8</td>
<td>Unclassified areas</td>
</tr>
<tr>
<td>Label W</td>
<td>Water</td>
</tr>
</tbody>
</table>

It should be noted that the agriculture and groundwater datasets did not cover the entire study area; data for the northern boreal regions of the province were missing. The extent of agricultural lands is very restricted in the north due to climate (i.e. short growing season) and geological (i.e. lack of soil) conditions. In this study, these northern areas were classified as unsuitable for agriculture (therefore suitable for siting an SMR). Similarly, the northern regions of the province are dominated by igneous and metamorphic rocks of Precambrian origin that severely limit access to groundwater resources. As indicated in Golder Associates (2014), Everitt et al.
(1996) reported that in Manitoba's Lac du Bonnet batholith, groundwater movement was measured down to about 200 m. It is expected that groundwater flow within Canadian Shield rocks in Saskatchewan will be similar to other locations in the Canadian Shield (Golder Associates 2014). Thus, the groundwater in northern Saskatchewan was considered to be scarce and likely deep, therefore very suitable for siting an SMR.

3.2. Data standardization

Since these data were measured on various enumeration scales, they needed to be standardized before being combined or changed. Common standardization scales include 0.0-1.0 real number scales and 0-255 integer scales (Drobne and Lisec 2009). Such scales could be used to develop fuzzy set membership functions (Drobne and Lisec 2009).

All map layer data were converted into a range between 1 and 5. In this case, the highest value was allocated to the maximum membership and the lowest value to the minimum membership. Table 5 describes the standardization values that were used.

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Unsuitable</td>
</tr>
<tr>
<td>2</td>
<td>Less suitable</td>
</tr>
<tr>
<td>3</td>
<td>Moderately suitable</td>
</tr>
<tr>
<td>4</td>
<td>Suitable</td>
</tr>
<tr>
<td>5</td>
<td>Very suitable</td>
</tr>
</tbody>
</table>
Fuzzy standardization is a method in which the truth values of variables may be between 0 and 1. It was applied to the evaluation criteria layers as shown in Table 6 for the Normal case and the Open and Restrictive cases are shown in the Appendix in section A. 1 and A. 2. The ranges used in each category are used for demonstration purposes. They represent reasonable estimates of the importance of each criterion based on observed ranges in the data and shared knowledge. It is acknowledged, however, that they may benefit from additional fine-tuning with input from domain experts. Even so, such expert knowledge is somewhat subjective and different experts may provide different recommendations.

Table 6: Evaluation criteria standardization values for the Normal case.

<table>
<thead>
<tr>
<th>Evaluation criteria</th>
<th>1 Unsuitable</th>
<th>2 less suitable</th>
<th>3 Moderate suitable</th>
<th>4 Suitable</th>
<th>5 Very suitable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populated areas</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>5-10 km</td>
<td>&gt;3-5 km</td>
</tr>
<tr>
<td>Surface water</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>5-10 km</td>
<td>0-5 km</td>
</tr>
<tr>
<td>Railways</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>5-10 km</td>
<td>0-5 km</td>
</tr>
<tr>
<td>Roads</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>5-10 km</td>
<td>0-5 km</td>
</tr>
<tr>
<td>Transmission lines</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>5-10 km</td>
<td>0-5 km</td>
</tr>
</tbody>
</table>

Most of the restriction criteria were standardized on a binary scale: either an SMR is permitted in this location or it is totally excluded. For example, airports, protected areas, wetlands, and areas of steep slopes were completely removed from the siting analysis. Fuzzy standardization scales were used for depth to groundwater and agricultural land use classes (Table 7).
Table 7: Agriculture and groundwater standardization table for the Normal case.

<table>
<thead>
<tr>
<th>Restriction criteria</th>
<th>Intensity of important</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Groundwater</td>
<td>Unsuitable</td>
</tr>
<tr>
<td></td>
<td>8 – 11 m</td>
</tr>
<tr>
<td>Agriculture (label)</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2.1. Minimum Mapping Unit (MMU)

In addition to standardizing the values among the data layers, a common spatial base for the analysis is required. The selection of an appropriate minimum mapping unit (MMU) is based on the resolution and precision of the source data as well as the level of detail required in the analysis. When selecting an appropriate MMU, it is difficult to balance precision and computational efficiency. As the MMU becomes smaller, the analysis becomes more precise, at the expense of an exponential increase in data storage and processing requirements. In the present study, the MMU needed to be large enough to situate an SMR yet not too big so that small but viable locations would be missed. It was decided that 4 hectares (200 m x 200 m) was an appropriate MMU since it is the smallest parcel of land on which an SMR could be located. For example, the Westinghouse SMR requires a total site area of 6 hectares for generating 225+ MWe (Golder Associates 2016). The 4 hectares spatial base used here facilitates units such as this, as well as less powerful SMRs that are anticipated to have smaller footprints. In addition, SMR sizes may decrease in the future as the technology matures.
3.3. Assigning weights to the selected criteria

Weights and scores are typically assigned based on the researchers’ knowledge of the study area and in consultation with local experts and decision makers (Al-Hanbali, Alsaaideh and Kondoh 2011). Generally, higher weightings are typically given to the principal factors that have a potentially stronger impact – for example, distance from urban areas. Factors with lesser impact or those readily adjusted by engineering processes – for example, distance to wells - are assigned lower weightings (Al-Hanbali, Alsaaideh and Kondoh 2011). Experts frequently use descriptive scales to weight the evaluation criteria, as shown in Table 8.

3.3.1. Analytic hierarchy process (AHP) method

Saaty (2008) developed a decision-making process, called the Analytical Hierarchy Process (AHP) method, which has been shown to have a wide application in determining preference from a wide range of tangible and intangible criteria (Fam, et al. 2017). The AHP method begins by calculating the pair-wise criteria weights, as following:

3.3.2. Pair-Wise Comparison Methods

The criteria are compared in pairs and the relative importance between each couplet is rated. Saaty (2008) used a 9-point scale to rate the comparisons (Table 8). The ratings are entered into an inverse symmetric matrix where the sum of each row is then used to define the relative weight of each criterion.
Table 8: Pair-Wise Comparison Rating Scale.

<table>
<thead>
<tr>
<th>Numerical ratings</th>
<th>Verbal judgments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equally important</td>
</tr>
<tr>
<td>3</td>
<td>Moderately more important</td>
</tr>
<tr>
<td>5</td>
<td>Strongly more important</td>
</tr>
<tr>
<td>7</td>
<td>Very strongly more important</td>
</tr>
<tr>
<td>9</td>
<td>Extremely more important</td>
</tr>
</tbody>
</table>

A weighted sum vector \( \{W_s\} \) is determined by multiplying the weight vector \( \{W\} \) for the first criterion times the first column of the original pair-wise comparison matrix \([C]\), then multiplying the second weight times the second column, the third criterion times the third column, and so on, to the last weight and, finally. This is expressed in a matrix form as (Drobne and Lisec 2009):

\[
\{W_s\} = [C] \ast \{W\}
\]  \hspace{1cm} (1)

Equations (2) to (4) show how a consistency ratio determines whether the comparison matrix is acceptable or not. A consistency vector is determined by dividing the weighted sum vector by the criterion weights established previously:

\[
\{consis\} = \{W_s\} \ast \{1/W\}
\]  \hspace{1cm} (2)

The consistency index is calculated as:

\[
CI = \frac{\lambda - n}{n - 1}
\]  \hspace{1cm} (3)
where $\lambda$ is the average value of the consistency vector and $n$ is the number of criteria.

A consistency ratio is defined as:

$$CR = \frac{CI}{RI}$$

(4)

where $RI$ is the random consistency index for $n \times n$ matrix if the pairwise comparisons were completely random as given in Table 9, and $CI$ is the consistency index which provides a measure of departure from consistency.

<table>
<thead>
<tr>
<th>Size</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.00</td>
<td>0.00</td>
<td>0.58</td>
<td>0.90</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

Table 9: The random consistencies index for random generated matrices (Drobne and Lisec 2009).

If $CR$ is less than 10%, then the matrix can be considered as having an acceptable consistency (Drobne and Lisec 2009).

For demonstration purposes, two different sets of criteria weights were tested in order to examine the sensitivity of the results to different weighting factors. The first set of criteria weights assign a higher priority to proximity to transmission lines and surface water and the second criteria weights prioritizes proximity to highways and railways. The pair-wise comparison matrices and associated ranking tables for each set are shown in Figure 7.
### Pairwise Comparison Matrix

<table>
<thead>
<tr>
<th></th>
<th>Transmission line</th>
<th>Railways</th>
<th>Highways</th>
<th>Populated areas</th>
<th>Surface water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission line</td>
<td>1.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Railways</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Highways</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Populated areas</td>
<td>2.0</td>
<td>1.0</td>
<td>3.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Surface water</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Weight Priority and Ranking

<table>
<thead>
<tr>
<th>Category</th>
<th>Criteria</th>
<th>Priority</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transmission line</td>
<td>19.60%</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Railways</td>
<td>17.20%</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Highways</td>
<td>15.40%</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Population</td>
<td>28.70%</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Surface water</td>
<td>19.10%</td>
<td>3</td>
</tr>
</tbody>
</table>

### Pairwise Comparison Matrix

<table>
<thead>
<tr>
<th></th>
<th>Transmission line</th>
<th>Railways</th>
<th>Highways</th>
<th>Populated areas</th>
<th>Surface water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission line</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Railways</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Highways</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Populated areas</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Surface water</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Weight Priority and Ranking

<table>
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<th>Priority</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>Transmission line</td>
<td>15.2%</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Railways</td>
<td>19.7%</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Highways</td>
<td>22.7%</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Population</td>
<td>22.7%</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Surface water</td>
<td>19.7%</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 7: Sample Criteria Weights and Rankings**

The consistency ratios for these weight sets were 5.4% and 1.7%, respectively.
3.4. Geospatial analysis

Once a set of criteria is selected, and relative weights defined, the final step in the analysis is to combine them with the intent of producing a map identifying the locations of candidate sites. This is known as a Multi-Criteria Decision Analysis (MCDA) process (Abudeif, Moneim and Farrag 2014).

The MCDA applies rules to describe a relationship between the input criteria and the output maps, with an emphasis on geographic data, the decision maker’s preferences, and data manipulation (Drobne and Lisec 2009). Two critical considerations for spatial MCDA are the GIS capabilities of data acquisition, retrieval, storing and analysis, and the system’s capacity to connect the geographic data and the decision maker’s preferences into a one-dimensional value of choices (Drobne and Lisec 2009).

Two important methods of MCDA commonly used in GIS are binary Raster overlay and weighted linear combination. These are detailed below.

3.4.1. Raster binary overlay methods

A Raster binary overlay is a common GIS operation where multiple data layers are merged for the purpose of finding the relationship between them as in Figure 6. Overlay methods create a composite map from multiple data layers by combining their geometry and attributes.

3.4.2. Weighted linear combination (WLC)

The weighted linear combination (WLC) is a combination method of multi-criteria decision analysis to incorporate relative criteria importance. The WLC is a weighted average: different criteria are standardized to a common numeric range, then composited by means of a weighted average (Drobne and Lisec 2009). A map of potential sites is obtained by multiplying the importance weight assigned to each criterion by the scaled value given to the attribute and
summing the products over all attributes (Drobne and Lisec 2009). The WLC scores are calculated and the highest overall score is chosen. The method, implemented using GIS, allows for interactive assessments of the map layer combinations in order to determine the final map layer (Drobne and Lisec 2009).

The WLC technique consolidates factors by applying a weight to every element to yield a suitability map. The determination of suitable siting alternatives is done by multiplying the average weight by the criteria scores and then by the product of restriction criteria, such as:

\[
S = \sum_{i=1}^{n} W_i X_i . \prod c_j
\]

(5)

where \(S\) is suitability, \(W_i\) is the weight of factor \(i\), \(X_i\) is the criterion score of factor \(i\), \(\prod c_j\) is a product operator.

Using the criteria determination, data standardization, assigning weights, and criteria combination were applied to the GIS database to characterize suitable areas for SMRs

3.5. Evaluation and restriction criteria maps

Figures 8-12 show the individual site criteria map layers for siting SMRs based on the selection of evaluation criteria. Figures 13-21 show the individual site restriction map layers. The following results from Figure 8-21 are only for the Normal case; maps for other cases appear in the Appendix. A discussion is given under each of the Figures.
The study areas in this map were evaluated using highways criterion, based on Table 6. Visibly, all the highways are in the south part, suggesting that this region of the study areas are more suitable to host a SMR.

The study areas in this map were evaluated using populated areas criterion, based on Table 6. Most of the population distribution is in the south part of the study areas, with a few evident in the north. A 3 km was considered around each populated area.

The study areas in this map were evaluated using railways criterion, based on Table 6. Since the railways are only in the south part of the study areas, this region can capably host a SMR.

The study areas in this map were evaluated using transmission lines criterion, based on Table 6. The transmission lines are in the south part of the study areas, supporting the regions’ suitability to host a SMR.
The study areas in this map were evaluated using surface water criterion, based on Table 6. Most of the surface water is in the north study region; major sources such as lakes and rivers.

The study areas in this map were evaluated using agriculture criterion, based on Table 7. Some suitable areas for sitting SMR appear in the south and many suitable areas appear in the north part due to the climate condition in the north.

The study areas in this map were evaluated using groundwater criterion, based on Table 7. Some suitable areas for sitting SMR appear in the south but many areas are unsuitable. The end section of the north region is suitable for sitting SMR due to the Canadian Shield.

The map shows the excluded areas using the land use restriction criterion, based on Table 1. The south part of the study area contains more excluded areas than the north region due to the population density activities in the south. The north has a few excluded areas.
The map shows the excluded areas using the population density restriction criterion. Due to the high density of some populated areas in the south, parts were excluded. The exclusion is based on the population density of more than 200 people per square km, as indicated in Table 1.

The map shows the excluded areas using the airports restriction criterion of 7 km, as indicated in Table 1. All airport types were considered in this criterion.
The map shows the excluded areas using the slope restriction criterion, as indicated in Table 1. The slope criterion results in significantly any excluded areas in both the north and south due to the flatness of the study areas. The angle was chose for the excluded areas is greater than 8°.

**Figure 18: Slope restriction criterion**

The map shows the excluded areas using the wetlands restriction criterion, as indicated in Table 1. More wetlands are excluded in the north part than the south, only a few areas are excluded.

**Figure 20: Wetlands restriction criterion**

The map shows the excluded areas using the flooding areas restriction criterion, as indicated in Table 1. The surface water data for flooding reveals that most of the flooding areas appear in the north.

**Figure 21: Flooding areas restriction criterion**

The map shows the excluded areas using the protected areas restriction criterion, as indicated in Table 1. Most of the excluded areas are visible in the south study area, with a few present in the north.

**Figure 19: Protected areas restriction criterion**
3.6. **SMR siting suitability maps**

All the suitability and exclusion criteria were combined using the GIS-MCDA methods to produce SMR siting suitability maps. Figures 22 and 23 show the SMR siting suitabilities for the Open suitability criteria distance ranges the distance ranges are shown in Table 1 of the restriction criteria for the Open case and in the Appendix for the evaluation criteria as in Tables A-1 and for the agriculture and groundwater is shown in Table A-2 with the first and second sets of evaluation criteria weights (shown in Figure 8), respectively. Figures 24 and 25 show the SMR siting suitabilities for the Normal distance ranges shown in Table 1 of the restriction criteria for the Normal case and in Tables 6 for the evaluation criteria and for the agriculture and groundwater is shown in Table 7. Suitable SMR sites under the Restrictive case the distance ranges appear in Table 1 of the restriction criteria for the Restrictive case and in the Appendix for the evaluation criteria as in Tables A-3 and for the agriculture and groundwater is shown in Table A-4 are shown in Figures 26 and 27.
A comparison of transmission lines criteria weights in Figure 22 (19%) and Figure 23 (15%) shows the north as having less suitability. Many suitable areas appear in the south due to its fit with the evaluation criteria and the small geographical measurements for the restriction criteria. The Open case offers more potential for suitable areas than do the other cases.
Figure 23: Open case of final map of siting suitability using the second evaluation criteria weights.

Figure 23 reveals less suitable areas in the north than does Figure 22, due to the high weight placed on highways and railways than on transmission lines. The north regions meet three of the evaluation criteria, but railways and highways accessibility are missing in the north, as shown in Figures 8 and 10. The southern part of the study areas reveals little change from figure 22 due to the changes in weighting criteria.
Figure 24: Normal case of final map of siting suitability using the first evaluation criteria weights.

Figure 24 reveals a significant amount of unsuitable areas, due to the geographical distances considered for the Normal case for both the evaluation criteria and restriction criteria. The change in weighting criteria has a comparable effect on the maps in Figures 22 and 23. This is clearly visible in the northern part of the study areas and in the south if we zoom into Figure 25.
Figure 25: Normal case of final map of siting suitability using the second evaluation criteria weights.

Compared to Figure 24, Figure 25 reveals less suitable areas in the northern part due to the weighting criteria applied. Most of the study areas are under the unsuitability condition. Only a few areas are suitable for siting SMR and they can be no more than 5%.
Figure 26 reveals no suitability sites for SMRs due to the geographical distance criteria for the Restrictive case. If Figure 26 is compared with figures 22 and 24, the suitable sites become fewer and fewer from the Open case to the Restrictive case. Clearly, the effect of the geographical distance criteria is significant.
Figure 27: Restrictive case of final map of siting suitability using the second evaluation criteria weights.

Figure 27 reveals that the evaluation criteria weights have less effect than the study cases. A comparison of figures 26 and 27, show the same case with different criteria weight; the net result is no suitable sites.
4. DISCUSSION

The Open case, as seen in Figures 22 and 23, show many suitable areas due to the small geographic distances for the restriction criteria exclusion zones. The Restrictive case, as in Figures 26 and 27, has no suitable areas due to the large geographic distances for the restriction criteria exclusion zones. The Normal case, as in Figures 24 and 25, falls between the other cases, with less suitable areas and many unsuitable areas when specifically compared with the Open case.

The criteria evaluation weights in the final results - for example, in Figures 22 and 23 - have less effect between the two figures due to the small variation between weights in the evaluation criteria weights, as seen in Figure 7. Thus, a significant increase in variation between weights will be reflected in a similar significant increase in changes in the maps. A comparison between the evaluation criteria weights and the study cases, reveals that the evaluation criteria weights have a minimal impact on the study areas whereas the study cases have the greatest impact.

Establishing appropriate criteria is a crucial step in any site selection study. The criteria considered in this study are for SMRs that produce energy between 25 MWe to 300 MWe. The criteria and safety requirements for SMRs are different than for traditional reactors. For example, a traditional reactor needs access to a large source of cooling water whereas water needs are greatly reduced in a SMR. Even though the final map in Figure 22 shows several suitable areas that are not close to major water sources, this can be deemed acceptable, given that some SMRs currently under development do not use any water for cooling. Thus, considering the important geographical criteria that suits the study area was a crucial component of the research.

The siting analyses criteria for Figures 22 to 27 were based on criteria defined by different Canadian federal regulation documents. All the criteria established in these studies need to be considered; however, some criteria are specific to a country’s location, geography, environment
and strategic policies. Essentially, different places lead to different site analyses. For example, the slope criterion, a negligible factor in Saskatchewan, as shown in Figure 20 for the Normal case, was a significant criterion in an American study, where approximately 40% of the land was excluded due to excessive slopes (Belles, Mays, et al. 2012). Another example considers how a reactor's cooling water requirements would lead to very different siting scenarios if it was to be built in Saudi Arabia or Saskatchewan. Saudi Arabian locations would be restricted to coastal regions; in Saskatchewan, water, as shown in Figure 12, is available from the lakes and rivers scattered across the province. The restriction criteria considered in this study are important for siting SMRs based on the geography of our study areas. The other criteria not considered for this study are still important for other siting SMR studies, based on their geographical locations. These criteria are mentioned in the Identifying the Criteria for Site Selection (section 2.2).

The evaluation criteria used in this study were chosen based on providing a high level of discrimination and readily available data for nominal SMR power plants operating at less than 300 MWe. Regardless of the SMR design, the reactor core and plant infrastructure require access to: railways for delivering the reactor core, waste transportation and roads for workers, construction and emergency response. The plants require water supply for operation. Transmission lines are essential to deliver electricity to customers. Other evaluation criteria not considered but of importance are uranium mining and retired power plant locations. These, too, are addressed in the Identifying the Criteria for Site Selection (section 2.2).

As SMRs pose less risk than larger nuclear power plants, they can be built relatively close to consumers to minimize the cost of service (e.g. power and heat) transmission. Also, safety improvements see them having a smaller Emergency Planning Zone (EPZ). SMRs can be relatively close to population areas and still minimize potential consequences (Lyman 2013). As
shown in Figures 22 and 23 for the Open case and in the populated areas criterion map in Appendix Figure A-2, a 1 km as a protected zone around the populated areas was considered as this case is only considering the small geographical distance and the opposite of that was for the Restrictive case. Also, SMR site suitability, in Figures 26 and 27 for the Restrictive case and in Figure A-16 for the populated areas criterion map (Appendix), were relatively far from the population areas, with a distance of 5 km. Considering 5 km for the Restrictive case resulted in losing many suitable areas, as seen in Figures 26 and 27 compared to Figures 22 and 23.

The Canadian Nuclear Safety Commission (2016) states: “There are no legislative or regulatory requirements for EPZ sizing in Canada and therefore no restrictions currently in place on minimum EPZ size.” The location of a SMR, however, still needs to “Mitigate the radiological consequences of potential releases of radioactive materials that may result from accident conditions” (Canadian Nuclear Safety Commission 2016). Belles and Omitaomu (2014) report that the recommended EPZ of SMRs in the USA be between 1 to 5 miles (1.6 to 8 km). The appropriate EPZ for SMR designs is an issue still under discussion with many studies and regulators. Technology developers are seeking ways to reduce EPZ size, taking into account technology improvements (Canadian Nuclear Safety Commission 2016). Reducing the protective area around each populated area offers more selections for suitable sites.

Some of the criteria considered important for siting SMRs are not expected to vary much with time. Examples of such static criteria include slope and groundwater. Other criteria are more dynamic, such as population density, flooding areas and surface water. In this study, more attention was paid these criteria. For instance, a 5 km zone was applied around the high populated areas for the Normal case, as in Figure 16, and a 3 km buffer zone around any potential flood areas, as in Figure 21.
Surface water refers to the major water source – lakes and rivers – found in a specific area. Siting SMRs close to water sources is vital for cooling many reactors. If the water source is far from a suitable site, as considered for some areas in the Open case for the surface water criterion map in Figure A-5 in the Appendix, different options of SMR technologies for cooling the reactor can be used. These offer the benefits of reducing water use, reducing the balance of plant acreage and expanding potential siting options.

Ecological and environmental aspects need to be considered in the event of accidents or radioactive releasing that may occur if a reactor plant is in proximity to important places. The distance between the reactor plant and the restriction criteria is a key consideration. For example, 3 km for protected areas was the smallest exclusion geographical distance considered for the Open case, as seen in Table 1. The improved design of present-day SMRs, with enhanced safety benefits and operations, means the site can be relatively close to consumer locations to supply both electricity and heat. A second ecological/environmental consideration is that of water sources. Typically, electric plants are located near rivers, lakes or other water bodies to supply the reactor with cooling water. Hot effluents from the reactor, which increase the water temperature and thereby pose serious risks to ecology and marine populations, need to be minimized. Figure 12, the surface water criterion map, considered major surface water sources, such as rivers and lake, but does not include smaller pools of water, such as ponds and wetlands. The following SMR coolant water technologies are currently under consideration for use with suitable sites located a distance from surface water sources:

**Dry Cooling** – this technology requires water for cooling but at much lower volumes. Although it has higher operation costs and produces less power, it offers an alternative when no water supply exists (Golder Associates 2016). Dry cooling is less efficient in hot weather.
**Wet/Dry Cooling** -- this technology needs more water than dry cooling and less than wet cooling. The wet/dry can be operated in different modes based on seasonal water availability and (Golder Associates 2016).

**Cooling Towers** – this technology, which relies on fans that pump water to the top of the tower and discharge it to the surface, is preferred for SMRs using wet cooling (Golder Associates 2016).

**Cooling Ponds and Reservoirs** – this technology uses evaporation from surface water bodies to consume heat (Golder Associates 2016).

Dry cooling, using a tower with a closed cooling type operation, has several benefits, such as minimizing the water impact from any water intake and allowing more flexibility in siting. Surface water is a liability for SMR siting due to the risk of watershed and fisheries contamination. Thus, a 1 km buffer zone, for the Open case, was applied to protect these areas, as shown in Table 1. Pipelines, to supply the reactor with water from nearby lakes and rivers, are possibilities. Both the buffer zone and pipelines help to minimize the potential of surface water contaminations or hazards.

The assignment of weighting criteria is a sensitive issue in siting studies, due to experts’ bias in value judgments and opinions about the relative importance of each criterion related to their specialization. Examining rationales for different weights enables one to see how the sensitivity of some criteria impacts the overall decision. For example, geologist experts evaluate criterion through a geological lens and thus, geologic criteria are given prominence. The average of criteria weights from the experts can maintain the accuracy of weight assigned to the criteria, as the weights directly bear on the final results. Figures 22 and 23 for the Open case for example, show that the impact of the evaluation weights used for the evaluation criteria were small, due to the
small variation ratio of weights between criteria. A high ratio of weights between criteria will be reflected with comparable higher impacts.

Except for wind and solar power, all industrial power generation facilities create waste, regardless of the fuel source; the waste must be managed to avoid any risk to humans and the environment. The nuclear reactor cycle produces a significant amount of energy using a small amount of fuel; a byproduct of the process is a small amount of radioactive waste. In disposing the high level of radioactive waste, The World Nuclear Association (2017) states: “Safe methods for the final disposal of high-level radioactive waste are technically proven; the international consensus is that geological disposal is the best option.” Common waste disposal options include (World Nuclear Association 2017):

- Near-surface disposal at ground level, or in caverns below ground level (at depths of tens of metres), which is applicable for most low-level radioactive waste and intermediate-level radioactive waste.
- Deep geological disposal (at depths between 250 m and 1000 m for mined repositories, or 2000 m to 5000 m for boreholes), which is applicable for long-lived intermediate-level radioactive waste and high-level radioactive waste.

The World Nuclear Association recommends that deep geological storage be confirmed as policy for radioactive waste disposal in Canada and other countries. In Finland and Sweden, a deep geological underground nuclear waste disposal units, 500 meters in depth and located within 1.9 billion-year-old granite, is under construction and expected to be operational by 2020 (World Nuclear Association 2017). The Canadian Nuclear Safety Commission (2016) DIS-16-04 states: “High-level radioactive waste at existing sites in Canada is normally stored onsite for several years in spent fuel pools before being moved to onsite dry storage facilities” (Canadian Nuclear Safety
Commission 2016). Long-term waste management and disposal needs to be considered during the planning stages of any reactor (Canadian Nuclear Safety Commission 2016).

In addition to generating electricity, SMRs can provide district heating, create hydrogen fuel and desalinate drinking water. Still, we wonder if these processes can be broadened, based on the type of SMR. For example, siting criteria considered in this study for different SMR applications focused on physical and biological variables. Thus, criteria can change depending on the reactors’ purpose and the vendors’ requirements. For example, the Washington State Energy Facility (2016) study was conducted for two types of LWR reactors: the mPower reactor designed to generate 180 MWe of electricity and the NuScale Power Module designed to generate 50 MWe of electricity. Site criteria were the same for both; criteria regarding specific SMR designs (technology and size) were not included. The criteria applied in this study may need to be reconsidered and refined when specific SMR technology and size variations are explored.

Some suitable sites for SMRs were selected as examples to validate our analysis, as shown in Figures 28, 29 and 30. The selected sites were taken from the Open case final map, with the first evaluation criteria weights applied. The selected sites are accessible to most of the major utilities, such as highways, transmission lines, railways, surface water, as well as in proximity to populated areas. The examples from various sections of the study area when taken together, offer a clear image about the entire study area.
Figure 28: First SMR suitable site example
Figure 29: Second SMR suitable site example
Figure 30: Third SMR suitable site example
5. CONCLUSIONS

The site selection criteria and data standardization applied in this study suits small reactors, without accounting for the reactors’ type, size and purpose. The study design allows criteria to be changed if design conditions or geographic considerations change.

The range of suitable SMR sites was based on objective data: criteria that were quantifiable and measurable and, specifically, geographical. The analysis did not include land availability, public perception or other discrepancies that may have merit in site decisions. These can be explored in further studies. Most suitable sites are in the southern part of Saskatchewan. This region is more accessible to the utility infrastructure and is home to the most populated areas, both of which are preferable for SMRs siting. Groundwater data is limited in the Canadian Shield regions of the province; the northern regions have more wetlands and lakes than does the south.

Based on the final maps, the Open case can be recommended. It features several suitable areas as compared to the other cases. Notable suitable characteristics include meeting the SMR Safety Benefits criteria and the Evaluation criteria of accessibility to utilities, such as surface water, transmission lines, highways, railways, and populated areas. These positive attributes offer significant SMR siting opportunities.

5.1. Limitations

The siting criteria used in this work did not include factors such as: energy supply and demand, SMR competition with other power generation technologies, public perception, cost and cultural resource issues. These factors need to be considered by the governing bodies of Saskatchewan.
The ranges used for the fuzzy standardization of the restriction and evaluation criteria were assigned based on observed ranges in the data and shared knowledge. While these ranges provide reasonable estimates that were useful for the present analyses, they should be fine-tuned by domain experts.

5.2. Future research

The criteria considered in this study fit the geographic aspect of SMR site suitability in Saskatchewan based on CNSC and applicable literature reviews. Criteria could be modified to consider reactor types, sizes and vendor requirements. Weightings criteria were applied only for demonstration purposes and could be further refined based on experts’ opinions. Fuzzy standardization criteria fit the geographic spatial measurements for Saskatchewan. The three study cases conformed to the trend of government perspectives, which could change once the project is in process.

More detailed topics that could be explored in the future include public perception of nuclear reactors, energy supply and demand and other topics not related to geography. A future study should explore the potential and limitations of siting SMRs in northern regions.

To conclude, this research presented analysis for identifying suitable sites for SMR across Saskatchewan; focusing on the geographical factors. It could be further refined if specific reactor types, sizes and purpose are considered.
REFERENCES


http://esask.uregina.ca/entry/saskatchewan.html.


https://nac.unl.edu/buffers/guidelines/5_protection/11.html.


A. APPENDIX

The Appendix section contains all the geographical distance values of criteria for both the Open case and the Restrictive case as shown in Tables A-1 to A-4, and the Open and Restrictive cases criteria maps. Figures A-1 to A-14 for the Open case and Figures A-15 to A28 for the Restrictive case.

A. 1. Data standardization for the Open case

Table A-1: Evaluation criteria standardization values for the Open case

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<th>Evaluation criteria</th>
<th>Intensity of important</th>
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<td>1</td>
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<tr>
<td></td>
<td>Unsuitable</td>
</tr>
<tr>
<td>Populated areas</td>
<td>&gt;20 km</td>
</tr>
<tr>
<td>Surface water</td>
<td>&gt;20 km</td>
</tr>
<tr>
<td>Railways</td>
<td>&gt;20 km</td>
</tr>
<tr>
<td>Roads</td>
<td>&gt;20 km</td>
</tr>
<tr>
<td>Transmission lines</td>
<td>&gt;20 km</td>
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Table A-2: Agriculture and groundwater standardization table for the Open case

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<tr>
<td></td>
<td>Unsuitable</td>
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<td>Groundwater</td>
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<tr>
<td>Agriculture</td>
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</table>
### A. 2. Data standardization for the Restrictive case

#### Table A-3: Evaluation criteria standardization values for the Restrictive case

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<td></td>
<td>Unsuitable</td>
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<td>Moderate suitable</td>
<td>Suitable</td>
<td>Very suitable</td>
</tr>
<tr>
<td>Populated areas</td>
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<td>20-25 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>&gt;5-10 km</td>
</tr>
<tr>
<td>Surface water</td>
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<td>15-20 km</td>
<td>10-15 km</td>
<td>3-10 km</td>
<td>0-3 km</td>
</tr>
<tr>
<td>Railways</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>3-10 km</td>
<td>0-3 km</td>
</tr>
<tr>
<td>Roads</td>
<td>&gt;20 km</td>
<td>15-20 km</td>
<td>10-15 km</td>
<td>3-10 km</td>
<td>0-3 km</td>
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<tr>
<td>Transmission lines</td>
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<td>15-20 km</td>
<td>10-15 km</td>
<td>3-10 km</td>
<td>0-3 km</td>
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#### Table A-4: Agriculture and groundwater standardization table for the Restrictive case

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<td>Moderate suitable</td>
<td>Suitable</td>
<td>Very suitable</td>
</tr>
<tr>
<td>Groundwater</td>
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<td>21 – 24 m</td>
<td>24 – 27 m</td>
<td>27 – 30 m</td>
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<tr>
<td>Agriculture</td>
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<td>3 - 4</td>
<td>5 - 6</td>
<td>7 - 8</td>
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</tr>
</tbody>
</table>
A.3. Evaluation and restriction criteria maps for the Open and Restrictive cases

The Figures from A-1 to A-14 are the results of criteria maps for the Open case. The figures from A-15 to A-28 are the results of criteria maps for the Restrictive case.
A.4

Figure A-1: Highways evaluation criterion

Figure A-2: Populated areas evaluation criterion

Figure A-3: Railways evaluation criterion

Figure A-4: Transmission lines evaluation criterion
Figure A-5: Surface water evaluation criterion

Figure A-6: Agricultural areas restriction criterion

Figure A-7: Groundwater restriction criterion

Figure A-8: Land use restriction criterion
Figure A-9: Population density (more than 200 people per square km) restriction criterion

Figure A-10: Airports restriction criterion

Figure A-11: Slope restriction criterion

Figure A-12: Protected areas restriction criterion
Figure A-13: Wetlands restriction criterion

Figure A-14: Flooding areas restriction criterion
Figure A-19: Surface water evaluation criterion

Figure A-20: Agricultural areas restriction criterion

Figure A-21: Groundwater restriction criterion

Figure A-22: Land use restriction criterion
Figure A-23: Population density (more than 200 people per square km) restriction criterion

Figure A-24: Airports restriction criterion

Figure A-25: Slope restriction criterion

Figure A-26: Protected areas restriction criterion
Figure A-27: Wetlands restriction criterion

Figure A-28: Flooding areas restriction criterion