Determination of Optimal Sites for Municipal Solid Waste-to-Value-Added Facilities for Canada through Geographical Information System Modelling

by

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Abstract

Sustainable management of municipal solid waste (MSW) is one of the biggest challenges faced by economies worldwide. Rising waste generation rates, limited land resources, and environmental and public health issues raised by conventional land disposal have shifted the focus of decision-makers towards alternative treatment and disposal techniques. Energy and material recovery from MSW have hence recently emerged as a necessary element of integrated solid waste management in Canada. The growing market for sustainable energy has further increased the prominence of waste-to-value-added (W2VA) technologies in sustainable waste management. The quantification of feedstock potential and identification of optimal locations, while ensuring compliance with environmental, social, and economic factors, are the key issues in setting up any sustainable W2VA facility. In the existing waste transportation framework, MSW is transferred from municipalities to existing transfer stations (TSs) for segregation of material and energy recovery operations and finally remaining portion is disposed of at different landfills.

This study focuses on the quantification of the MSW potential, analyzes geographical point source locations for the distributed MSW feedstock, determines the optimal locations for W2VA facilities across Canada, and prioritizes these sites. A quantification model was developed based on the Thiessen polygon approach to calculate MSW potential at each TS. In 2016, the annual MSW potential in western Canada (includes British Columbia, Alberta, Saskatchewan and Manitoba) and eastern Canada (includes Ontario, Quebec, Newfoundland and Labrador, New Brunswick, Nova Scotia and Prince Edward Island) were around 8.7 and 16.2 million wet tonnes that have 15% and 50% moisture content, on average, for thermal and biodegradable portion, respectively . In order to minimize adverse environmental, economic, and social impacts and ensure the shortest possible waste transportation distance from TSs to

W2VA facilities, careful identification of optimal locations for W2VA facilities is essential. A four-stage decision-making model comprising exclusion analysis, preferential analysis, suitability analysis, and network analysis was developed to determine ten and fifteen optimal sites for W2VA facilities in western Canada and eastern Canada, respectively. Analytic hierarchy process (AHP) and fuzzy logic were used with geographic information systems (GISs) in an integrated decision-making network to prioritize the preference factors in the determination of a land suitability map (LSM). Subsequently, candidate sites identified from the LSM were used in a network analysis with road and rail network to select and prioritize optimal sites based on the shortest between the facility and existing TSs.

The method outlined in this study was used to determine optimal sites for W2VA facilities in compliance with social, environmental, and economic factors. The adaptability of the applied decision-making model, the competency of the developed LSM, and the flexibility of the network analysis provide a competent supporting tool for the authorities in siting optimal locations of W2VA facilities and improving their sustainability.

Preface

This thesis is an original work by Mohammad Shafiqul Islam under the supervision of Dr. Amit Kumar.

Chapter 2 of this thesis will be submitted as “Optimal siting of municipal solid waste-to-value-added facilities using a GIS-based framework for Western Canada” by Mohammad Shafiqul Islam, Roshni Mary Sebastian, Vinoj Kurian, and Amit Kumar to the journal *Resources, Conservation and Recycling.*

Chapter 3 of this thesis will be submitted as “Selection and prioritization of municipal solid waste-to-value-added facilities across Eastern Canada using GIS and Fuzzy AHP” by Mohammad Shafiqul Islam, Roshni Mary Sebastian, Vinoj Kurian, and Amit Kumar to the *Journal of Environmental Management.*

I was responsible for the data collection, data analysis, model development, and manuscript composition. Roshni Mary Sebastian and Vinoj Kurian reviewed the developed models, assessed the results, provided feedback on research structure, and corrected journal papers. Amit Kumar was the supervisory author and provided supervision on concept formulation, models and results validation, and manuscript edits.

Dedicated to my parents

Mohammad Golam Mostafa and Mosammat Amena Khatun

&

my wife Ayesha Siddika

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Here I take the opportunity to extend my sincerest gratitude to my parents and my wife for their support, comfort, and inspiration. I could not have pursued research at this point in my life without the care and guidance from them. I am especially grateful to my wife, Ayesha Siddika, for her support, understanding, and patience in this journey.

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List of Abbreviation

AHP	Analytic hierarchy process
CSRS	Canadian Spatial Reference System
ESAs	Environmentally sensitive areas
ESRI	Environmental Systems Research Institute
FAHP	Fuzzy analytic hierarchy process
FANP	Fuzzy analytic network process
GCS	Geographical coordinate system
GHG	Greenhouse gas
GIS	Geographic information system
GRASP	Greedy randomized adaptive search procedure
LSM	Land suitability map
LCA	Life cycle assessment
MCDA	Multi-criteria decision analysis
MSW	Municipal solid waste
NAD	North American Datum
SI	Suitability index
TSs	Transfer stations
UTM	Universal Transverse Mercator
W2VA	Waste-to-value-added
WtE	Waste-to-energy

Chapter 1: Introduction

1.1 Background

Integrated municipal solid waste (MSW) management has been a challenging task worldwide. The growth in both size and density of the population, combined with rising urbanization rates and living standards, have led to an increase in MSW generation, which has subsequently put pressure on disposal sites and has become a concern for local waste management authorities (Singh and Dubey, 2012). The world generated more than 2 billion tonnes of MSW in 2016, at least 33% of which was not managed in an environmentally safe manner (The World Bank, 2019). The World Bank estimates that with rapid population growth and urbanization, annual waste generation will increase by 70% from 2016 levels to 3.40 billion tonnes by 2050. In 2016, around 40% of this generated waste was disposed of in landfills or openly burned while only 13.5% and 5.5% of the world's waste were recycled and composted, respectively (Ellis, 2018). Meanwhile, the disposed MSW accounted for approximately 1.6 billion tonnes of carbon dioxide equivalent greenhouse gas (GHG) emissions in 2016, which was nearly 5% of global GHG emissions (Lee et al., 2017). Without improvements in the waste management system, MSW-related emissions are anticipated to increase to 2.6 billion tonnes by 2050 (Kaza et al., 2018). An estimated 10-15% in global GHG emissions could be reduced through sustainable waste management (Scarlat et al., 2019).

A sustainable solid waste management system is a hierarchical series of activities and processes that includes reducing waste generation, reusing and recycling waste materials, recovering resources from waste streams, and/or disposing the unrecoverable portion of waste in a landfill. It is important to note that a portion of waste cannot be recovered for technical or economic reasons and is ultimately disposed in a landfill. Thus, two approaches are available for the handling and disposal of generated MSW: (i) the direct disposal of unprocessed waste in a landfill and (ii) waste processing to recover resources, followed by landfilling. Though the first is cheaper, it results in significant environmental problems such as air pollution and leachate generation (Ojha et al., 2007). Environmental challenges, combined with social, economic, technical, and political issues and land availability, are major concerns that need to be addressed in waste management (Lein, 1990). The second approach is widely accepted by waste management experts and environmentalists and has become an integral part of sustainable waste management. Processing waste recovers energy from waste streams or converts waste to value-added materials; only what is not used is disposed to a landfill. While it is costlier than landfilling, it achieves the goals of increasing the waste diversion rate and conserving resources and as a result has low environmental impacts (i.e., reduced air pollution and leachate generation) (Huang et al., 2001).

In Canada, most of the generated waste ends up in landfills, and thus 30% of Canada's landfills reached or surpassed their capacity in 2010 (PPP Canada, 2014). Moreover, MSW landfilled in Canada contributes to around 20% of national methane emissions (Government of Canada, 2020a). The conversion of waste-to-valued-added (W2VA) materials like electricity, biofuels, compost, etc., is deemed a viable diversion technique to reduce landfilling of wastes. Not only does this reduce the volume of landfilled wastes but it provides an alternative renewable energy source, in turn mitigating the GHG emissions to an extent (Smith et al., 2001). Waste-to-energy (WtE) conversion technology, the preferred W2VA technology, can be a potential source of renewable energy by producing electricity and biofuels from disposed wastes and is expected to play an increasingly important role in the sustainable management of MSW in Canada.

Several researchers have conducted economic and environmental assessments of waste management systems. A few studies focused on energy and economic assessment for specific technologies (Fernández-González et al., 2017; Lee et al., 2017; Nagpure, 2019; Viau et al., 2020). Bing et al. (2016) studied current solid waste scenarios, management challenges, and future possibilities in several EU countries. Malinauskaite et al. (2017) did a comprehensive review of MSW management systems considering WtE conversion technologies as a viable solution in a circular economy for selected European countries. Some researchers conducted comprehensive analyses on environmental impacts and life cycle assessments (LCA) of MSW management. Cremiato et al. (2018) performed a comparative analysis of the environmental impact of MSW management alternatives using LCA. Viau et al. (2020) evaluated the modelling of substitution in an LCA of materials recovered from waste streams through MSW management systems. A number of studies have been performed to find suitable locations for sanitary landfills using geographic information systems (GIS) (Eghtesadifard et al., 2020; Rahimi et al., 2020; Zhou et al., 2020). Asefi et al. (2020) demonstrated an integrated approach to assess the suitability of MSW landfills in Australia. Karakuş et al. (2020) outlined a GIS-based multi-criteria decision analysis (MCDA) approach for MSW landfill site selection in Turkey.

Site selection is one of the crucial steps in setting up W2VA facilities. Selecting a site without proper assessment may adversely affect the W2VA facility's operational efficiency (Tavares et al., 2009; Singh, 2019b). MSW incinerators used to produce electricity by burning waste are a source of air pollution (Moustakas et al., 2020; Mukherjee et al., 2020). W2VA incineration plants in the USA, China, India, and elsewhere have been shut down due to social concerns, odours, noise, and litter issues (Lober, 1995b; Mohammed et al., 2019). Ill-defined W2VA facility locations can have adverse impacts on surrounding environmental health as well (Brinkmann, 2020; Parashar et al., 2020). Careful identification of optimal locations is essential to minimize environmental, economic, and social impacts and ensure the sustainability of W2VA facilities. Thus, site selection for W2VA facilities is considered a multi-disciplinary decision-making problem that involves social, technical, environmental, and economic factors (Shah et al., 2019; Karunathilake et al., 2020; Rahimi et al., 2020). The outcome of the assessment of the relative importance of these factors and corresponding characteristics is often conflicting and inconsistent (Ren et al., 2020). This complex assessment process is ideal for the MCDA method in a GIS environment (Singh, 2019a; Zhou et al., 2020). Many researchers have determined optimal locations for W2VA facilities by conducting suitability analysis, integrating MCDA methods in a GIS environment (Rahmat et al., 2017; Chabuk et al., 2019; Karimi et al., 2020; Tsai et al., 2020). The models used in these studies prioritized quantitative and qualitative criteria through the analytic hierarchy process (AHP) for MCDA by considering the relative importance of contributing factors to create a suitability map for the study areas. The information available for MSW conversion facility site selection, however, is not comprehensive. There is no comprehensive study on W2VA facility siting incorporating both road and rail networks to minimize waste transportation costs and the municipal guidelines. These are critical to optimal location of the facilities. This study aims to address these gaps in literature.

1.2 Research Motivation

The issues outlined below were the motivation for the current research.

- Landfills in some cities and counties are nearing the end of their life, and space for new landfills is increasingly scarce. Moreover, landfilled waste generates GHGs and leachates, hence the need for waste diversion and recovery. The key concerns in establishing waste conversion facilities are technical feasibility, proper site selection, financing the facilities, and public perception towards W2VA facilities.

- Siting sanitary landfills in compliance with social, technical, environmental, and economic issues through GIS-based assessment is a well-established practice. The same criteria and methods should be used to determine the locations for W2VA facilities. However, research on siting W2VA facilities using GIS technology by defining point source locations of transfer stations (TSs) is limited, to our best knowledge.

- The cost of transporting MSW from TSs is the most significant factor in the economic feasibility of a W2VA facility. Determining optimal sites by using existing road and rail networks along with municipal guidelines with the aim of minimizing waste collection costs is a critical aspect that can help waste management authorities and urban planners build new W2VA facilities.

- Whether to build a W2VA facility depends on several factors such as waste availability, economic viability, suitable waste treatment technologies, remaining landfill life, and available spaces for new landfills. Since around 25 million wet tonnes of MSW are disposed of in Canadian landfills annually, it is important to adopt a sustainable waste management pathway.

1.3 Research Objectives

The overall objective of this study is to determine the optimal location of W2VA facility in various Canadian provinces based on municipal guidelines, road network and rail network. The specific objectives of this study are to:

❖ Quantify the MSW potential in existing TSs through the Thiessen polygon [1]approach by defining point source locations of those TSs;

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[1] Thiessen polygon Thiessen polygons are shaped around a sample point, such that any location inside the polygon is closer to that point than to all other points

- Create a land suitability map for W2VA facility development through a GIS-based assessment of each Canadian province and determine optimal locations of W2VA facilities in compliance with social, environmental, and economic factors; and

- Calculate the transportation distance of waste feedstock from TSs to corresponding optimal W2VA facility sites using both road and rail networks by incorporating GIS and other attributes (road speed limits, direction of traffic, etc.)

1.4 Scope and Limitation of this Study

This study used data up to the year 2016, the last year a census was taken, to estimate MSW potential in every province in Canada. The study integrated GIS-based MCDA approaches in a network analysis to select optimal sites for W2VA facilities for most of Canada. GIS analyses could not be performed for the Northern Territories (Yukon, Northwest Territories, and Nunavut) as insufficient data is available.

In this study, optimal locations for W2VA facilities were determined based on minimizing the waste transportation distance from existing TSs to potential W2VA facilities. Whether to build a new W2VA facility at an optimal site depends heavily on economic competitiveness, i.e., the MSW potential at the site, the composition of the waste stream, and the feasibility of appropriate environmentally friendly waste conversion technology. Therefore, a techno-economic assessment of each facility is required before a new W2VA facility is built.

Selecting optimal sites to minimize adverse environmental impacts and ensure the sustainability of W2VA facilities depends on several factors. Some of the environmental and social parameters considered in this study are specific to Canada and may be different elsewhere, and so the model must be modified accordingly. However, the flexibility of the performed network analysis provides a competent supporting tool for authorities in siting optimal W2VA facilities.

1.5 Organization of the Thesis

This thesis consists of four chapters along with a table of contents, list of tables, list of figures, and references. This thesis is written in a paper-based format; Chapters two and three are two papers and are expected to be published in peer-reviewed journals. As the thesis is a consolidation of papers, some concepts and data are repeated.

Chapter one, the current chapter, describes the research background, motivation, objectives, scope and limitations of the study, as well as the organization of the thesis.

The second chapter focuses on the optimal siting of W2VA facilities in western Canada using GIS technology in compliance with social, environmental, and economic factors. It describes the economic feasibility of the considered preference parameters, which are ranked from 1 to 10. The GIS-based model was applied to find ten optimal sites for W2VA facilities using both road and rail networks in western Canada.

Chapter three presents the process used to quantify the MSW potential in eastern Canadian TSs and prioritize the optimal locations of W2VA facilities. It describes the current MSW scenario in six eastern Canadian provinces. The results and discussion section explain the distribution of optimal sites among those six provinces.

Chapter four presents the conclusion and recommendations for future work.

Appendices with related information are included following the references.

Chapter 2: Optimal Siting of Municipal Solid Waste-to-Value-Added Facilities using a GIS-Based Framework for Western Canada

2.1 Introduction

Rising population, economic growth, and the simultaneous increase in urbanization have led to a large surge in municipal solid waste (MSW) generation rates globally (Sumathi et al., 2008). High income countries produce about 34% (683 million tonnes) of the world's waste with only 16% of the total population (The World Bank, 2020). MSW management has become one of the most challenging tasks for policymakers and regulatory authorities worldwide. Canada's population increased by nearly 11.38% from 33.75 million in 2009 to 37.59 million in 2019 (Worldometers, 2020), and annual MSW generation was 31 million tonnes (Community Research Connections, 2020). Alarmingly, more than 70% of this MSW is disposed of on land (Community Research Connections, 2020). Since land disposal has environmental and public health issues, there is increased emphasis on diverting MSW from landfills to material and energy recovery facilities by waste management authorities and local communities.

The disposal of MSW in landfills is one of the key factors contributing to human health and surrounding environment (Asefi et al., 2020). In Canada, greenhouse gas (GHG) emissions from landfills account for about 20% of methane emissions of the country (Environment and Climate Change Canada, 2019). Given increased regulations to reduce fossil fuel use and to ultimately discontinue using fossil fuels, the concept of waste-to-value-added (W2VA) facilities is receiving increased attention. Recovering material and energy from solid waste is considered environmentally preferable. This helps in MSW management and can help offset GHG emissions (Jeswani and Azapagic, 2016). Although energy recovery techniques are part of integrated MSW management in Canada, social opposition creates NIMBY (not in my back yard) or NIMNBY (not in my neighbour's back yard) syndromes for siting a new facility and has become a deterrent to operating such facilities (Colebrook and Sicilia, 2007). W2VA plants in the USA, China, India, etc., were shut down due to social concerns, predominantly odours, noise, and litter issues (Lober, 1995a; Mohammed et al., 2019). Selecting a site for a W2VA facility without proper assessment may adversely affect its operational efficiency (Tavares et al., 2009; Singh, 2019b). To minimize adverse environmental, economic, and social impacts and ensure the sustainability of W2VA facilities, carefully identifying optimal locations is essential.

The consideration of multi-dimensional criteria through multi-criteria decision analysis (MCDA) for siting ensures that sustainability factors are included (Singh, 2019b; Karunathilake et al., 2020). To reduce the uncertainty of complex decision-making that involves multiple criteria, different MCDA techniques have been used, including the analytical hierarchy process (AHP), fuzzy membership function, analytical network process (ANP), weighted linear combination, Preference Ranking Organization METHod for Enrichment and Evaluation (PROMETHEE), ordered weighted average (OWA), etc., (Aksoy and San, 2019; Aderoju et al., 2020; Asefi et al., 2020). MCDA integrated with geographic information systems (GIS) is widely used to incorporate spatial data and multi-dimensional factors (Feyzi et al., 2019; Zhou et al., 2020). Kemal Korucu and Erdagi (2012) conducted a comprehensive literature survey of GIS-MCDA in decision-making situations that outlines the approaches for creating maps and then classified those maps by areas of application. Sankar Cheela and Dubey (2019) conducted a review on the applications of MCDA, GIS and life-cycle analysis (LCA) in development of integrated MSW management for a smart city.

Several studies assess locations for landfill facilities using technical, social, economic, environment and geological properties. Farahbakhsh and Forghani (2018) developed a GIS-AHP approach based on seven parameters to minimize environmental pollution, improve service, and reduce costs for selecting optimal landfill sites in Kerman, Iran. Purkayastha et al. (2019) developed a model using AHP to determine optimum time duration for MSW collection during each visit by a waste collection vehicle. Pasalari et al. (2019) outlined a simplified method combining MCDA and fuzzy memberships in a GIS environment to determine suitable landfill sites for a county in southern Iran. Mohammed et al. (2019) considered population growth and expected waste production by integrating AHP with GIS analysis to site an optimal and sustainable landfill for MSW management in Malaysia. Rahimi et al. (2020) introduced a framework on GIS and MCDA methods to select landfill sites considering fourteen parameters based on environmental, economic and social criteria. Lokhande et al. (2020) conducted comprehensive spatial analyses and weighted overlay of different data layers using GIS technologies to determine the potential suitable waste transfer stations (TSs) locations within the study area. Lokhande et al. (2020) integrated GIS and MCDA approaches in landfill site selection based on fourteen parameters classified under economic, sociocultural, and environmental issues. Osra and Kajjumba (2020) used AHP in weighing relative importance of eleven factors considered in GIS analyses to select new sanitary landfill sites in Makkah, Saudi Arabia.

Canada’s federal government, as a part its climate change mitigation efforts, is assessing MSW diversion options through material and energy recovery (Government of Canada, 2019). The impact of MSW-to-energy conversion initiatives on GHG emissions is twofold: GHG emissions from garbage disposed in landfills decreases and non-renewable sources of electricity are replaced with renewable sources. Khan et al. (2018) conducted a comprehensive assessment on waste availability at existing transfer stations (TSs) and used the provincial road network to locate solid W2VA facilities for the province of Alberta. Sultana and Kumar (2012) determined a relationship between the optimum capacity of bio-refineries and the number of average-sized facilities using the road network across the province of Alberta. In Canada, the rail network also has a significant role in fuel transportation. However, there is no detailed location-allocation study on W2VA facility siting that incorporates both the real road and the rail networks to minimize waste transportation costs. Using the rail network to haul waste would minimize transportation cost and reduce fuel consumption GHG emissions. The four western Canadian provinces have similar waste management goals and initiatives, and waste is transferred inter-provincially (Giroux Environmental Consulting, 2014). Thus, performing a detailed aggregated analysis on waste transfer and management for western Canada will help developing sustainable interprovincial MSW management practices. This research aims to integrate both road and rail networks for transportation of MSW in a comprehensive study on waste management aggregation for utilization in western Canada. The specific objectives of this study are to:

- modify the integrated GIS-AHP framework to consider social, economic, and environmental factors pertaining to the western Canadian provinces for determination of optimal location of W2VA facility;
- develop a land suitability map (LSM) through exclusion and preference analyses specific to western Canada for determination of optimal location of W2VA facility; and,
- conduct a network analysis with the existing road and rail networks to locate suitable W2VA facility sites based on minimization of transportation distance.

2.2 Background and Context of Study Area

The four provinces – British Columbia (BC), Alberta (AB), Manitoba (MB), and Saskatchewan (SK) – are referred to in this study as western Canada and cover around 2703,159 km^2 (~29%) of the land area of Canada. British Columbia is often referred to as "the west coast". Alberta, Saskatchewan, and Manitoba are often grouped together and are known as the Prairie Provinces. Statistics Canada estimated in 2019 that the population of western Canada was nearly 12.1 million, or 31.9% of the country's population, of which approximately 5.11 million were in British Columbia and 4.40 million in Alberta, 1.17 million in Saskatchewan, and 1.37 million in Manitoba (Statistics Canada, 2020b).

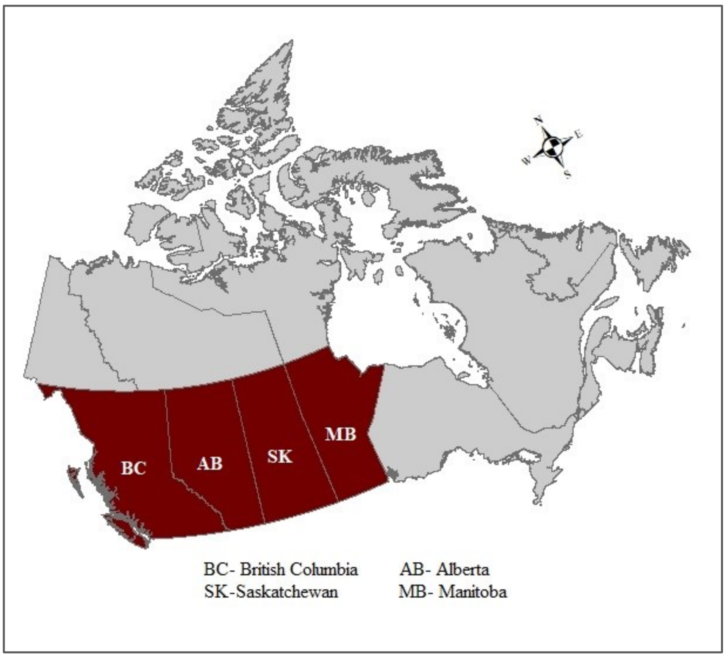
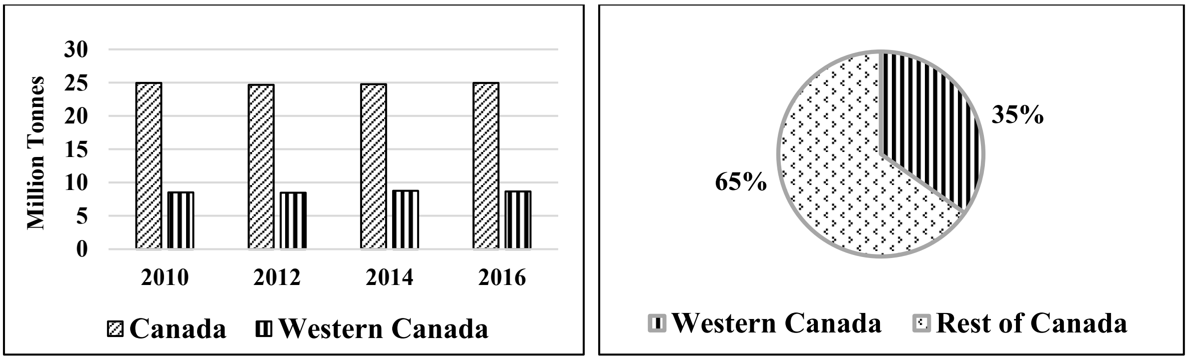


Figure 2.1: Map of western Canada as considered in this study

The waste generated in Canada is among the highest in the world at 0.901 tonne/capita/year yet the country recycles only 27% of it (Community Research Connections, 2020). As Figure 2.2 shows, western Canada alone disposed around 8.7 million tonnes of MSW in 2016, almost 35% of the country's total waste disposal.



A B

Figure 2.2: (A) Solid waste generation, western Canada, 2010-2016 (B) MSW generation ratio, 2016

MSW refers to recyclables and compostable materials, as well as garbage generated from homes, businesses, institutions, and construction and demolition sites. Western Canadians disposed of 2.88 million tonnes of residential waste in 2016, an increase of around 1.6 percent from 2014 (Government of Canada, 2020b). Meanwhile, the level of non-residential waste, i.e., from the institutional, commercial, and construction & demolition sectors, declined by almost 1.7 percent between 2014 and 2016. On a provincial level, residential waste in Alberta and Saskatchewan increased between 2014 and 2016, whereas it declined in BC and Manitoba. Meanwhile, Figure 2.3 shows the steady decline in BC's residential waste between 2010 and 2016.

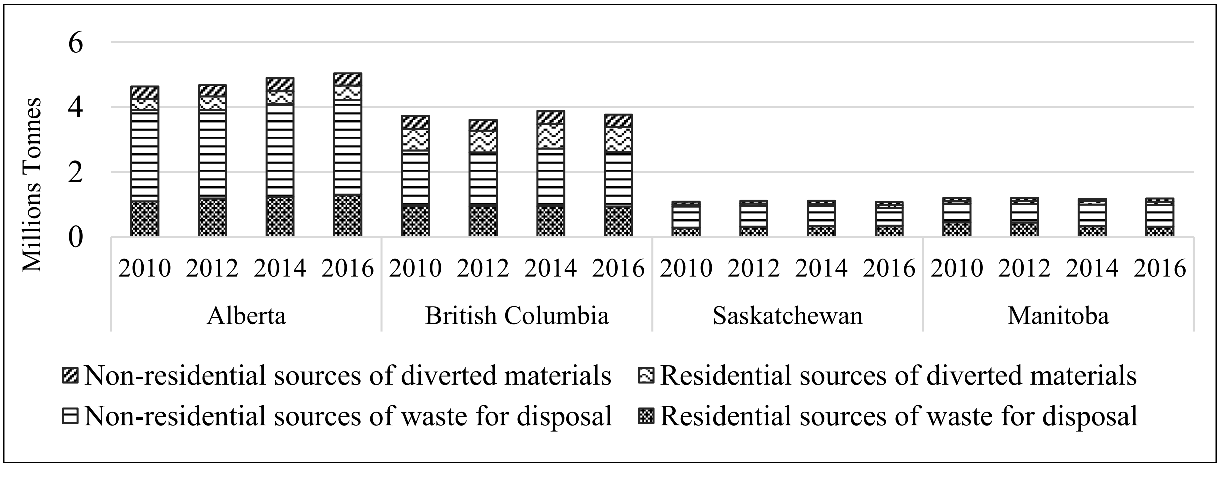
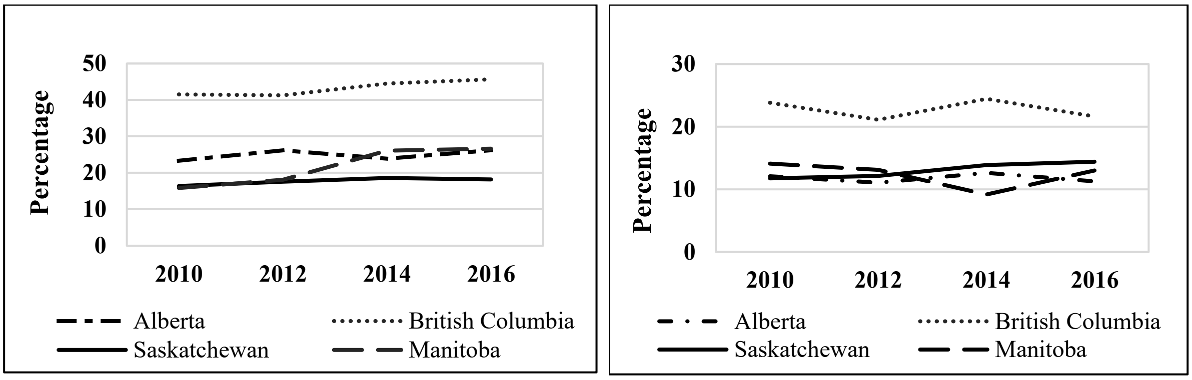


Figure 2.3: Solid waste diversion and disposal, western Canada, 2010-2016

Solid waste generation in western Canada increased by 5.6% between 2010 and 2016, and the amount of waste disposed in waste collection facilities increased by 1.82%. As shown in Figure 2.3, the amount of waste diverted from the non-residential sector in Alberta exceeded the amount diverted from the residential sector in 2016 in both Alberta and British Columbia.



A **B**

Figure 2.4: Solid waste diversion rate, western Canada, 2010-2016 (A) residential (B) non-residential

Diverting waste by recycling and composting reduce the adverse impact of MSW on the environment. In this study, the diversion rate is the ratio of waste diverted from landfills to the total waste disposed of at and diverted from landfills. In western Canada, most solid waste ends up in landfills, and in 2016 only 25.45% of it was diverted (Government of Canada, 2020b). Figure 2.4 shows the rates of waste diversion from residential and non-residential sources by province. BC had a higher diversion rate than the other provinces for both residential and non-residential waste. In 2016, the province diverted 42% of its residential sector waste, and its non-residential waste diversion rate fell to 22%. In the Prairie Provinces, the residential sector waste diversion rate fluctuated between 19% and 27% between 2010 and 2016. Waste diverted from the non-residential sector fluctuated between 12% and 14% in the three provinces between 2010 and 2016.

2.3 Method

In this study, MSW potential in western Canada was assessed and developed a land suitability map (LSM) of candidate sites for W2VA facilities. ArcGIS 10.4 (ESRI, 2015), a GIS-based software, was used to locate optimal sites based on different social, environmental and economic criteria. Figure 2.5 shows the flowchart of the various analyses performed. In this study, geospatial data were collected from different sources such as provincial government websites, published reports, statistics documents, papers, etc.

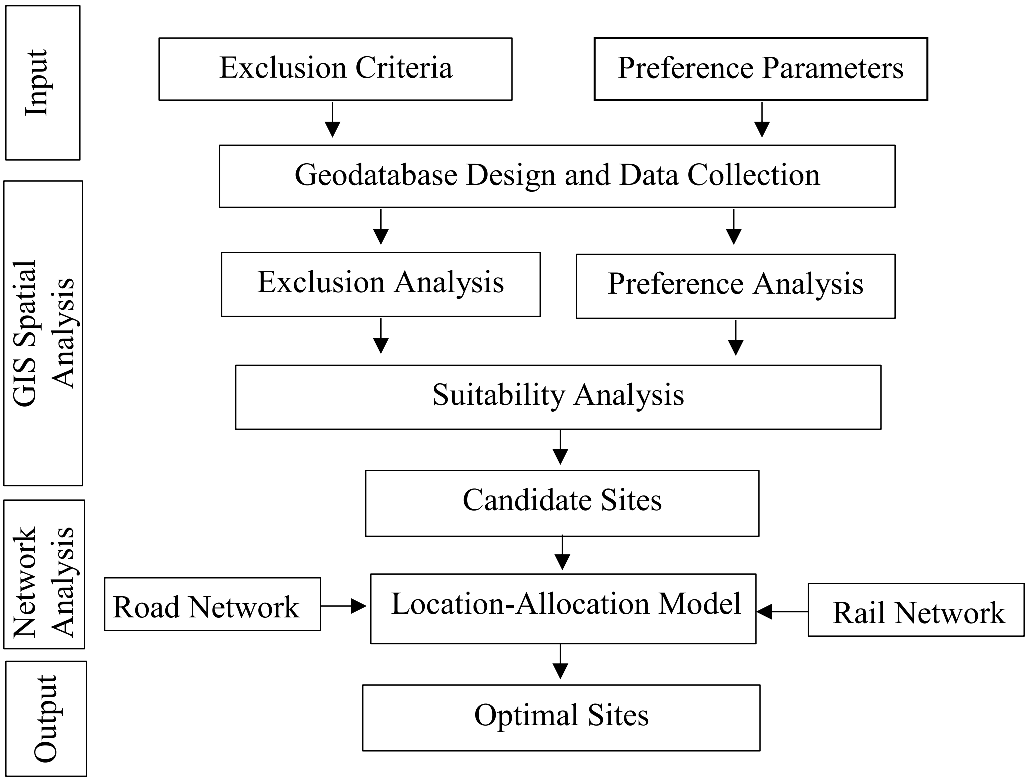


Figure 2.5: Flowchart of the different GIS analyses used (Sultana and Kumar, 2012)

Most of the data used in this study was available in vector format in Geographic Coordinate System (GCS) North American 1983 and GCS North American 1983 CSRS Canadian Spatial Reference System (CSRS). In this study, the Universal Transverse Mercator (UTM) NAD 1983 projection coordinate system was used to perform GIS analyses for collected data and raster files. Data for land surface gradient and land cover are available in raster format (Appendix-E). Using a three-step approach, a LSM of western Canada, as shown in Figure 2.12, was created to identify candidate sites. The existing road and rail networks were incorporated in network analysis. Later sections describe the study's method in detail.

2.3.1 Exclusion analysis

An exclusion analysis was performed that considered social, environment, and economic criteria to screen out unsuitable areas. Fourteen criteria used in earlier studies were selected that could restrict the development of a W2VA facility in our study area (Al-Jarrah and Abu-Qdais, 2006; Sultana and Kumar, 2012). These criteria are listed in Table 2.1. Applying constraints ensures that a new facility complies with current environmental and conservation practices. A buffer zone corresponding to criteria was created and maps were converted to raster maps with a cell size of 30 m x 30 m (Appendix-E) The cells were then reclassified to transform the raster maps into binary maps (Appendix-F) in which the values "1" and "0" represent areas outside and inside of the buffer zone, respectively. Binary maps of all exclusion criteria were combined as per the following equation to obtain the final exclusion map:

$$C_{E,i} = \prod_{m=1}^{n} C_{i,m} \tag{1}$$

where $C_{E,i}$ presents cell value in Boolean (0, 1) for the final exclusion analysis map as shown in Figure 2.7; $C_{i,m}$ is the cell value in Boolean (0, 1) for the ith cell in mth criteria and n is the total number of exclusion criteria. Like the binary function, cell values of ''0'' and "1" in the final exclusion map indicate areas unsuitable and suitable, respectively, for locating W2VA facilities. Figure 2.6 (A) gives a brief overview of the exclusion analysis and Table 2-1 lists the exclusion criteria considered in the exclusion analysis with corresponding buffer distances.

Table 2-1: Identified exclusion criteria and corresponding buffer zone distance

Criteria	Description
Rivers, lakes, and other waterbodies	Buffer of 100 m from water bodies (Ma et al., 2005)
Rural and urban areas	Buffer of 1 km from rural and urban areas (Eskandari et al., 2012)
Airports and heliports	Buffer of 8 km from international airports and 3 km from local airports (Eskandari et al., 2012)
Coal field	Buffer of 1 km from coal fields (Khan et al., 2018)
Industrial zones	Buffer of 1 km from those sites (Sultana and Kumar, 2012)
Gas and oil field	Buffer of 1 km from gas and oil fields (Sultana and Kumar, 2012)
Environmentally sensitive areas (ESAs)	Buffer of 1 km from ESAs (Eskandari et al., 2012)
Natural gas and oil pipelines	Buffer of 100 m from natural gas and oil pipelines (Ma et al., 2005)
Park and recreational areas	Buffer of 500 m from these sites (Khan et al., 2018)
Roads	Buffer of at least 30 m far from roads (Ma et al., 2005)
Power plants and substations	Sites falling within a buffer of 200 m are avoided (Ma et al., 2005)
Land surface gradient	Land with slopes greater than 15% are removed (Ma et al., 2005)
Rail network[2]	Buffer of 30 m from rail tracks
Forest areas	Buffer of 1 km from forest areas (Martino, 2001)

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[2] Similar to road network, a buffer zone of 30m was considered for rail network in this study.

2.3.2 Preference analysis

In preference analysis, relative preference grading was assigned to different regions within the study area. For western Canada, nine factors (listed in Table 2-2) were considered based on social, environmental, and economic criteria consistent with provincial and federal government regulations (Ma et al., 2005; Eskandari et al., 2012; Sultana and Kumar, 2012; Farahbakhsh and Forghani, 2018).

Several buffer rings[3], as shown in Figure 2.8, were generated around each of the factors, which were assigned grading values on a scale of 0-10 depending on their distance from the corresponding factor. A grading value of 10 is the most preferable area and a value of 0 is the least. Land cover and slope data were available in raster form only. Multiple buffer rings could not be created for those two criteria. Instead, raster values of those two files were reclassified on a scale of 0-10 to represent most and least preferable areas, respectively.

The relative weightage of each preference factor was calculated using the MCDA-AHP method. The AHP approach makes a pairwise comparison by assigning a relative score on a scale of 1-9 (Saaty, 1984). Once this was done all the maps were combined using the relative weights (given in Table 2-2) to obtain the final preference analysis map as shown in Figure 2.11. The calculated consistency ratio[4] (CR) for this pairwise comparison is 1.47%, which is well below the 10% acceptability margin (Saaty, 1984). The value of the different cells of the final preference analysis map were calculated through the following equation:

$$C_{p,i} = \sum_{k=1}^{l} W_k \ C_{i,k} \qquad 0 \leq W_j \leq 1 \qquad (2)$$

---

[3] Buffer rings are defined as an area within which no new construction can be built.

[4] Consistency Ratio is calculated by dividing the Consistency Index for the set of judgments by the Index for the corresponding random matrix.

Consistency index = $\frac{\lambda \max - n}{n-1}$, where λmax is the maximum eigen value and n is the number of parameters.

where $C_{p,i}$ is a grading value of the i^{th} cell in final preference map, $C_{i,k}$ is the preference value of i^{th} cell in k^{th} factor, l is the total number of preference factors and W_k is the relative weightage of the k^{th} factor. Figure 2.6 (B) gives a brief overview of the preference analysis.

Table 2-2: Preference factors and calculated relative weightages

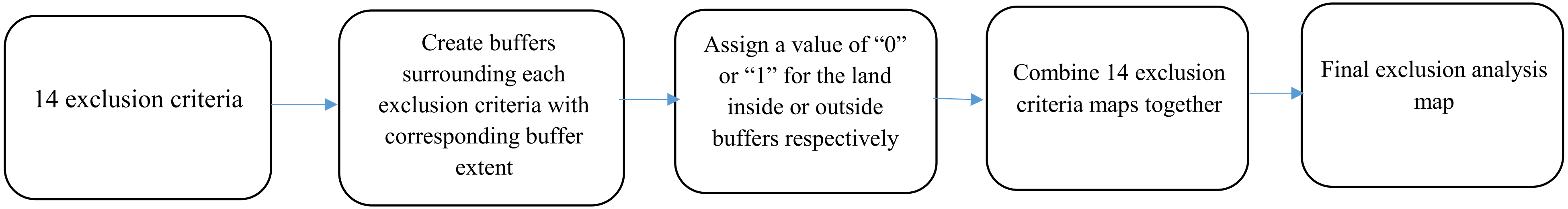
Preference factors	Relative weightage
Transfer stations	0.41
Urban	0.18
Water	0.12
Roads	0.07
Rail	0.07
Transmission lines	0.05
Substation	0.04
Land cover	0.03
Slope	0.03

2.3.3 Suitability analysis

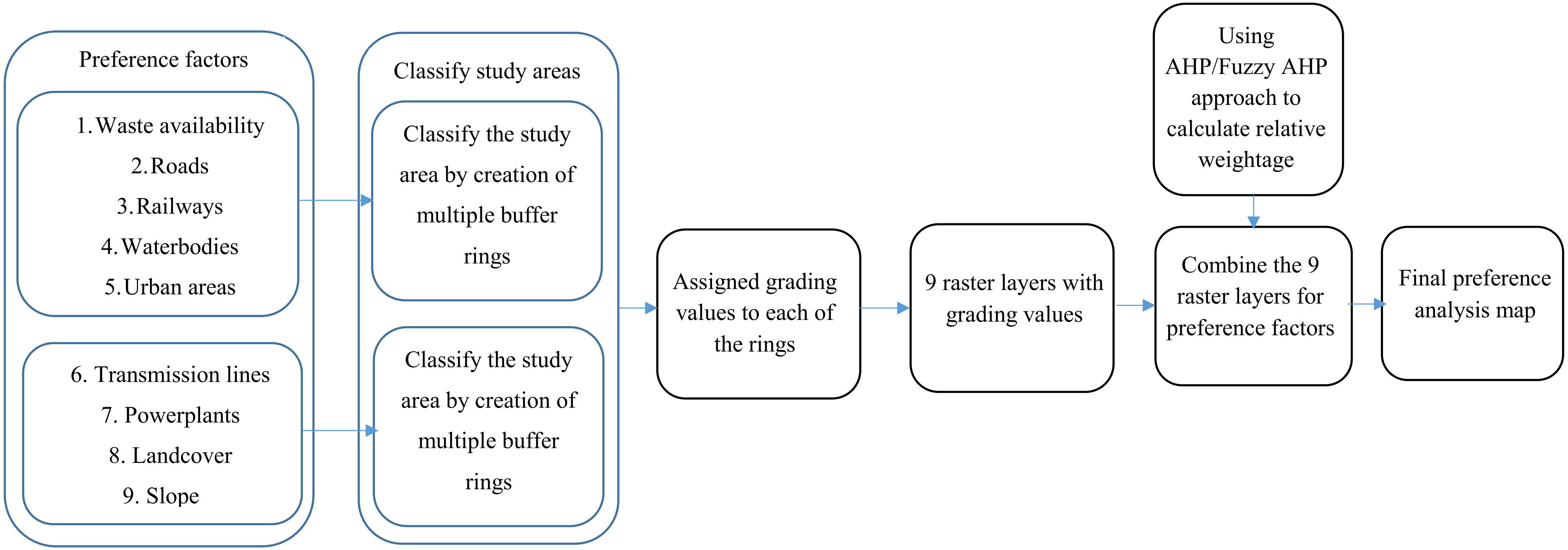
A suitability analysis was performed to determine suitable regions to build W2VA facilities. The final exclusion and preference analysis maps were integrated to create the LSM. The value in each LSM cell is the suitability index (SI) that can be calculated using the following equation:

$$SI_i = C_{E,i} \times C_{P,i} \tag{3}$$

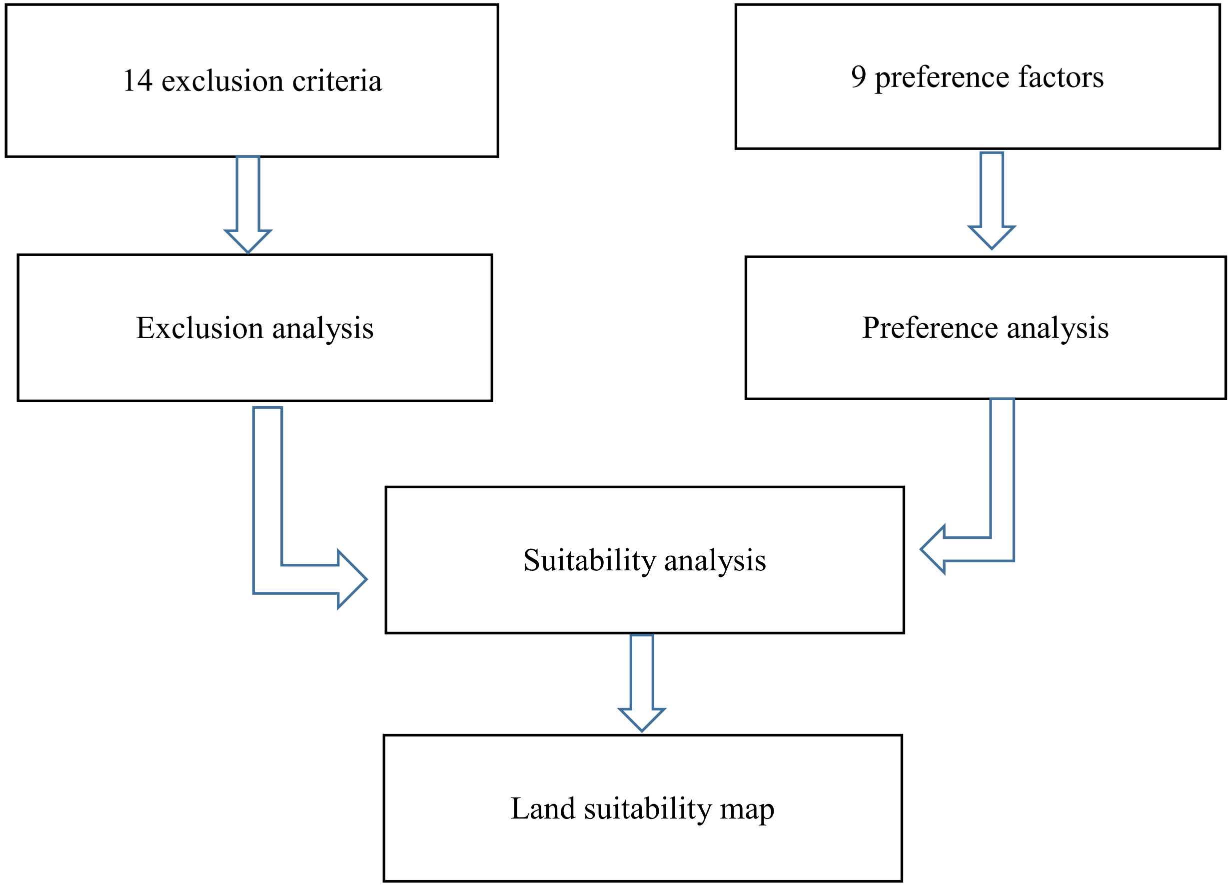
where SI_i is the SI of i^{th} cell in LSM. The cell values range from 0 to 10; ‘‘0’’ indicates excluded areas and ‘‘10’’ indicates suitable sites for locating a W2VA facility. Figure 2.6 (C) gives a brief overview of the suitability analysis.


14 exclusion criteria
Create buffers surrounding each exclusion criteria with corresponding buffer extent
Assign a value of “0” or “1” for the land inside or outside buffers respectively
Combine 14 exclusion criteria maps together
Final exclusion analysis map

(A)


Preference factors
1. Waste availability
2. Roads
3. Railways
4. Waterbodies
5. Urban areas
6. Transmission lines
7. Powerplants
8. Landcover
9. Slope
Classify study areas
Classify the study area by creation of multiple buffer rings
Classify the study area by creation of multiple buffer rings
Assigned grading values to each of the rings
9 raster layers with grading values
Using AHP/Fuzzy AHP approach to calculate relative weightage
Combine the 9 raster layers for preference factors
Final preference analysis map

(B)



(C)

Figure 2.6: (A) Overview of exclusion analysis (B) Overview of preference analysis (C) Overview of suitability analysis

2.3.4 Network analysis

Transporting MSW disposed at TSs to W2VA facilities is a significant economical concern (Al-Jarrah and Abu-Qdais, 2006; Chaudhary et al., 2019). Existing road and rail networks, as shown in figure Figure 2.9 (A) and Figure 2.9 (B), play an important role in reducing the waste collection cost. To identify potential W2VA locations with the lowest transportation costs, a network analysis was conducted. Different spatial analysis tools are available from the ArcGIS Network Analyst to solve complex routing problems using transportation network data. In this study, the “minimize impedance” option was used to determine optimum facility locations by minimizing the weighted distances between selected sites and connected TSs. The ArcGIS location-allocation analyzer creates an origin-destination matrix between selected facilities and waste collection points through Dijkstra’s algorithm (Sultana and Kumar, 2012).

2.4 GIS Analysis and Results

In this study, spatial coordinates of input files were defined in linear units using a projected coordinate system rather than the angular degrees used for a geometric coordinate system. Hence, the latitude and longitude coordinates were transformed to x and y coordinates on the flat surface. Several projected coordinate systems are available for Canada (ESRI, 2016). Because western Canada comprises of four provinces, it is important to use a proper projected coordinate system to define data in ArcGIS. In this study, NAD 1983 BC Environment Albers projected coordinate system was used as a reference coordinate system and all spatial ArcGIS files were transformed accordingly.

2.4.1 Exclusion analysis

Forests and waterbodies (lakes, rivers, and wetlands) were found to be the most significant factors in the exclusion analysis. The exclusion analysis map for western Canada, shown in Figure 2.7, screened out 73.6 % of the study area, leaving 713633.9 km^2 (26.4%). Alberta has an area of 661848 km^2, more than 57% of it forested and 2.95% made up of rivers and other waterbodies. With all 14 exclusion criteria considered, around 82.8% of the province was excluded. In British Columbia, Saskatchewan, and Manitoba, forests cover around 64%, 44%, and 66% of the province, respectively. The shares of waterbodies are 2.1%, 9.2%, and 15.6%, respectively. With all fourteen exclusion criteria included, around 74.7%, 72.5%, and 79.2% of British Columbia, Saskatchewan, and Manitoba, respectively, were excluded from the study area. Overall, forest and waterbodies cover around 58.4% and 6.9% of western Canada. Only 26.4% of the region was left after all 14 exclusion criteria in the exclusion analysis were considered.

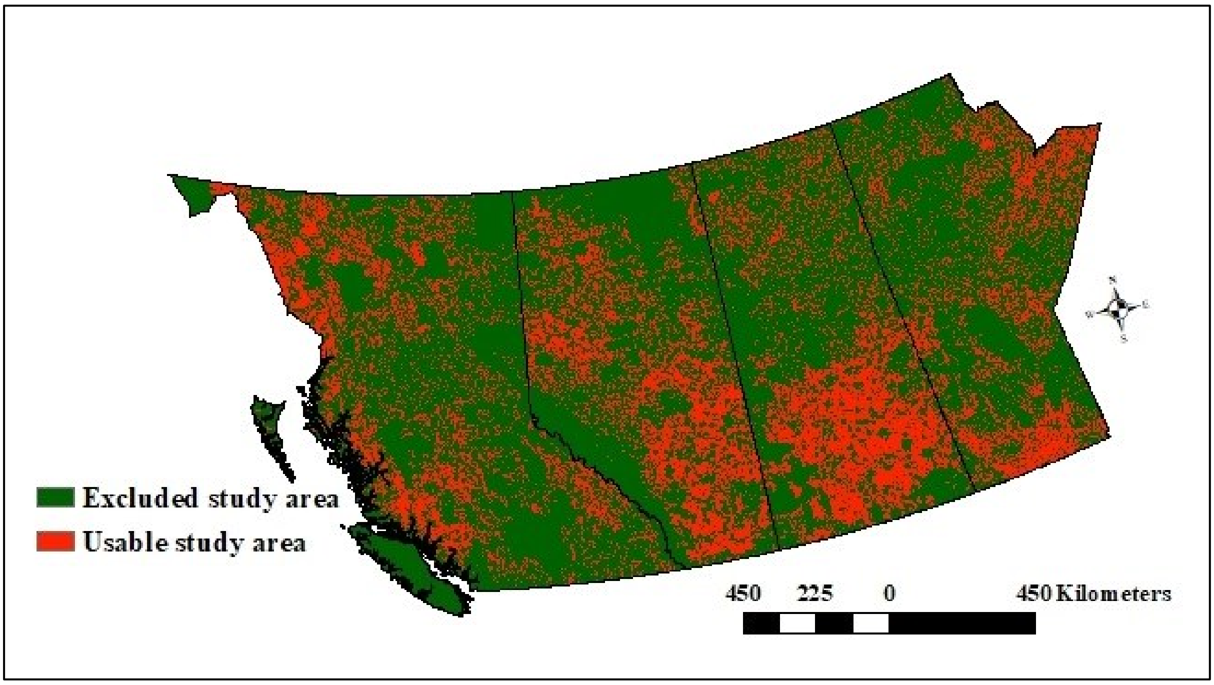


Figure 2.7: Exclusion map for western Canada showing the useable area

2.4.2 Preference analysis

2.4.2.1 MSW availability and distance from existing TSs

The MSW potential from TS in Canada was not readily available. Hence, thiessen polygons were used to calculate the potential based on the annual per capita disposal rate from Statistics

Canada (Statistics Canada, 2020a) and the population for the year 2019 (Statistics Canada, 2020b). The population within each polygon was multiplied by the per capita disposal rate of the corresponding province to obtain the amount of MSW available in each polygon. Since each polygon has a TS as a point input feature, the calculated MSW within a Thiessen polygon boundary represents the available MSW at the corresponding TS. To minimize transportation costs, it is preferable to locate W2VA facilities close to connected TSs. In this analysis, multiple buffer rings were created based on the distance from corresponding TSs and a grading value was assigned to each buffer ring. Table 2-3 lists the assigned values for different buffer rings and Figure 2.8 is a map showing grading values based on distances from existing TSs across western Canada. A grading value of 10 indicates most preferable areas and 0 least preferable.

Table 2-3: Grading values for preference parameters

Preference level	**Grading values**	**Road & Rail network (km)**	**Substation & pipelines (km)**	**Urban areas (km)**	**Transfer stations (km)**	**Slope (degree)**	**Water -bodies (km)**	**Land cover (type)**
Very suitable	9-10	0.03-0.2	0.2-1	> 5	< 30	< 10	0.1-0.5	Exposed land grassland
Suitable	7-8	0.2-0.5	1-2	4-5	30-60	10-15	0.5-1	Developed land
Almost suitable	5-6	0.5- 1	2-3	3-4	60-90	-	1-1.5	Roads, rail, agricultural land
Unsuitable	3-4	1-2	3-5	2-3	90-120	-	1.5-2	Boreal forest, mixed forest
Very unsuitable	1-2	> 2	> 5	1-2	120-150	-	> 2	Snow, ice, rock/rubble
Not suitable at all	0	< 0.03	< 0.2	< 1	> 150	>15	< 0.1	Lakes, waterbodies

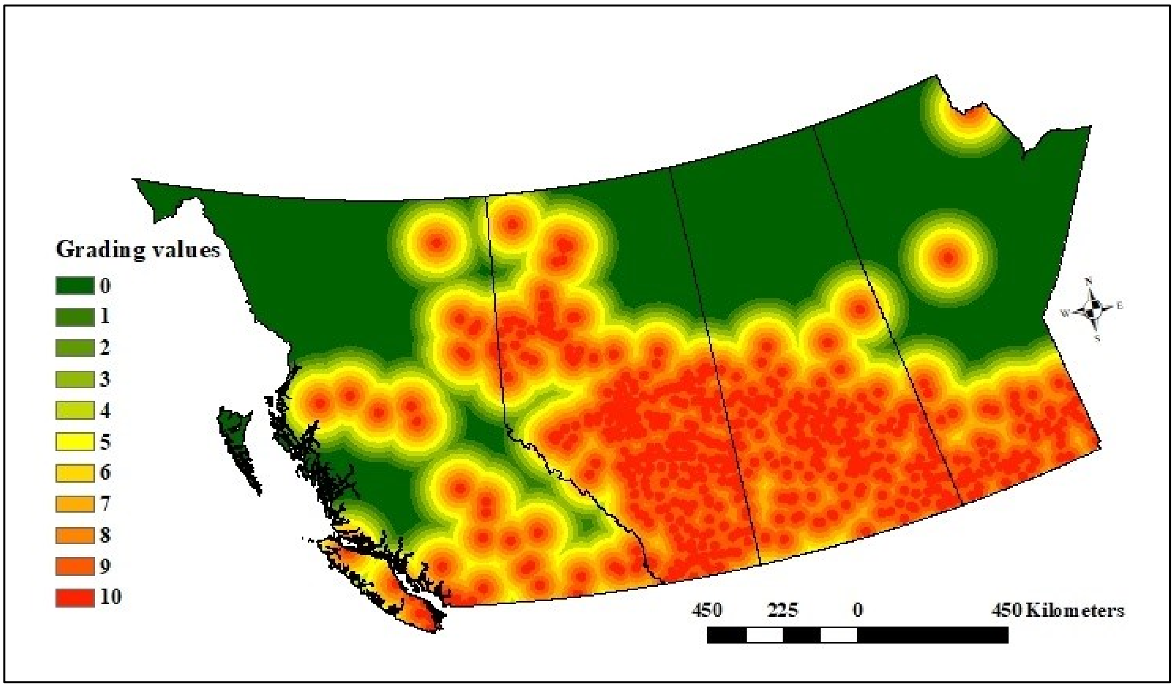


Figure 2.8: Map showing grading values based on distance from TSs

2.4.2.2 Distance from roads and rail tracks

Both road and rail networks were used to determine optimal W2VA facility sites while incorporating a restricted buffer zone of 30 meters. A facility should be located beyond this restricted zone to comply with government rules and norms. Buffer rings were created around the roads and rail tracks based on the distance. Table 2-3 shows the grading value for each buffer ring on a scale from 0 to 10. Grading values increase as the distance from roads or rail tracks decreases. Figure 2.9 (A) and Figure 2.9 (B) present the resultant maps for road and rail networks with assigned grading values.

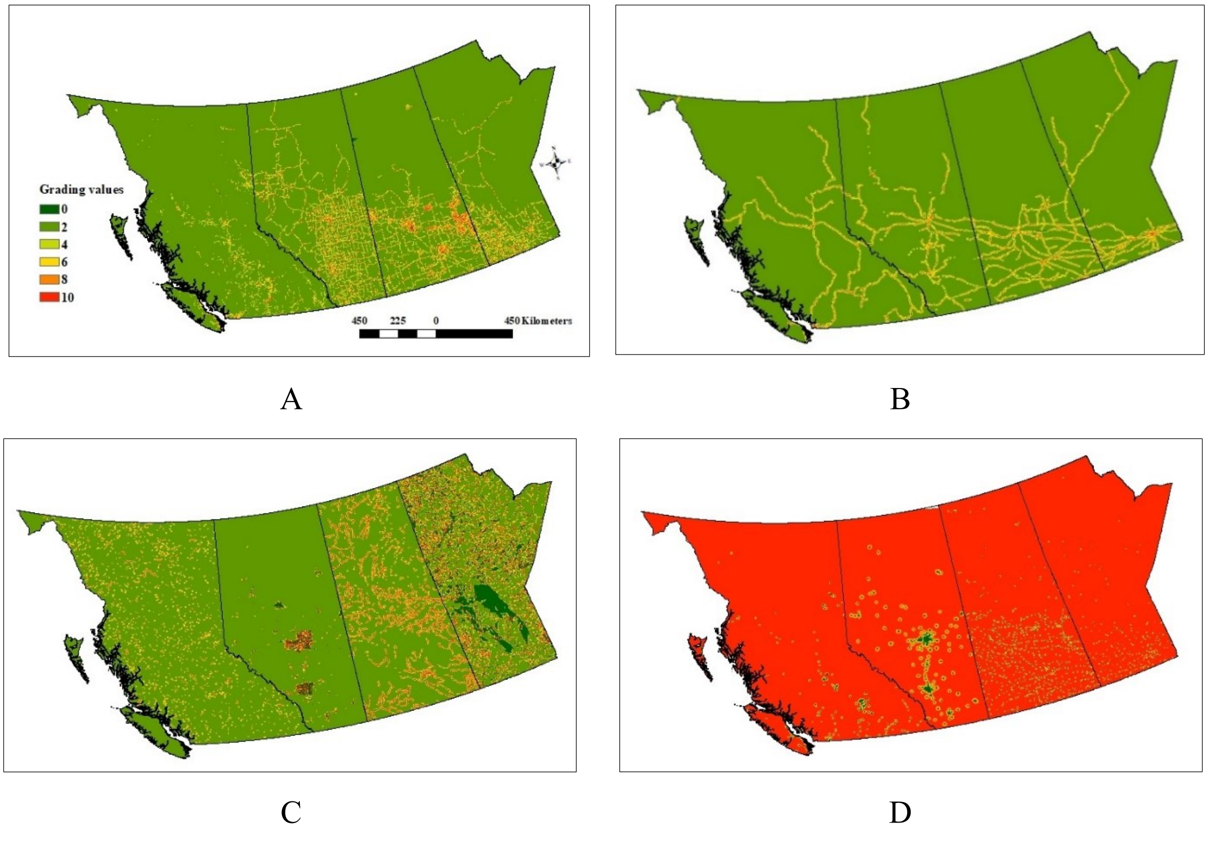
2.4.2.3 Distance from waterbodies

In this study, “waterbody” denotes rivers, lakes, wetlands, and other surface water sources. Water availability at a proposed W2VA facility is a preference factor since a considerable volume of water will be withdrawn from nearby waterbodies (Martín, 2015). A restricted buffer zone of 100 m was assumed to prevent surface water contamination (Khan et al., 2018).

Multiple buffer zones were generated around all forms of waterbodies. Table 2-3 shows the grading values assigned to different areas and Figure 2.9 (C) illustrates grading values based on distance from waterbodies.

2.4.2.4 Distance from urban areas

A distance of 1 km from urban areas was considered to site a W2VA facility in order to minimize social resistance. Available data on urban areas were used to generate multiple buffer rings, and grading values were assigned to each ring. Table 2-3 shows that the grading value beyond the restricted zone increases as buffer distance from urban areas increases. Figure 2.9 (D) shows the assigned grading values used to obtain suitable site locations based on the distance from nearby urban areas. The legend used in Figure 2.9 (A) is applicable to Figure 2.9 (B), (C), and (D).



A

B

C

D

Figure 2.9: Maps showing grading values based on distance from (A) roads, (B) rail, (C) waterbodies, and (D) urban areas

2.4.2.5 Distance from transmission lines and substations

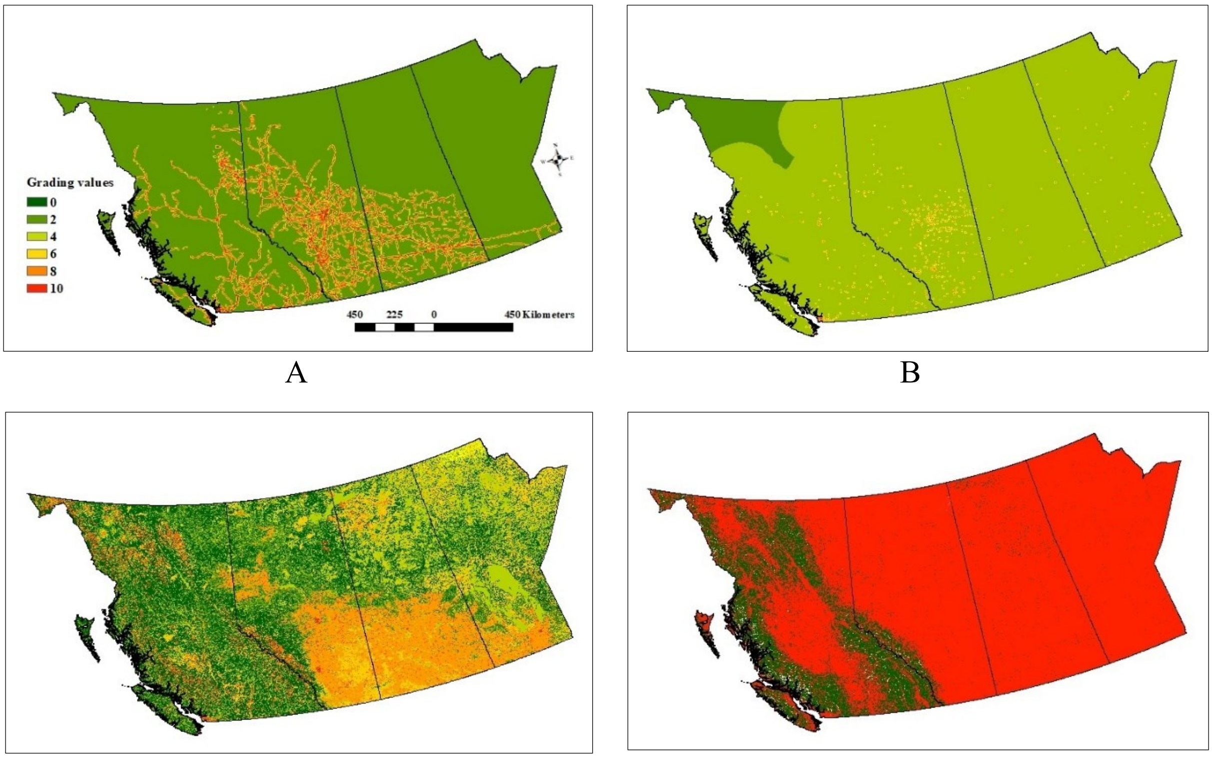
Existing electricity transmission lines are considered as a preference factor since the closer the W2VA facilities are to the substations, the lower the transmission cost. Multiple buffer rings were generated around the transmission lines and existing substations to obtain preference areas. Table 2-3 provides the grading values given to multiple buffer zones; assigned values decrease as distance increases. A buffer zone of 100 m was used in keeping with the regulations and practices in the Prairie Provinces. Figure 2.10 (A) and (B) show the preferable areas based on distance from transmission lines and existing substations.

2.4.2.6 Land cover

Grading values for land cover were assigned based on land type and present use. Exposed lands and grasslands were most preferable as they can be used for planned development; snowy, rocky, and icy areas were considered very unsuitable (see Table 2-3). Lakes and other waterbodies were excluded and thus given a grading value of “0”. Figure 2.10 (C) presents the assigned values to different zones.

2.4.2.7 Land slope

It is important to site the W2VA facility in a place with minimal sloping as there is a cost to level land. In our study, areas with slopes greater than 15° were assigned a value “0” and areas with slopes of less than 15° were assigned a value of “10,” the latter indicating preferable locations to set up W2VA facilities (Ma et al., 2005). Figure 2.10 (D) shows the land grading values based on slope degree. The legend used in Figure 2.10 (A) is applicable to the others.



A B

C D

Figure 2.10: Maps showing grading values based on (A) distance from transmission lines, (B) distance from substations, (C) land cover, and (D) slope

2.4.2.8 Overlay analysis and final preference map

In this study, nine preference factors were selected based on social, environmental, and economic criteria. The relative weightage of those preference factors was calculated using the AHP, as shown in Table 2-2. Eventually, all nine raster maps for preference factors were overlain with the weighted overlay tool based on the relative weightage of the corresponding preference factors to get a single preference map of the study area. Figure 2.11 shows the final preference map for the study area with a grading scale from 1 to 10.

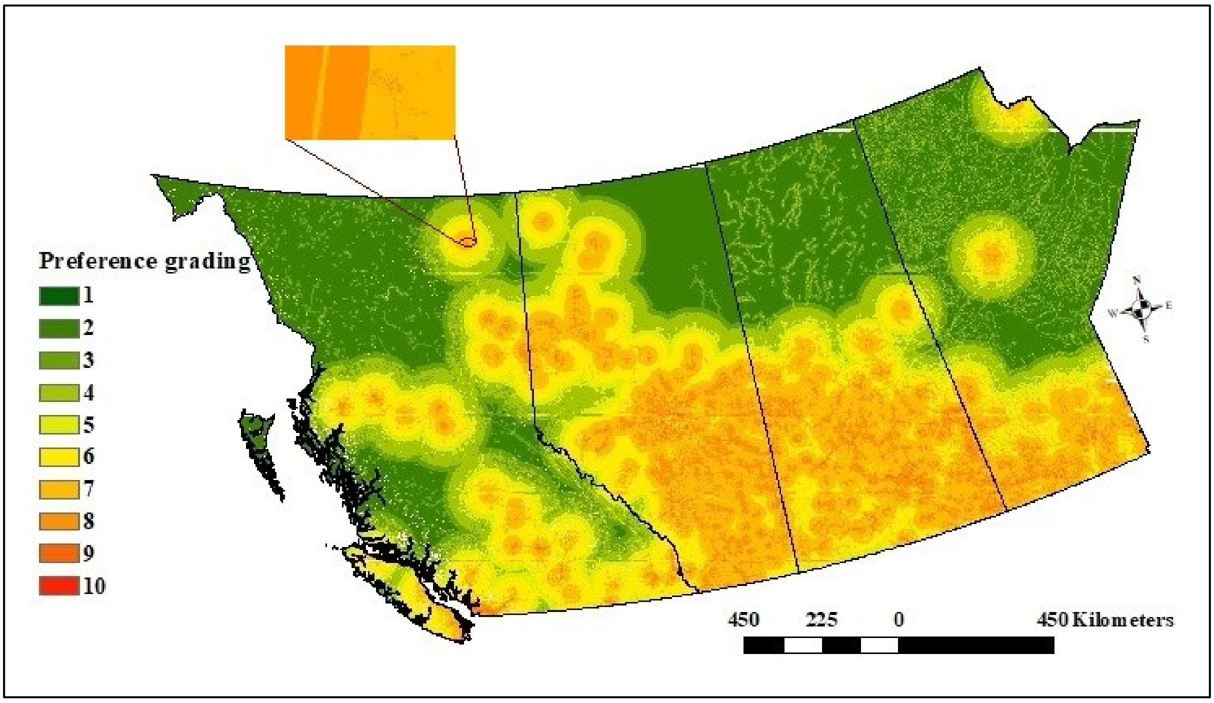


Figure 2.11: Final preference map for western Canada

2.4.3 Suitability analysis

In suitability analysis, the raster layers of the final exclusion analysis map and the preference analysis map were combined together to produce the final LSM for western Canada. Figure 2.12 shows this map with a suitability index (SI) of 0 to 10. ‘‘0’’ refers to the excluded areas and ‘‘10’’ the most suitable candidate sites. The centroids from high SI polygons (SI 10 and 9) are considered candidates to be studied further as potential W2VA sites.

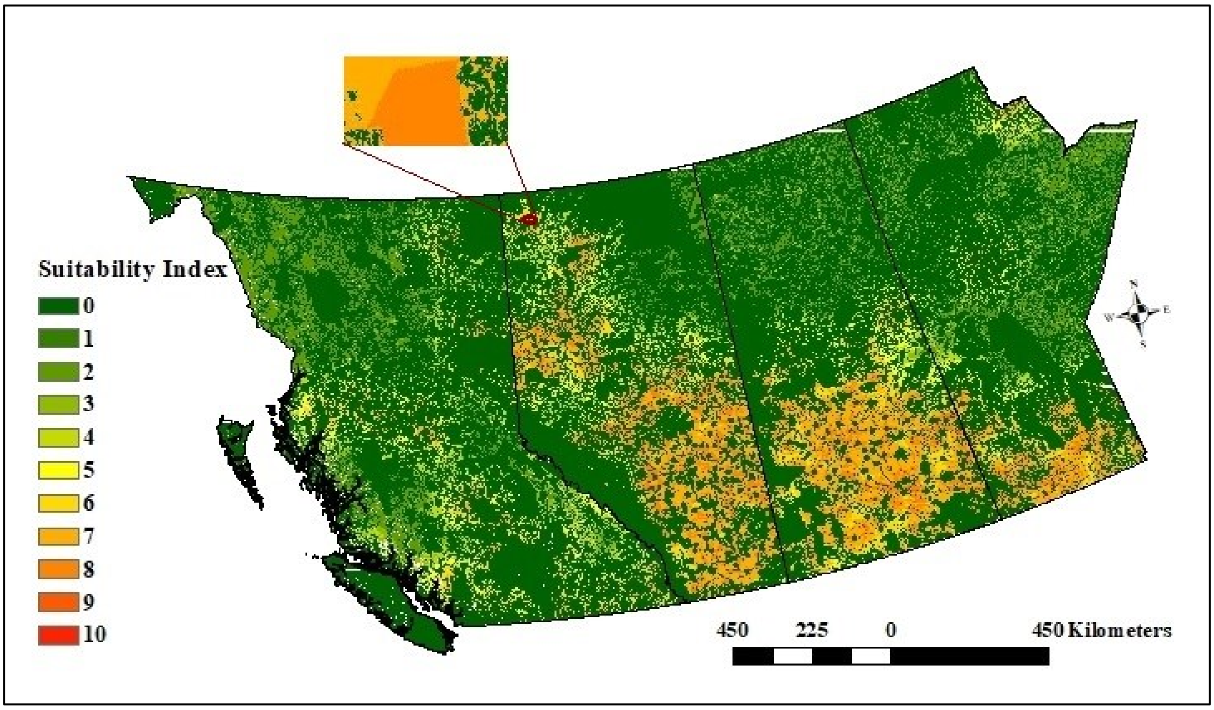


Figure 2.12: Final land suitability map for western Canada

2.4.4 Network analysis (location-allocation)

In this study, TSs across western Canada were considered as demand point locations. To minimize transportation costs, the "minimize impedance" concept, mentioned in section 2.3.4, was used to perform a network analysis. Figure 2.13 shows the network analysis with ten optimal sites for locating W2VA conversion facilities across western Canada.

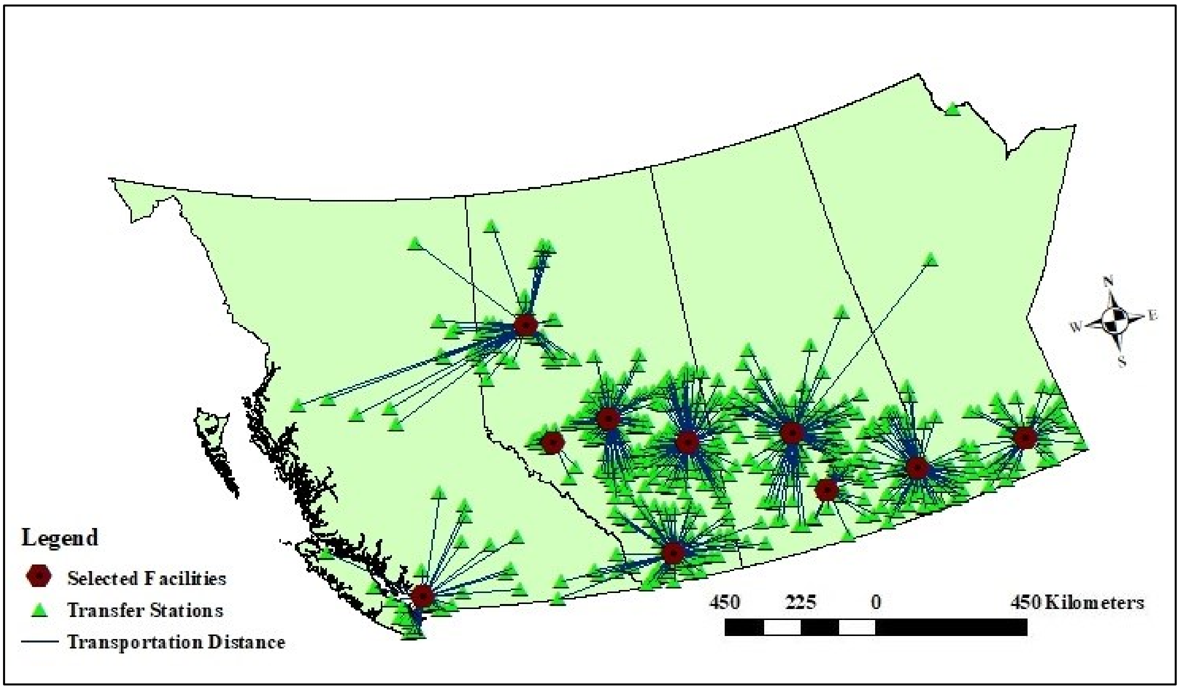


Figure 2.13: Determined optimal location in western Canada for W2VA facility

Since population density is comparatively higher in the southern parts of all four provinces, optimum sites were mainly located in the south. These choices were made based on waste availability, diversion rate, and the number of the existing TSs. Five of the ten optimal sites were located in Alberta, as the availability of waste in that province was around 48.4% of the total waste availability of western Canada with an annual disposal rate of 1.03 tonne/capita (Clancy, 2018). Moreover, in 2016, Alberta had the lowest waste diversion rate (16.76%) among the four provinces and the highest number (282) of active TSs. On the other hand, British Columbia had the highest diversion rate (67.13%) among the four provinces and 63 operational TSs. Hence, only one optimal site (of the ten) was located in British Columbia. Three W2VA facilities were proposed for Saskatchewan and one for Manitoba. This study found 199 active TSs in Saskatchewan and 63 in Manitoba with 18.89% and 21.76% overall waste diversion rates, respectively. Table 2-4 provides the longitude, latitude, and province name for the selected sites with NAD 1983 BC Environment Albers as the reference projected coordinate system.

Table 2-4: Optimal locations of the selected W2VA facility sites

Sites	MSW availability (million tonnes/yr)	Number of connected TSs	Longitude (degree)	Latitude (degree)	Province
1	2.12	74	-112.62	49.75	Alberta
2	1.96	84	-114.37	53.57	Alberta
3	1.38	39	-123.03	49.34	British Columbia
4	0.87	46	-97.26	49.95	Manitoba
5	0.54	101	-106.55	52.13	Saskatchewan
6	0.52	55	-117.55	56.37	Alberta
7	0.26	24	-105.77	50.42	Saskatchewan
8	0.26	99	-111.06	52.55	Alberta
9	0.21	76	-101.89	50.24	Saskatchewan
10	0.04	15	-116.98	53.19	Alberta

2.5 Conclusion

Environmental, social, and economic criteria are involved in siting a new waste-to-value-added (W2VA) facility to ensure sustainable operability. The present study used a geographic information system – multi-criteria decision analysis based analytical approach to determine and assess optimal W2VA facility sites across western Canada. The optimal locations of potential W2VA facilities were determined through exclusion and preference factors and their relative weightages. In a three-step approach that included fourteen exclusion and nine preference factors, a land suitability map (LSM) was developed. Candidate sites with SIs of 9 and 10 were chosen from the LSM and studied further in a network analysis to select ten optimal locations for W2VA facilities. The method presented here is an efficient approach to deal with multi-faceted factors to determine optimal locations while weighing the relative importance of considered factors.

In this study, MSW availability at different transfer stations was found to be the most significant preference factor and is influenced by the population density of a region. This study focused on determination of ten optimal sites for W2VA facilities based on minimizing transportation cost for waste collection while ensuring environmental, economic, and social viability. However, the decision of building a new W2VA facilities in an optimal site is strongly dependent on the economic competitiveness of a new facility considering potential of MSW at that site, composition of waste stream and economic feasibility of an appropriate environment-friendly waste conversion technology. In general, this method can be used as a decision-making tool anywhere in the world in compliance with relevant exclusion and preference factors to build a W2VA facility through future feasibility study. This methodology can be used for determination of optimal location of W2VA facilities in other jurisdictions of the world.

Chapter 3: Selection and Prioritization of Sites for Municipal Solid Waste-to-Value-Added Facilities across Eastern Canada using GIS and Fuzzy AHP

3.1 Introduction

Municipal solid waste (MSW) is produced by human activities and varies with population, extent of urbanization, and living standards. Managing MSW is a big concern for waste management authorities as urban migration has significantly increased waste generation rates. This increase limits land availability for waste disposal. The management of waste disposal sites, moreover, is challenging as landfilling brings multiple problems such as leachate generation and air pollution. In 2016, Canadians produced 901 kg/capita/year on average, which was around 4.5 times higher than the global rate (World Bank Group, 2019; Statistics Canada, 2020a). Disposal of waste at existing landfills generates greenhouse gases (GHGs), which make up 20% of national methane emissions (Environment and Climate Change Canada, 2019). Rising population, moreover, has led to an increase in fossil fuel consumption (Khan et al., 2018). Fossil fuel combustion for energy generation is one of the leading sources of GHG emissions in Canada (Unniversity of Winnipeg, 2018). In this context, converting MSW to energy is a promising pathway to environmental sustainability that provides an environmentally friendly means of producing cleaner energy and offsetting GHG emissions.

A waste-to-value-added (W2VA) conversion system that integrates material and energy recovery technologies can reduce the reliance on landfills and, in turn, mitigate the associated GHG emissions. A crucial step in setting up W2VA conversion facilities is site selection, since ill-defined locations may adversely impact environmental health (Tavares et al., 2009; Singh, 2019b). Optimal site selection for waste management facilities is a multi-disciplinary decision-making problem involving technical, environmental, social, and economic factors (Sumathi et al., 2008; Goorah et al., 2009; Gorsevski et al., 2012). Determining the relative importance of these characteristics is often conflicting and inconsistent (Singh and Dubey, 2012). This complexity is a good fit for multi-criteria decision analysis (MCDA) and geographic information systems (GIS) (Kontos et al., 2003). Many researchers have tackled optimal siting by integrating MCDA in a GIS environment for the suitability analysis of the study areas (Hale and Moberg, 2003; Javaheri et al., 2006; Wang et al., 2009; Moeinaddini et al., 2010; Rahmat et al., 2017; Chabuk et al., 2019; Karimi et al., 2020; Tsai et al., 2020). These studies have prioritized quantitative and qualitative criteria through the analytic hierarchy process (AHP) in an MCDA that considered the relative importance of contributing factors to picturize a suitability map for the study areas. Intharathirat and Abdul Salam (2020) integrated the AHP in an MCDA to determine suitable waste conversion technology based on 11 criteria. Aderoju et al. (2020) outlined a GIS-based MCDA for selecting six sanitary landfill sites in Nigeria. Neehaul et al. (2020) identified the best W2VA technology in Mauritius in an AHP model that considered technical and sustainability indicators in a GIS environment. However, a few researchers reported some drawbacks to the AHP in the MCDA, as it did not consider the uncertainty in the judgment of decision-makers (Yang and Chen, 2004; Bana e Costa and Vansnick, 2008). Subjectivity in the decision-making influences the AHP result greatly (Smith and von Winterfeldt, 2004). The fuzzy analytic hierarchy process (FAHP) was developed to address these problems, that is, to allow decision-makers to express approximate preferences using fuzzy membership functions (Mikhailov and Tsvetinov, 2004; Erensal et al., 2006; Wang et al., 2008). Kharat et al. (2019) presented a method to weigh the relative importance of social, economic environmental, and technical criteria. Pasalari et al. (2019) performed a case study to determine six suitable landfill areas using a hybrid FAHP system based on GIS analysis. Feyzi et al. (2019) used an MCDA that considered the relative importance of environmental, economic, and socio-cultural criteria based on fuzzy analytic network process (FANP) calculations to site an MSW incineration plant in northern Iran. Karimi et al. (2020) developed a method to site and rank landfills based on the FAHP in a GIS environment using night-time satellite images. Ubando et al. (2020) introduced a decision support system using the FAHP to site an algal industry; the system evaluate different regions based on environmental impact, costs, and social aspects. Khoshand et al. (2020) developed a framework based on the FAHP to prioritize four types of construction and demolition waste management alternatives – landfilling, recycling, reusing, and reducing in Iran (2020). Kharat et al. (2020) demonstrated a reliable MCDA framework to select the best MSW treatment and disposal technology using the FAHP. Bahrami et al. (2020) integrated the FAHP in an MCDA using seven criteria to develop landslide susceptibility maps. Eghtesadifard et al. (2020) developed an integrated GIS-MCDA method for the selection of MSW using thirteen criteria based on an FAHP assessment.

With Canada's efforts to reduce landfilling through material and energy recovery technologies, many studies have explored the MSW utilization pathways. Some authors have studied the availability of MSW for the production of valuable products through various waste conversion technologies and considering the actual road network to minimize transportation costs (Khan et al., 2018; Rizwan et al., 2018). Sultana and Kumar (2012) developed a method to determine suitable locations and optimal sizes of biomass-based facilities that considered Alberta's road network. Khan et al. (2018) conducted a comprehensive assessment and used waste availability at existing transfer stations (TSs) along with the road network to locate W2VA facilities for Alberta. However, no comprehensive study has been done, to the best of our knowledge, on optimal site selection for W2VA facilities that incorporates both the road and the rail networks to minimize waste transportation costs for whole of Canada. Moreover, the six eastern Canadian provinces have similar waste management goals and initiatives and waste is transferred interprovincially (Giroux Environmental Consulting, 2014). An aggregate MSW analysis on the eastern Canadian provinces should allow a sustainable waste management with inter-provincial engagement. This research aims to perform a detailed aggregate quantitative analysis on waste management for eastern Canada that integrates both road and railway networks. The specific objectives of this study are to:

- modify the integrated GIS-AHP framework using fuzzy logic to consider social, economic, and environmental factors pertaining to eastern Canadian provinces;
- create a land suitability map through exclusion and preference analyses and conduct a network analysis using the existing road and rail networks to site optimal W2VA facilities;
- prioritize the selected optimal sites based on minimum transportation distance for the processing of per million tonne of MSW.

In this study, the term "waste-to-value-added facilities" includes waste-to-electricity facilities, waste-to-biofuel facilities, and anaerobic digestion and composting facilities.

3.2 The State of Waste Management in eastern Canada

Eastern Canada is the region of Canada east of Manitoba consisting of six provinces: Ontario (ON), Quebec (QC), Newfoundland and Labrador (NL), New Brunswick (NB), Nova Scotia (NS), and Prince Edward Island (PEI). The land area of the region is 2.783 million km^2; this represents 30.6% of the land area of Canada. The population of the region is about 25.3 million in 2019, or 67.8% of Canada's population, including approximately 14.4 million people in Ontario and 8.4 million in Quebec (Statistics Canada, 2020b) .

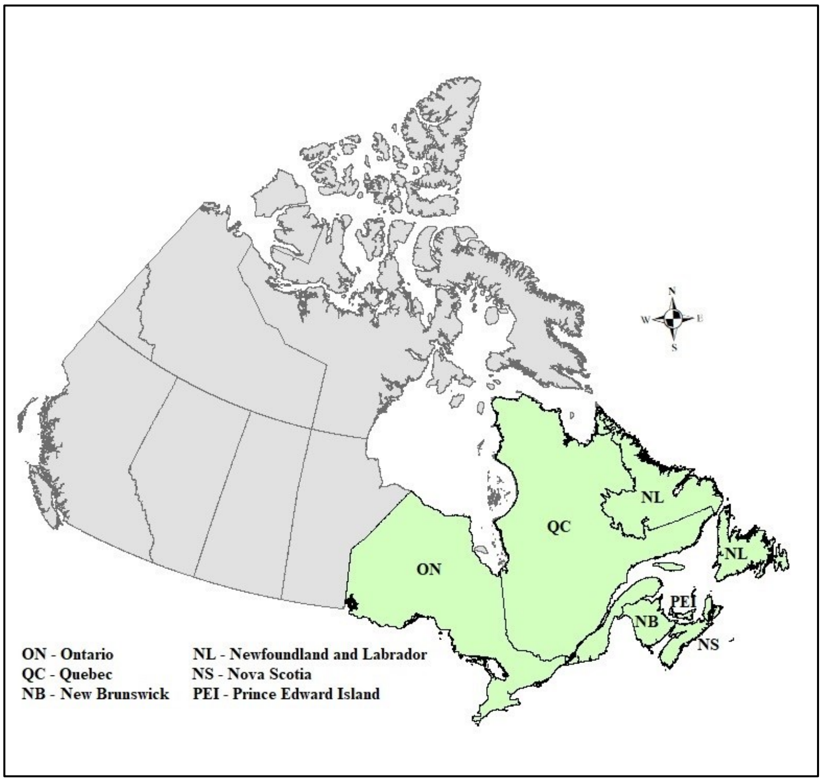


Figure 3.1: Map of eastern Canadian provinces considered in this study

Canadians produced about 0.932 tonne of solid waste per person (0.932 tonne/cap/y) in 2016 and recycled only 27% of this waste (Community Research Connections, 2020). That same year, approximately 25 million tonnes of MSW from the residential and non-residential sectors were sent to private and public disposal facilities. Figure 3.2 shows that eastern Canada alone disposed of around 16.2 million tonnes of MSW in 2016; this is almost 65% of the total waste disposed of in Canada. However, the total amount of MSW disposed of in eastern Canada declined from 2008 to 2014. Solid waste disposal in the region rose by 1.5% from 15.9 million tonnes in 2014 to approximately 16.2 million tonnes in 2016. Statistics Canada did not report information from PEI[5], so data from that province was collected from an annual report published by the provincial government in 2016 (Island Waste Management Corporation

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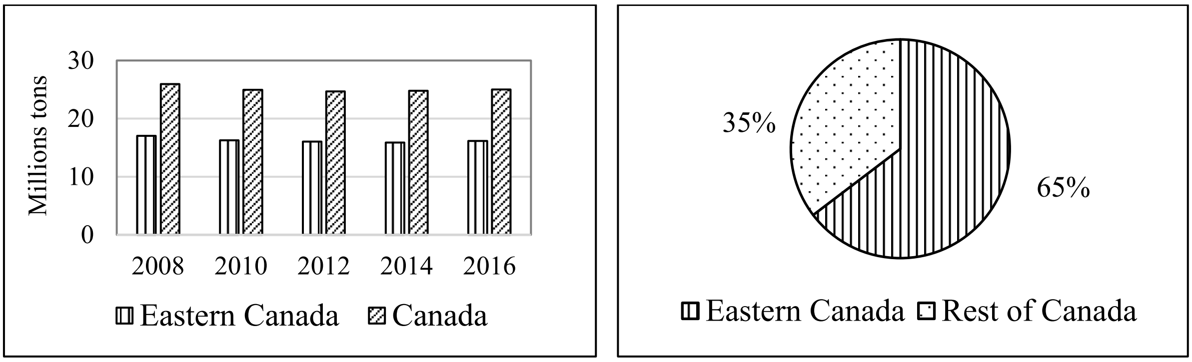
[5] In most cases, Statistics Canada does not include data from Prince Edward Island or Newfoundland and Labrador because of the confidentiality requirements of the Statistics Act.

(IWMC), 2018). Inclusion of MSW data for that province could influence the disposal trend from 2014 to 2016.



A B

Figure 3.2: (A) MSW disposal, eastern Canada and Canada, 2008-2016; (B) MSW disposal ratio, eastern Canada and the rest of Canada, 2016

Figure 3.3 illustrates the differences in the total and per capita waste disposal rates by province in 2016. It was observed that the most populated provinces (Ontario and Quebec) had the highest waste disposal, while provinces with lower population density like Prince Edward Island had the lowest disposal in eastern Canada. In 2016, every Canadian disposed around 0.71 tonne waste annually. Nova Scotia had the lowest per capita disposal rate in 2016 of 0.41 tonne. New Brunswick, Quebec, and Prince Edward Island also disposed of less waste per capita than the national average. Per capita annual waste disposal in Ontario was just below the national average by only 5 kilograms. The province with the highest per capita disposal was Newfoundland and Labrador at 0.76 tonne per person.

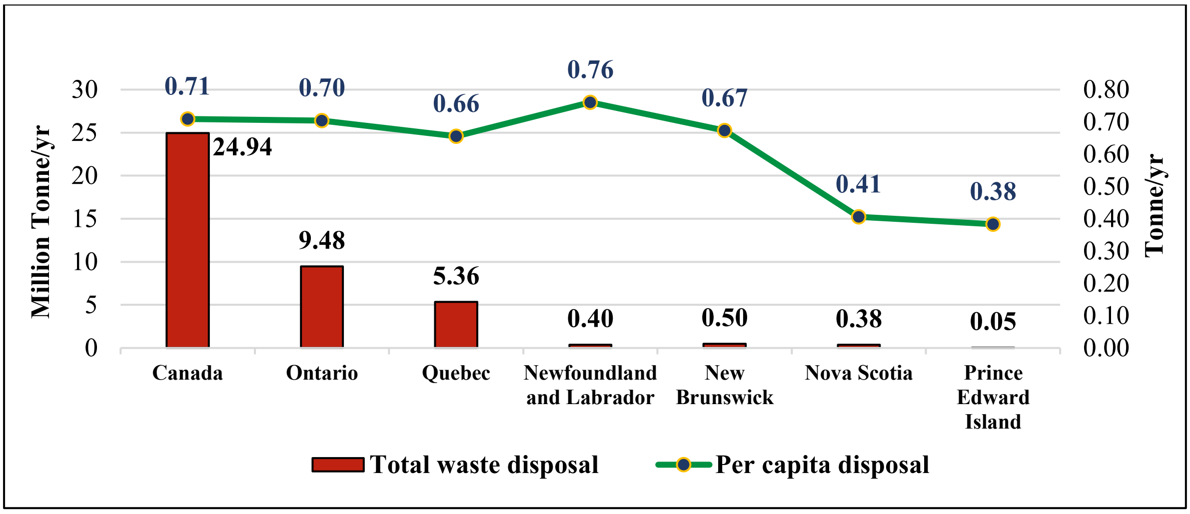


Figure 3.3: Total and per capita waste disposal by eastern Canadian provinces in 2016

Table 3-1 illustrates that non-residential waste exceeded residential waste disposed of in 2016 for all provinces except Quebec. Across eastern Canada, non-residential waste decreased by 5.47% between 2012 and 2016 and reached 8.60 million tonnes in 2016. Meanwhile, residential waste increased to 7.11 million tonnes.

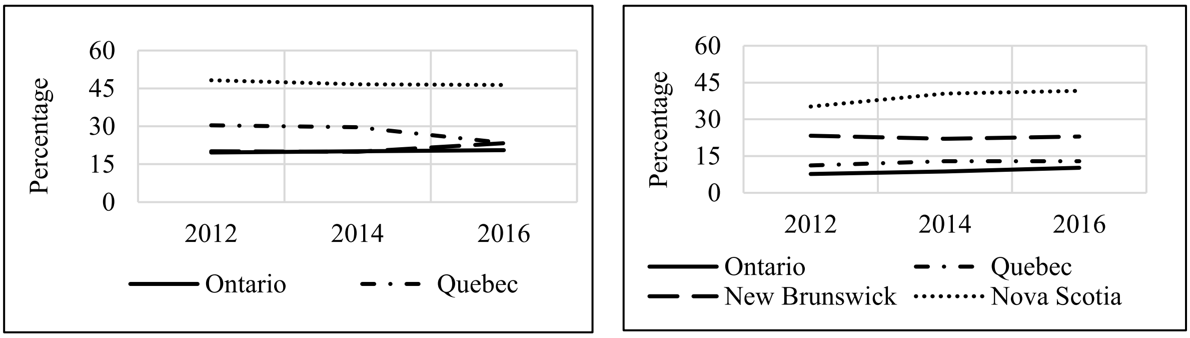
Table 3-1: Total MSW in eastern Canada between 2012 and 2016 (million tonnes/year)

Area	Residential sources			Non-residential sources			All sources		
	2012	2014	2016	2012	2014	2016	2012	2014	2016
Canada	9.68	9.80	10.23	15.00	14.96	14.71	24.68	24.77	24.94
Ontario	3.39	3.49	3.70	5.82	5.67	5.77	9.21	9.17	9.48
Quebec	2.80	2.83	3.01	2.78	2.58	2.35	5.58	5.41	5.36
New Brunswick	0.22	0.23	0.23	0.28	0.27	0.28	0.49	0.51	0.50
Nova Scotia	0.15	0.16	0.17	0.22	0.20	0.21	0.37	0.36	0.38
Prince Edward Island	X	x	x	x	x	x	x	0.05	0.05

Area	Residential sources			Non-residential sources			All sources		
Newfoundland and Labrador	X	x	x	x	x	x	0.39	0.42	0.40

Source: (Statistics Canada, 2020a)

In 2016, most solid waste was landfilled and merely 28.6% of this was diverted. Figure 3.4 shows the rate of diverted MSW from the residential and non-residential sectors for Ontario, Quebec, New Brunswick, and Nova Scotia from 2012 to 2016. By province, Nova Scotia had a higher diversion rate for both residential and non-residential waste. Ontario, on the other hand, was below the average as only 20.6% of residential waste and 10.2% of non-residential waste were diverted in 2016.



A

B

Figure 3.4: Solid waste diversion rate in eastern Canada, 2012-2016: (A) Residential (B) Non-residential

3.3 Materials and Methods

Selecting an optimal W2VA facility site requires the consideration of relevant exclusion and preference criteria and appropriate evaluation to obtain a land suitability map (LSM) for the study area. The MSW potential was identified for the six provinces in eastern Canada by defining point source locations of transfer stations (TSs). As MSW potential at TSs was not available, the thiessen polygon approach was used. The MSW potential was estimated based on the annual per capita disposal rate by the population for the year 2016 (Statistics Canada, 2020a). ArcGIS 10.4 (ESRI, 2015), a GIS-based software, was used to perform the corresponding GIS analyses. Figure 2.5 presents the overall method used in this study. The method has four parts, described in the subsequent sections.

3.3.1 Exclusion analysis

W2VA facilities cannot be constructed in a region with geographical and physical features such as rivers, parks, airports, power stations, forests, mountains, etc. Moreover, some regions in the study area do not meet government sustainability rules and regulations. In the exclusion analysis, with descriptions from earlier studies and the context of the study area, fourteen criteria that restrict the development of a W2VA facility were considered; they are shown in Table 2-1. A buffer distance, based on published data, was created around each criterion and the resultant maps were then converted to raster maps with a cell size of 30 m x 30 m. The raster maps were transformed into binary maps in which the cell values 0 and 1 represent areas inside and outside the exclusion zone, respectively. The final binary exclusion map, called the exclusion analysis map, was obtained by integrating binary maps of all exclusion factors as per Eq. 1:

$$C_{E,i} = \prod_{m=1}^{n} C_{i,m} \tag{1}$$

where $C_{E,i}$ is the Boolean value (0, 1) of the i^{th} cell of the final exclusion map, $C_{i,m}$ is the Boolean value (0, 1) of the i^{th} cell in the m^{th} criteria considered in this study, and n is the number of criteria. Similar to the binary function, cell values of 0 and 1 in the final exclusion map present areas not suitable and suitable for locating W2VA facilities. Figure 2.6 (A) gives an overview of the exclusion analysis.

3.3.2 Preference analysis

A preference analysis was performed to assign relative preference to the different regions in the study area. Nine factors were considered in compliance with provincial and federal government regulations (Eskandari et al., 2012; Sultana and Kumar, 2012; Environment and Climate Change Canada, 2019). Multiple buffer rings were generated around each preference factor, and each buffer ring was assigned a grading value on a scale of 0-10, depending on its distance from the corresponding factor. A grading value of 10 is the most preferable and a grading value of 0 the least. Land cover and slope data were available in raster format only. Multiple buffer rings are not possible around these factors and so the raster values were reclassified on a 0-10 scale for these two factors (Khan et al., 2018).

The relative weightage of nine preference factors was calculated using the fuzzy analytic hierarchy process (FAHP). This method makes a pairwise comparison by assigning a relative score on a scale of 1-9 (Saaty, 2001). In this study, fuzzification was used to quantify the uncertain comparison judgment. A triangular fuzzy number is a special class of fuzzy number whose membership is defined by three real numbers, expressed as l, m, and u, as shown in Figure 3.5. Here l, m, and u are the lower, mean, and upper bounds of the triangular fuzzy number, respectively, and the membership function μ belongs to the fuzzy number A (Vahidnia et al., 2009).

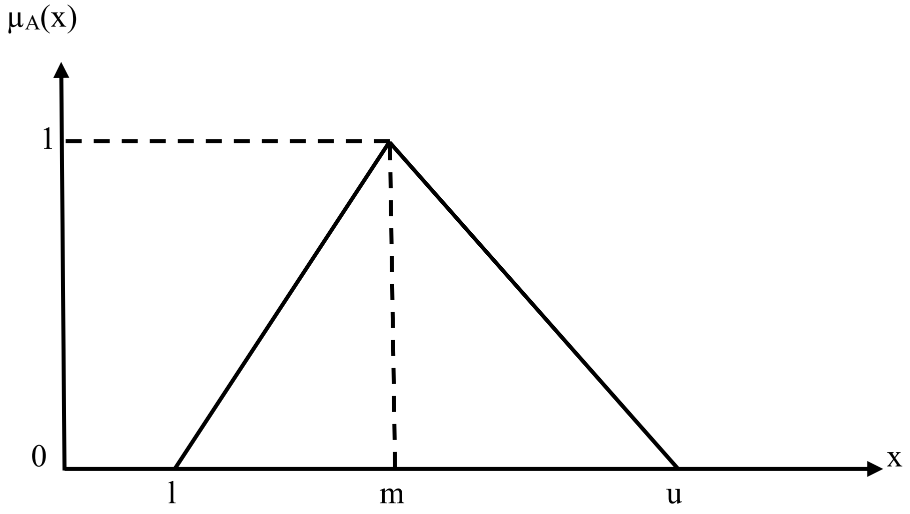


Figure 3.5: Fuzzy Triangular Number A= (l, m, u) (Vahidnia et al., 2009)

In this study, fuzzy extent analysis was used to calculate the relative weightage of nine preference factors. The triangular fuzzy comparison matrix is:

$$\tilde{A} = (\tilde{a}_{ij})_{nxn}$$

$$= \begin{bmatrix} (1,1,1) & (l_{12}m_{12}u_{12}) & \cdots & (l_{1n}m_{1n}u_{1n}) \\ (l_{21}m_{21}u_{21}) & (1,1,1) & \cdots & (l_{2n}m_{2n}u_{2n}) \\ \vdots & \vdots & \cdots & \vdots \\ (l_{n1}m_{n1}u_{n1}) & (l_{n2}m_{n2}u_{n2}) & \cdots & (l_{nn}m_{nn}u_{nn}) \end{bmatrix}$$

where $\tilde{a}_{ij}$= (l_{ij}, m_{ij}, u_{ij}) and ${\tilde{a}_{ij}}^{-1}$ = (1/u_{ji}, 1/m_{ji}, 1/l_{ji}) for i,j = 1….n and i ≠ j

The triangular fuzzy numbers for the considered preference factors and their definitions, using the method proposed by Chang (1996), are shown in Table 3-2.

Table 3-2: Triangular fuzzy number with definitions

Linguistic variables	Triangular fuzzy number	Reciprocal triangular fuzzy number
Equally important	(1,1,1)	(1,1,1)

Linguistic variables	Triangular fuzzy number	Reciprocal triangular fuzzy number
Equally to moderate important	(1,2,3)	(1,1/2,1/3)
Moderately more important	(2,3,4)	(1/2,1/3,1/4)
Moderately and strongly important	(3,4,5)	(1/3,1/4,1/5)
More strongly important	(4,5,6)	(1/4,1/5,1/6)
Strongly and very strongly important	(5,6,7)	(1/5,1/6,1/7)
More very strongly important	(6,7,8)	(1/6,1/7,1/8)
Very strongly to extremely important	(7,8,9)	(1/7,1/8,1/9)
Extremely more important	(9,9,9)	(1/9,1/9,1/9)

Finally, all the maps were combined to obtain the final preference analysis map of the study area using the relative weightages listed in Table 3-3. The value of the different cells of the final preference analysis map were calculated with the following equation:

$$C_{p,i} = \sum_{k=1}^{l} W_k \; C_{i,k} \qquad 0 \leq W_j \leq 1 \tag{2}$$

where $C_{p,i}$ represents the grading value of the i^{th} cell of the final preference map, $C_{i,k}$ is the grading value of i^{th} cell for the k^{th} preference factor, l is the number of preference factors considered for this study, and W_k is the relative weightage of the k^{th} preference factor. Figure 2.6 (B) gives a brief overview of the preference analysis.

Table 3-3: Calculated relative weightage of the considered preference factors

Preference factors	Relative weightage	Preference factors	Relative weightage	Preference factors	Relative weightage
Transfer station	0.41	Road	0.07	Substation	0.05

Preference factors	**Relative weightage**	**Preference factors**	**Relative weightage**	**Preference factors**	**Relative weightage**
Urban	0.17	Rail	0.07	Land cover	0.03
River	0.12	Transmission lines	0.05	Slope	0.03

3.3.3 Suitability analysis

A suitability analysis was then conducted to determine which areas were suitable for building W2VA facilities. Exclusion and preference analysis maps were combined to obtain the LSM; the value in each cell of the LSM is the suitability index (SI). The SI was calculated using following equation:

$$SI_i = C_{E,i} \times C_{P,i} \tag{3}$$

Where SI_i is the SI in the i^{th} cell in the LSM. A cell value of 0 indicates an excluded area and 10 represents the most suitable location for siting a W2VA facility. Figure 2.6 (C) gives a brief overview of the suitability analysis.

3.3.4 Network analysis

The transportation of MSW collected at different TSs to W2VA facilities is a major economic concern (Jankowski and Nyerges, 2001; Al-Jarrah and Abu-Qdais, 2006). A network analysis was performed using the higher SI areas to identify the locations with the lowest transportation costs. Both road and rail networks play important roles in the transportation of MSW. In this study, the “minimize impedance” option was used to determine optimum facility locations based on the minimization of weighted distances between each facility and surrounding TSs.

3.4 GIS Analysis and Results

In this study, projected coordinate systems with linear units were used to define spatial coordinates of input files (rather than angular degrees used in the geometric coordinate system). The latitude and longitude coordinates were transformed to x, y coordinates on the flat surface. ESRI (2016) provides several projected coordinate systems for Canada. It is important to use a projected coordinate system that properly aligns all six provinces in eastern Canada on a single layer in ArcGIS software. In this study, the NAD 1983 UTM Zone 16N projected coordinate system was used as a reference coordinate system to transform all spatial ArcGIS files.

3.4.1 Exclusion analysis

In exclusion analysis, forests and waterbodies (lakes, rivers and wetlands) dominated over other twelve exclusion factors. Figure 3.6 illustrates the exclusion analysis map for eastern Canada, in which 69.1% of the study area is screened out, thereby reducing the useful area to 518271.1 km^2 (30.9%). On a provincial level, Ontario has an area of 1076395 km^2, of which more than 66% is covered by forest and around 14.74% by water. In Quebec, Newfoundland and Labrador, New Brunswick, Nova Scotia, and Prince Edward Island, forest areas cover around 44%, 45%, 85%, 75%, and 44% of the province, respectively, and waterbodies 11.5%, 7.7%, 2.7%, 2.6% 9.2% and 15.6% and 0%, respectively. Overall, forests and waterbodies covered around 52.1% and 11.7% of the total area of eastern Canada. Only 30.9% of the region was left after all fourteen exclusion criteria in the exclusion analysis were considered.

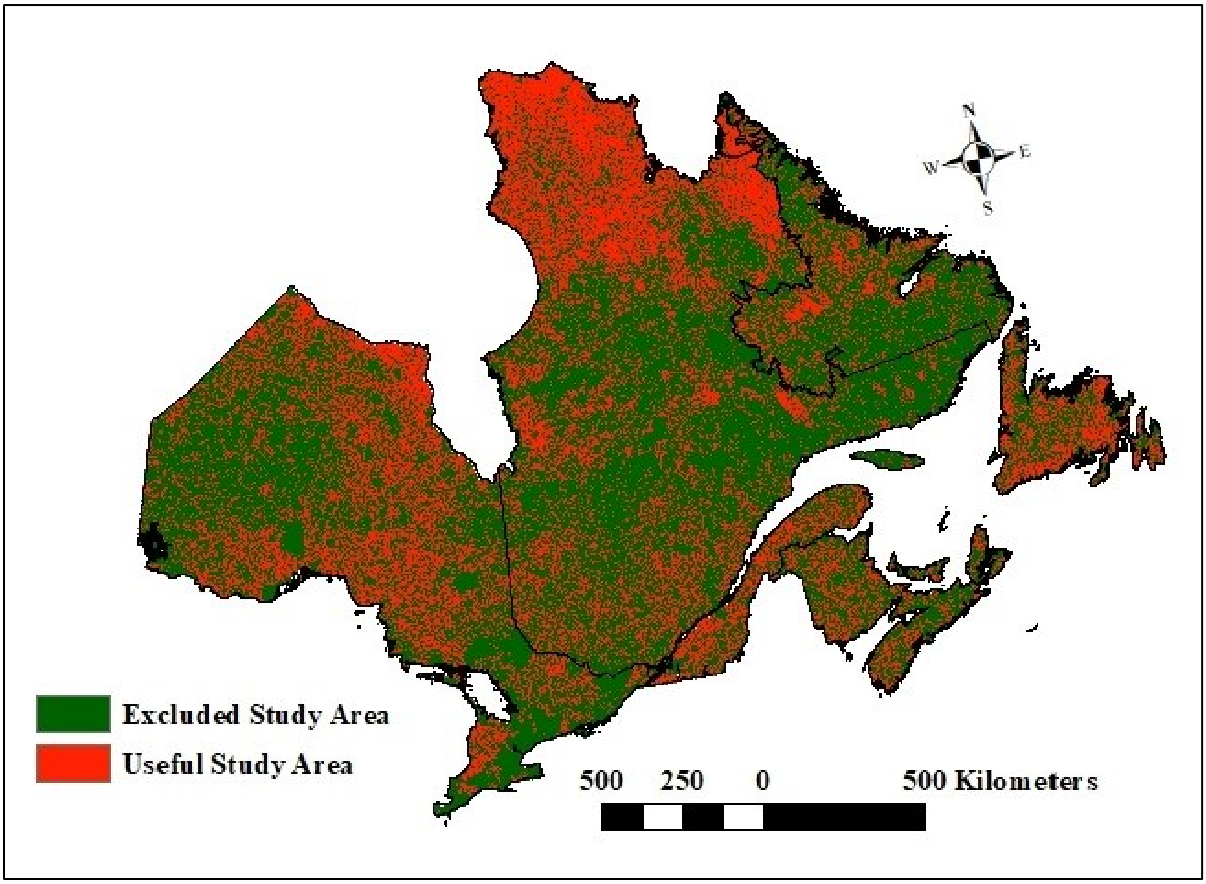


Figure 3.6: Exclusion map for eastern Canada showing the useable study area

3.4.2 Preference analysis

In the preference analysis, nine factors (listed in Table 3-3) were selected based on social, environmental, and economic criteria to assign relative preference to different regions of the useful study area. Each preference factor was subdivided into one of six preference class levels, as mentioned in Table 2-3, based on required government rules and norms. In other words, W2VA facilities should be located outside a restricted buffer zone to comply with environmental and social requirements. A grading value of 0 on a scale of 0 to 10 indicates an area in the useful study area that not suitable at all, and a grading value of 9 or 10 indicates an area that is very suitable. Multiple buffer zones were created for each preference factor based on the preferred distances. Grading values, as shown in Table 2-3, were assigned to generate buffer zones using a reclassification tool.

In this study, the FAHP, mentioned in section 3.3.2, was used to calculate the relative weightage of the nine preference factors considered. All nine raster maps generated by creating multiple buffer rings and reclassifying preference factors were overlaid using the weighted overlay tool incorporating the relative weightage of the corresponding preference factors (ESRI, 2010). Figure 3.7 shows the superimposed preference analysis map for the study area with preference grading on a scale of 1 to 10. A grading value of 10 is the most preferable and a value of 1 is the least preferable in the useful study area.

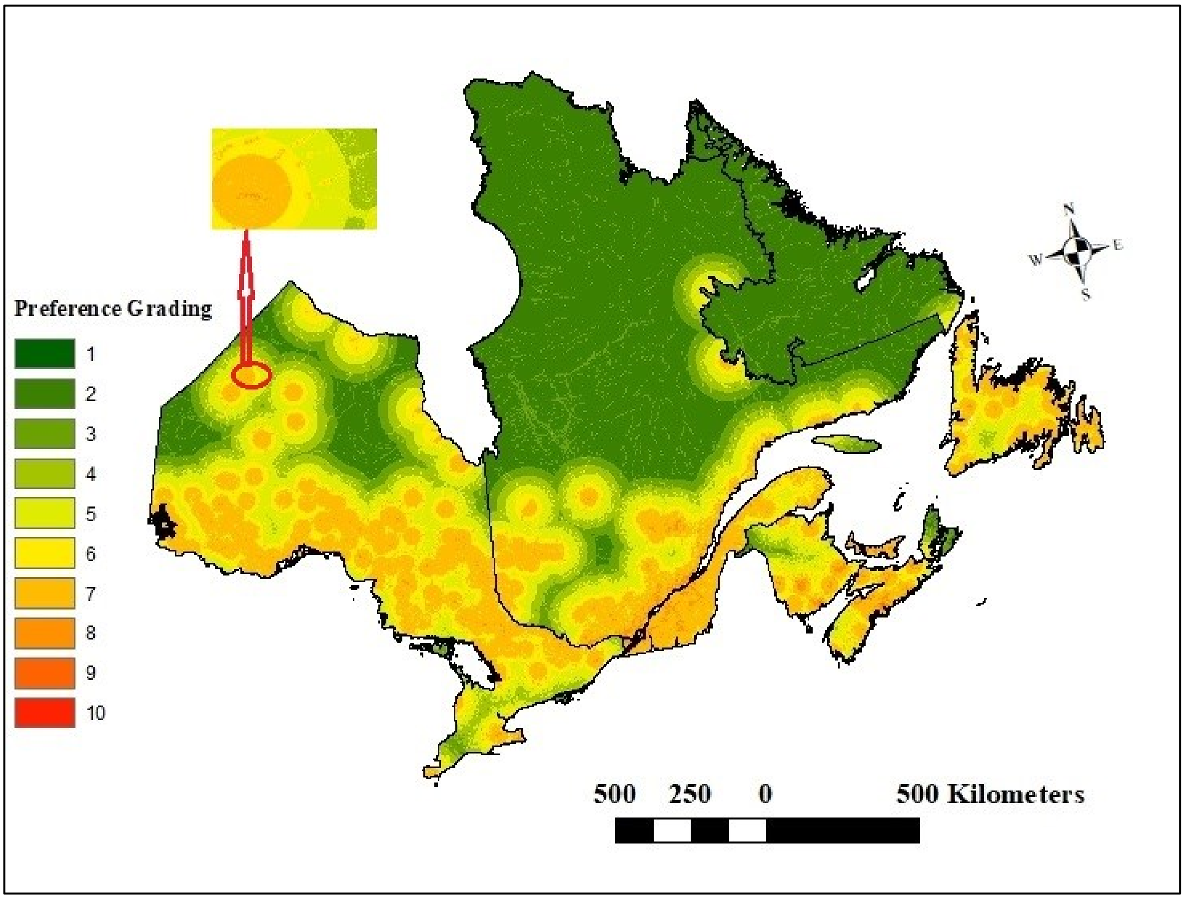


Figure 3.7: Final preference map for eastern Canada

3.4.3 Suitability analysis

In the suitability analysis, the raster layers from the exclusion and preference analyses were combined to generate the final LSM for eastern Canada. Figure 3.8 shows the suitability analysis map with SIs on a scale of 0 to 10; 0 indicates the excluded areas and 10 the areas most suitable as candidate sites. Centroids with high SI (10 and 9) polygons are considered candidate sites for optimal W2VA sites and require further analysis.

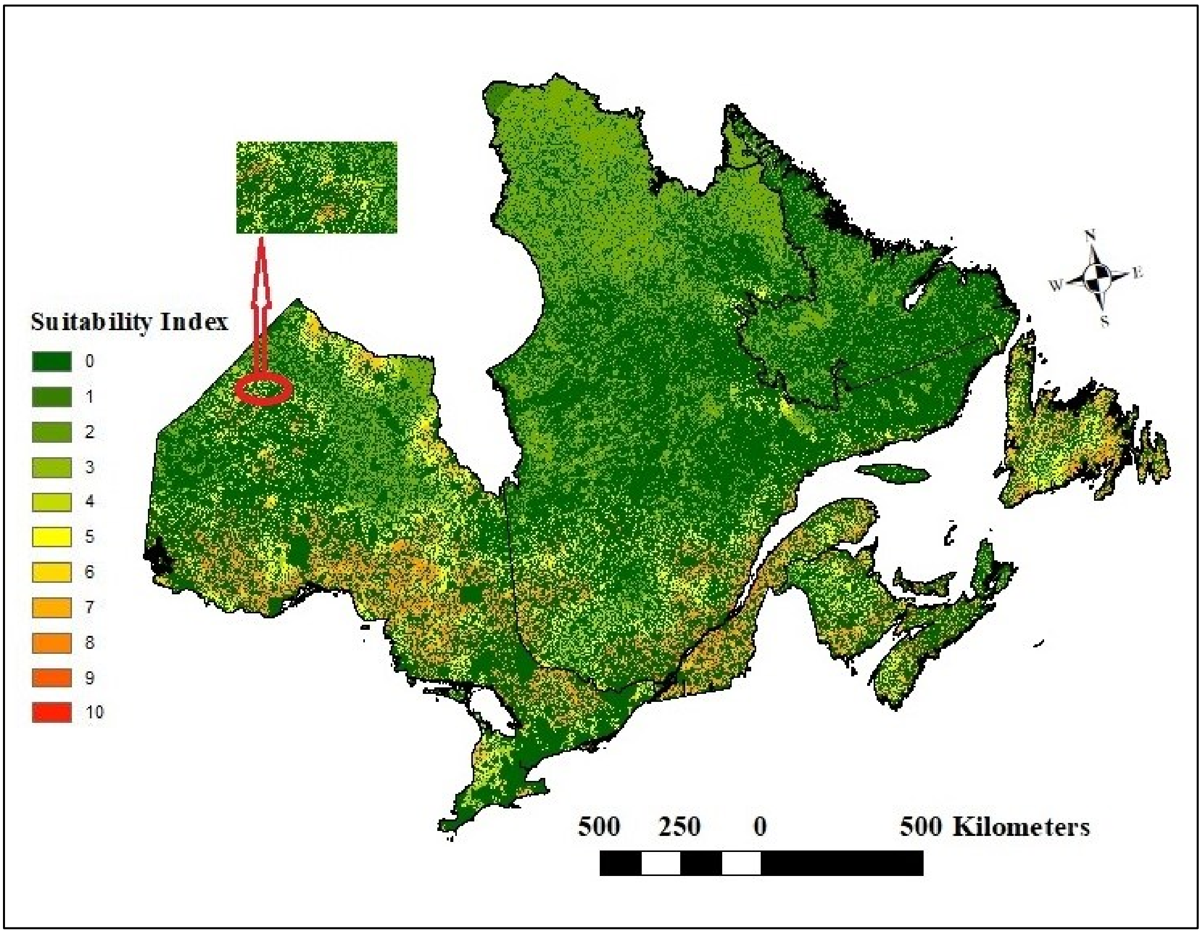


Figure 3.8: Final land suitability map for eastern Canada

3.4.4 Network analysis (location-allocation)

In Canada, TSs usually separate the recyclable portion of solid waste from the waste stream (Giroux Environmental Consulting, 2014). The biodegradable portion of solid waste is transported to composting facilities and the rest should be transported to W2VA facilities for further recovery options. In this study, TSs were considered demand points, and the sites identified through the suitability analysis were considered potential facility locations. Transporting MSW from TSs to selected W2VA facilities should be economically favorable.

The economics have been studied in a network analysis through, the concept of "minimize impedance," mentioned in section 3.3.4, by Sing and Yalcinkaya (Singh, 2019b; Yalcinkaya, 2020). Figure 3.9 shows the network analysis with fifteen optimal locations for siting W2VAfacilities across eastern Canada.

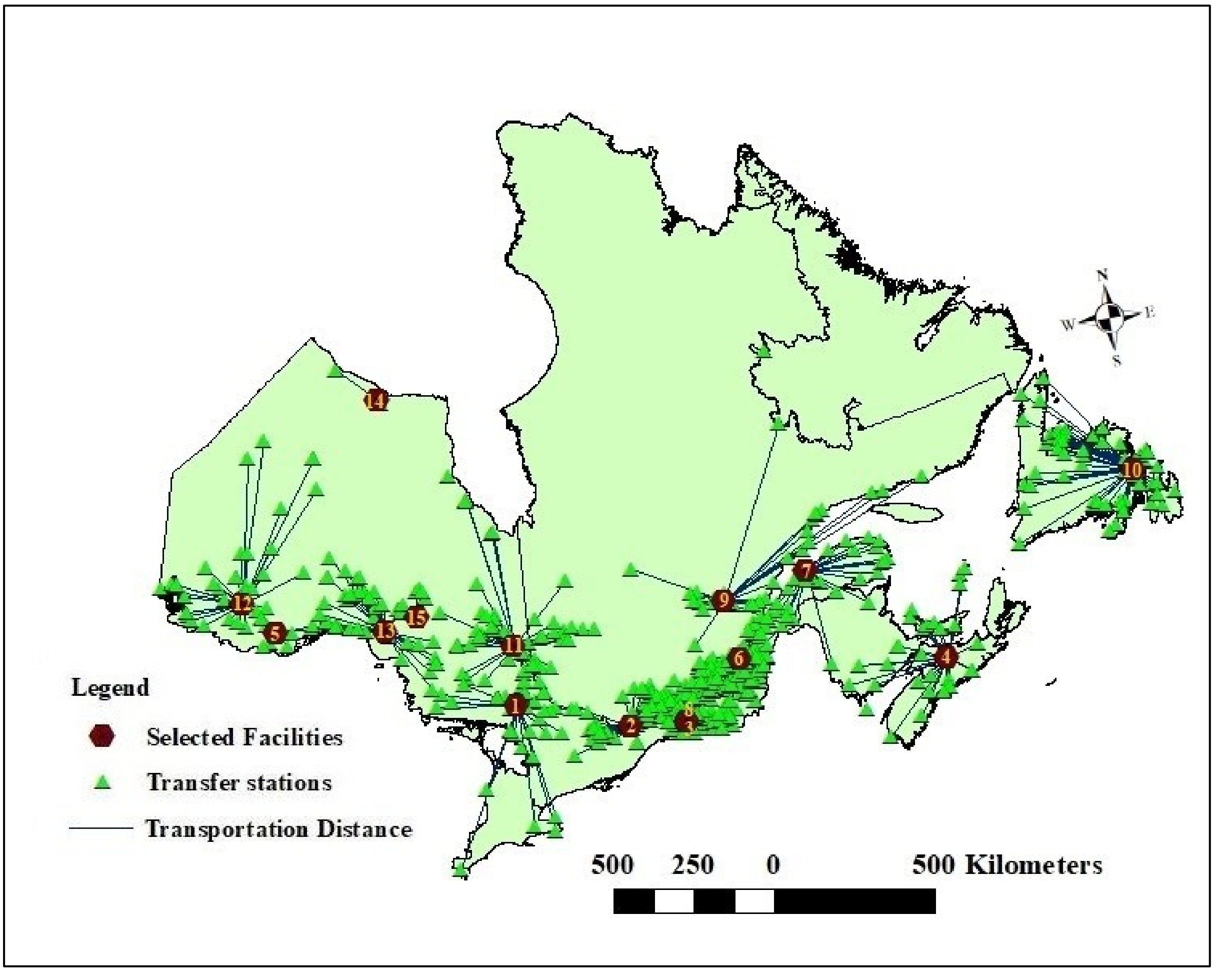


Figure 3.9: Determined optimal location in eastern Canada for W2VA facility

MSW production is correlated to population density, level of economic development and living standard (Karimi et al., 2020). Thus, the number of optimal sites in a region is related to the waste potential and waste diversion rate in that region. Seven of fifteen optimal sites across eastern Canada were identified in Ontario as the availability of waste in that province was around 58.5% of eastern Canada's total in 2016. In addition, in 2016, Ontario had a low waste diversion rate (25.89%), but a higher annual disposal rate of 0.705 tonne/capita. Quebec, the second most populated province in eastern Canada, generated 7.8 million tonnes (35.49%) of MSW and had a diversion rate at 30.98% in 2016; this waste could be managed by six optimally located W2VA facilities. In 2016, NL, NB, NS, and PEI shared around 2%, 3%, 3%, and 0.5% of the MSW generated in eastern Canada, respectively. One optimal site was identified in each of NS and NL to convert waste into value added products. The lowest number of active TSs, 10, led to no optimal W2VA facility location in New Brunswick. Prince Edward Island showed the highest diversion rate (48.25%) among the six provinces in eastern Canada and thus no optimal location was identified there either. Table 3-4 shows the longitude, latitude, and province name for the selected sites based on NAD 1983 UTM Zone 16N as the reference projected coordinate system.

From an economic point of view, sometimes policymakers want to set up W2VA facilities in different phases (year-to-year) after performing a techno-economic assessment of the newly constructed W2VA facility. The selected sites were prioritized to address this requirement. In this study, the fifteen optimal sites were prioritized based on the transportation distance per million tonnes of MSW from their connected TSs. Site 1, with 42 TSs, has the highest priority as it can receive one million tonnes of MSW with 1,015.6 kilometers transportation distance. The transportation distance for site 15 to collect one million tonnes of MSW, however, is 3,535,094 kilometers, and thus this site has the lowest priority.

Table 3-4: Optimal locations of the selected sites for W2VA facilities

Site	MSW (million tonne)	Transportation distance (km)	Connecting TSs number	Latitude (degree)	Longitude (degree)	Province	Transportation distance/MSW (km/million tonne)
1	7.47	7591.31	42	46.42	-80.23	ON	1015.63

Site	MSW (million tonne)	Transportation distance (km)	Connecting TSs number	Latitude (degree)	Longitude (degree)	Province	Transportation distance/MSW (km/million tonne)
2	1.74	4283.92	37	45.49	-75.80	QC	2467.20
3	2.97	9563.38	131	45.39	-73.62	QC	3223.79
4	0.74	4890.47	27	45.42	-63.25	NS	6642.26
5	0.03	265.28	9	48.62	-90.02	ON	8510.89
6	1.12	10566.32	119	46.80	-71.11	QC	9445.40
7	0.24	4515.55	24	48.75	-67.67	QC	19055.79
8	0.06	1847.94	5	45.39	-73.63	QC	30188.08
9	0.26	9076.97	33	48.46	-71.25	QC	34413.97
10	0.38	16799.59	57	48.25	-53.97	NL	43648.48
11	0.18	9892.14	54	48.10	-80.11	ON	55283.13
12	0.11	10458.31	37	48.67	-85.46	ON	98004.89
13	0.02	9402.73	44	49.35	-91.53	ON	392706.79
14	0.001	190.73	2	55.11	-85.61	ON	435196.03
15	0.001	2562.05	6	49.06	-84.11	ON	3535094.08

3.5 Conclusion

The present study was conducted to quantify the annual potential of MSW at transfer stations in eastern Canada, identify geographical locations, and identify optimal locations for waste-to-value-added facilities. Given the unavailability of data on MSW at transfer stations, a Thiessen Polygon approach was used to calculate the MSW potential. Around 16.10 million wet tonnes of MSW are disposed of annually at eastern Canadian landfills that have, on average, 15% and 50% moisture content for thermal and biodegradable portion; this MSW can be considered for waste-to-value-added conversion technologies. In this study, a GIS-based framework was developed to perform land suitability analysis, which determined candidate sites for waste-to-value-added facilities using various geographical criteria chosen based on social, economic, and environmental factors. Finally, a network analysis was performed to select fifteen optimum waste-value-added facility sites, taking into account the minimization of waste collection distance and using existing road and railway networks. However, the decision to build a new waste-to-value-added facility depends highly on the MSW potential at that site, the composition of the waste stream, and the economic feasibility of an appropriate waste conversion technology. In general, the approach outlined in this study can be used in other studies on the technical and economic feasibility of the transition from landfilling to establishing waste-to-value-added sites.

The developed method can also be used as a supporting tool by waste management authorities to understand MSW potential and determine optimal locations for siting a waste-to-value-added facility. This integrated approach considered exclusion and preference criteria, which can be changed for any geographical area to comply with government standards. Furthermore, this method included a suitability index grading scale to determine the most suitable areas to site a waste-to-value-added facility; this can be used as a practical metric for land management systems in any locality.

Chapter 4: Conclusion and Recommendations for future work

4.1 Conclusion

MSW management is a major concern today due to rapid urbanization and population growth along with the scarcity of land for waste disposal. The motivation for this research was to determine optimal locations for waste-to-value-added (W2VA) facilities to sustainably manage MSW and in turn to generate products such as electricity, biofuel, compost, etc. The W2VA facility approach is considered the most prominent waste recovery technology for clean energy production and better solid waste management.

The present study quantified the MSW potential at transfer stations (TSs) and identified optimal locations for W2VA facilities based on waste availability and the existing road and rail networks and municipal guidelines to minimize waste collection cost. The annual MSW potential for the year 2016 in Canada was 24.97 million wet tonnes with an average of 15% and 50% moisture content for thermal and biodegradable streams, respectively. In this study, thiessen polygons were used to calculate the MSW at provincial TSs, as no MSW data was available from TSs. Figure 4.1 shows the locations of existing TSs in Canada along with their annual MSW potential. A three-step GIS analysis was used to perform land suitability analysis to determine suitable areas for W2VA facilities based on social, environmental, and economic factors. The land suitability map (LSM) was used as a suitability metric tool to identify potential candidate sites for W2VA facilities. Candidate sites with suitability indexes (SIs) of 9 and 10 were determined from the LSM and used as demand points in a network analysis. The location-allocation analysis layer in the network analysis has “minimize impedance” tool, which was used to select optimal sites for W2VA facilities based on minimizing waste transportation distance.

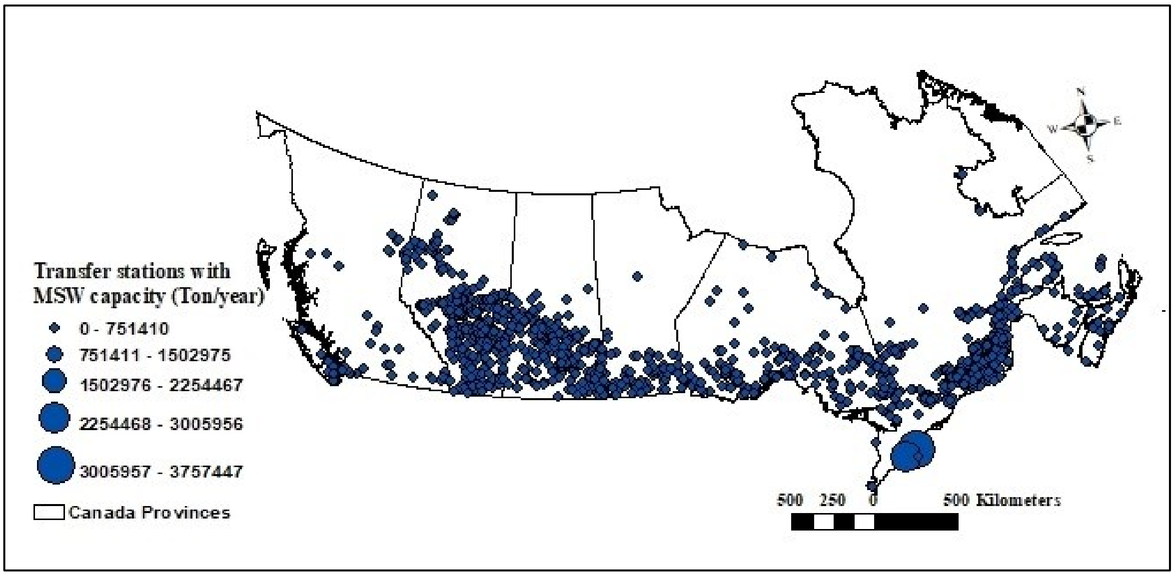


Figure 4.1: Locations of existing MSW TSs along with their annual availability

The research work was done in two stages. In the first stage, the decision-making framework was used to identify ten optimal locations in western Canada. In 2016, around 8.7 million wet tonnes of MSW was disposed in western Canadian landfills that had 15% and 50% moisture content, on average, for thermal and biodegradable portion, respectively (Patel, 2018). Ten optimal W2VA facility sites were determined to avail disposed MSW with minimal waste collection cost. In the second stage, we used the same framework to quantify the MSW potential at provincial TSs in eastern Canada. Data available from Statistics Canada showed that around 16.2 million wet tonnes of MSW that had, on average, 15% and 50% moisture content for thermal and biodegradable portion, respectively, was disposed of at landfills in 2016 across eastern Canada. The fuzzy analytic hierarchy process (FAHP) was used in an integrated decision-making network to prioritize the preference factors and, in turn, develop the LSM for eastern Canada. The candidate sites identified from the LSM were used in a network analysis with the road and rail networks to select fifteen optimal sites based on the shortest distances between the potential facility and existing TSs in eastern Canada. The selected sites were prioritized based on the transportation distance per million tonnes of MSW from the connected TSs.

An integrated network analysis was performed based on the ten and fifteen optimal locations determined for western Canada and eastern Canada, respectively. Figure 4.2 shows the connectivity among TSs and corresponding optimal sites. A common projected coordinate system was used to properly align all ten provinces. The NAD 1983 UTM Zone 13N projected coordinate system was used as a reference coordinate system to show the locations of the twenty-five optimal sites. Table 4-1 lists the locations of the optimal sites for W2VA conversion facilities in Canada.

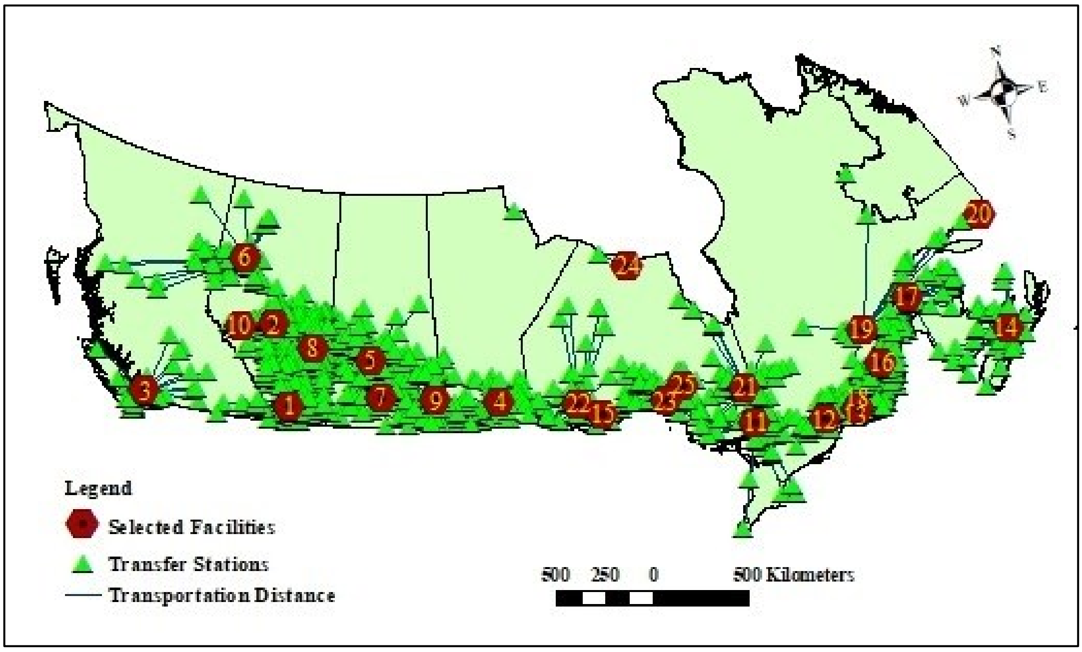


Figure 4.2: Optimal W2VA facility locations for all ten Canadian provinces

Table 4-1: Optimal locations of the selected W2VA facility sites

Site	MSW (Million tonnes)	Number of Connecting TSs	Latitude (degree)	Longitude (degree)	Province	Region
1	2.12	74	49.75	-112.62	AB	
2	1.96	84	53.57	-114.37	AB	

Site	**MSW (Million tonnes)**	**Number of Connecting TSs**	**Latitude (degree)**	**Longitude (degree)**	**Province**	**Region**
3	1.38	39	49.34	-123.03	BC	Western Canada
4	0.87	46	49.95	-97.26	MB	
5	0.54	101	52.13	-106.55	SK	
6	0.52	55	56.37	-117.55	AB	
7	0.26	24	50.42	-105.77	SK	
8	0.26	99	52.55	-111.06	AB	
9	0.21	76	50.24	-101.89	SK	
10	0.04	15	53.19	-116.98	AB	
11	7.47	42	46.42	-80.23	ON	Eastern Canada
12	1.74	37	45.49	-75.80	QC	
13	2.97	131	45.39	-73.62	QC	
14	0.74	27	45.42	-63.25	NS	
15	0.03	9	48.62	-90.02	ON	
16	1.12	119	46.80	-71.11	QC	
17	0.24	24	48.75	-67.67	QC	
18	0.06	5	45.39	-73.63	QC	
19	0.26	33	48.46	-71.25	QC	
20	0.38	57	48.25	-53.97	NL	
21	0.18	54	48.10	-80.11	ON	
22	0.11	37	48.67	-85.46	ON	
23	0.02	44	49.35	-91.53	ON	

Site	MSW (Million tonnes)	Number of Connecting TSs	Latitude (degree)	Longitude (degree)	Province	Region
24	0.001	2	55.11	-85.61	ON	
25	0.001	6	49.06	-84.11	ON	

This study uses an integrated multi-dimensional decision-making framework in a GIS system to identify optimal locations for W2VA facilities. The proposed facilities ensure environmental, economic, and social sustainability. However, a detailed techno-economic assessment is essential at these sites to determine plant technology and capacity.

Overall, the site selection method outlined in this study in a GIS environment can be used to assess waste management options for different jurisdictions taking into account economic, social, and environmental factors. The adaptability of the applied decision-making model, competency of the developed LSM, and flexibility of the performed network analysis provide a competent supporting tool for authorities in siting optimal locations of W2VA facilities.

4.2 Recommendations for Future Work

The following are recommendations to promote MSW use in Canada:

1. Although there are different types of biomass feedstock, this study was performed only for MSW. Therefore, quantification models should be developed to determine the potential for other biomass, i.e., agricultural and forest residue, livestock manure, etc.

2. The developed GIS model can be extended to identify the locations of biomass collection points (BCPs) for agricultural and forest residues and to determine optimal sites for integrated W2VA facilities for multiple biomass feedstock.

3. This study determined twenty-five optimal locations based on the minimization of waste transportation distance from existing TSs to potential W2VA facilities. However, a techno-economic assessment that considers MSW potential and the composition of the waste stream is necessary to ensure the operational feasibility and sustainability of a new W2VA facility at any identified site.

4. The composition of MSW varies significantly, and the W2VA technology choice depends strongly on the composition of the MSW available. MSW composition should, therefore, be determined either through theoretical or experimental methods to ascertain the feasibility of W2VA technologies at the chosen sites.

5. The GIS model should be modified to correspond to other geographic features or different future regulations.

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Appendices

Appendix A: Sample Calculation of Suitability Index Values

Table A-1 presents a sample calculation of suitability index values for any cell of the study area.

Table A-1: Sample calculation

Preference factors	Grading values (C)	Relative weightage (w)	Cell value $C_p=C\times w$	Preference cell value (ΣC_p)	Exclusion map value for corresponding cell, C_E= 0 or 1	Suitability index, $SI=C_E\times C_p$
Transfer stations	9	0.41	3.69			
Urban areas	8	0.18	1.44			
Water	7	0.12	0.84			
Roads	6	0.07	0.42	7.34	1	7.34 ≈ 7
Railways	6	0.07	0.42			
Transmission lines	5	0.05	0.25			
Substations	4	0.04	0.16			
Land cover	3	0.03	0.09			
Slope	1	0.03	0.03			

Appendix B: Analytic Hierarchy Process (AHP)

Saaty developed the AHP in the 1970s (1971-1975). It is a structured technique used to evaluate the relative importance of a set of criteria in a multi-criteria decision-making problem. It accurately combines qualitative and quantitative criteria to determine weightage information, which provides a mechanism for decision-making. A standardized comparison scale is used to find the relative importance of the criteria. Table B-1 illustrates the scale of relative importance, Table B-2 presents the values assigned to nine preference factors based on this scale, and Table B-3 depicts the calculated relative weightage.

Table B-1: Scale of relative importance (Saaty, 1984)

Definition	Relative importance	Description
Equal importance	1	Two activities contribute equally based on experiment and judgement
Moderately more important	3	One activity is slightly favored over another
Strongly important	5	One activity is strongly favored over another
Very strongly important	7	Experience and judgement strongly favor one activity
Extremely important	9	The judgement favoring one activity over another is of the highest possible order of affirmation
Intermediate values	2,4,6,8	Used when compromise is needed between two adjacent judgment

Reciprocal values	If activity i has one of the above non-zero numbers compared to activity j, then j has the reciprocal value

Table B-2: Values of preference factors on a standardized comparison scale

Preference factors	WA	Urban	Water	Roads	Railway	Transmission	Substation	Land cover	Slope
WA	1	3	5	7	7	8	9	9	9
Urban	0.333	1	2	3	4	4	4	5	6
Water	0.2	0.5	1	2	2	3	3	4	5
Roads	0.143	0.33	0.5	1	1	2	2	3	3
Railway	0.143	0.25	0.5	1	1	2	2	3	3
Transmission	0.125	0.25	0.33	0.5	0.5	1	1	2	2
Substation	0.111	0.25	0.33	0.5	0.5	1	1	2	2
Land cover	0.111	0.2	0.25	0.333	0.333	0.5	0.5	1	1
Slope	0.111	0.167	0.2	0.333	0.333	0.5	0.5	1	1

The result of the pairwise comparison on *n* criteria can be summarized in an *n* x *n* evaluation matrix A as follows:

$$A=\begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{bmatrix} \qquad a_{i,j}=1,\ a_{j,i} = 1/a_{i,j},\ a_{i,j} \neq 0$$

The steps to calculate the weight vector W_j are as follows:

1. If *aij* is the intensity of relative importance between criteria i and criteria j and $a_{j,i} = \frac{1}{a_{i,j}}$

2. Compute each column of A where $A_j = 1/n \sum_{i=1}^{n} a_{i,j}$

3. Normalize each element of matrix A,

   $\tilde{a}_{ij} = a_{i,j}/A_j$

4. Average across the row,

$W_i = 1/n \sum_{j=1}^{1} \tilde{a}_{ij}$ where n is the total number of criteria.

5. Divide pairwise comparison value for each factor by W_i to get relative weightage,

$$W_j = a_{i,j}/W_i$$

Table B-3: Calculated relative weightage

Preference factors	WA	Urban	Water	Roads	Railway	Transmission	Substation	Land cover	Slope	Relative weightage
WA	0.44	0.50	0.49	0.45	0.42	0.36	0.39	0.30	0.28	0.40
Urban	0.15	0.17	0.20	0.19	0.24	0.18	0.17	0.17	0.19	0.18
Water	0.09	0.08	0.10	0.13	0.12	0.14	0.13	0.13	0.16	0.12
Roads	0.06	0.06	0.05	0.06	0.06	0.09	0.09	0.10	0.09	0.07
Railway	0.06	0.04	0.05	0.06	0.06	0.09	0.09	0.10	0.09	0.07
Transmission	0.06	0.04	0.03	0.03	0.03	0.05	0.04	0.07	0.06	0.05
Substation	0.05	0.04	0.03	0.03	0.03	0.05	0.04	0.07	0.06	0.04
Land cover	0.05	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
Slope	0.05	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03

To check the consistency of the pairwise comparison and credibility of weights the consistency ratio (*CR*) is calculated as:

1. Calculate the maximum eigen value λ_{max} of the matrix

2. Compute the consistency index (CI) for the matrix

$$CI = \frac{\lambda_{max} - 1}{n-1}$$

3. Compute the consistency ratio can through following formula

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

where *RI* is the the random index for different *n*

Table B-4 shows the value of the RI for matrices of the order 1 to 10 using a sample size of 500 (Saaty, 2001). A smaller (< 1) *CR* value indicates a better pairwise comparison. A higher RI value indicates that pairwise comparisons need to be revised to reduce inconsistencies in judgments.

Table B-4: Average random index (RI) at different matrix sizes (Saaty, 2001)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

Appendix C: Fuzzy Analytic Hierarchy Process (FAHP)

The FAHP method follows a pairwise comparison by assigning a relative score on a scale of 1-9 (Saaty, 2001). A triangular fuzzy number is a special class of fuzzy number whose membership is defined by three real numbers, expressed as *l*, *m*, or *u*, as shown in Figure C-1. Here *l*, *m* and *u* are the lower, mean, and upper bounds of the triangular fuzzy number respectively, and the membership function μ belongs to the fuzzy number A.

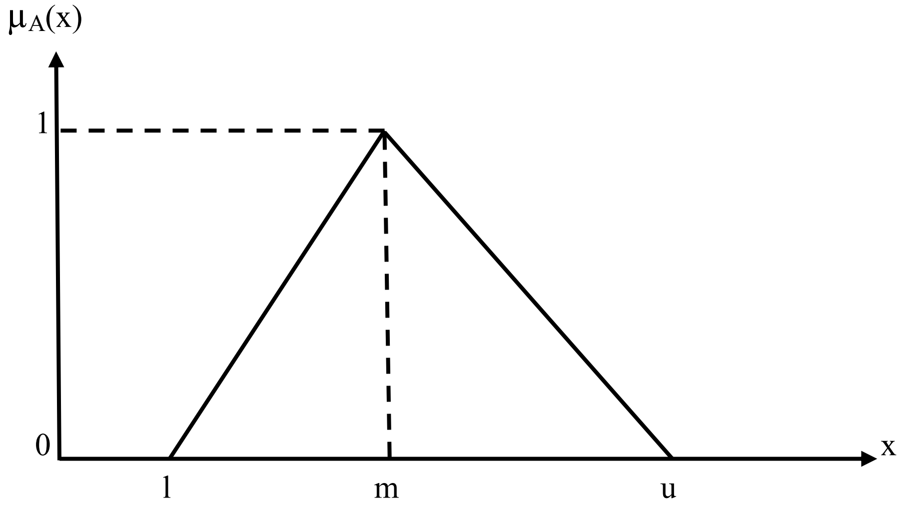

Figure C-1: Fuzzy triangular number A= (*l*, m, *u*) (Vahidnia et al., 2009)

The triangular fuzzy numbers for the considered preference factors and their definitions were expressed as shown in Table C-1, and Table C-2 presents the values assigned to nine preference factors based on this scale.

Table C-1: Triangular fuzzy number with definitions

Linguistic variables	**Triangular fuzzy number**	**Reciprocal triangular fuzzy number**
Equally important	(1,1,1)	(1,1,1)
Equally to moderate important	(1,2,3)	(1,1/2,1/3)
Moderately more important	(2,3,4)	(1/2,1/3,1/4)
Moderately and strongly important	(3,4,5)	(1/3,1/4,1/5)
More strongly important	(4,5,6)	(1/4,1/5,1/6)
Strongly and very strongly important	(5,6,7)	(1/5,1/6,1/7)
More very strongly important	(6,7,8)	(1/6,1/7,1/8)
Very strongly to extremely important	(7,8,9)	(1/7,1/8,1/9)
Extremely more important	(9,9,9)	(1/9,1/9,1/9)

Table C-2: Values of preference factors on standardized comparison scale

Preference factors	WA	Urban	Rivers	Roads	Rail	Transmission	Substation	Land cover	Slope
WA	1,1,1	2,3,5	4,5,6	6,7,8	6,7,8	7,8,9	7,8,9	9,9,9	9,9,9
Urban	0.2,0.33,0.5	1,1,1	1,2,3	2,3,4	2,3,4	3,4,5	3,4,5	4,5,6	4,5,6
Rivers	0.167,0.2,0.25	0.33,0.5,1	1,1,1	1,2,3	1,2,3	2,3,4	2,3,4	3,4,5	3,4,5
Roads	0.125,0.14,0.167	0.25,0.33,0.5	0.33,0.5,1	1,1,1	1,1,1	1,2,3	1,2,3	2,3,4	2,3,4
Railway	0.125,0.14,0.168	0.25,0.33,0.6	0.33,0.5,2	1,1,1	1,1,1	1,2,3	1,2,3	2,3,4	2,3,4
Transmission	0.11,0.125,0.143	0.2,0.25,0.33	0.25,0.33,0.5	0.33,0.5,1	0.33,0.5,1	1,1,1	1,1,1	1,2,3	1,2,3
Substation	0.11,0.125,0.144	0.2,0.25,0.34	0.25,0.33,0.6	0.33,0.5,1	0.33,0.5,1	1,1,1	1,1,1	1,2,3	1,2,3
Land cover	0.11,0.11,0.11	0.167,0.2,0.25	0.167,0.2,0.25	0.25,0.33,0.5	0.25,0.33,0.5	0.33,0.5,1	0.33,0.5,1	1,1,1	1,1,1
Slope	0.11,0.11,0.11	0.167,0.2,0.25	0.167,0.2,0.25	0.25,0.33,0.5	0.25,0.33,0.5	0.33,0.5,1	0.33,0.5,1	1,1,1	1,1,1

Expressing judgments in triangular fuzzy numbers resulted in the triangular fuzzy comparison matrix of

$$\tilde{A} = \left(\tilde{a}_{ij}\right)_{nxn}$$

$$= \begin{bmatrix} (1,1,1) & (l_{12}m_{12}u_{12}) & \dots & (l_{1n}m_{1n}u_{1n}) \\ (l_{21}m_{21}u_{21}) & (1,1,1) & \dots & (l_{2n}m_{2n}u_{2n}) \\ \vdots & \vdots & \dots & \vdots \\ (l_{n1}m_{n1}u_{n1}) & (l_{n2}m_{n2}u_{n2}) & \dots & (l_{nn}m_{nn}u_{nn}) \end{bmatrix}$$

where $\tilde{a}_{ij}$= (l_{ij}, m_{ij}, u_{ij}) and $\tilde{a}_{ij}{}^{-1}$ = (1/u_{ji}, 1/m_{ji}, 1/l_{ji}) for i,j = 1….n and i ≠ j

The weight vector W_j can be calculated as follows:

1. Sum each row of the matrix $\tilde{A}$ and then then normalize the row sums by the fuzzy arithmetic operation:

$$\tilde{S}_i = \sum_{j=1}^{n} \tilde{a}_{ij} \oplus \left[\sum_{k=1}^{n}\sum_{j=1}^{n} \tilde{a}_{kj}\right]^{-1}$$

$$= \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} l_{kj}} \right) \quad \text{for i = 1... n,}$$

where ⊕ denotes the extended multiplication of two fuzzy numbers.

2. Determine the degree of possibility for $\tilde{S}_i \geq \tilde{S}_j$, by the following equation:

$$P(\tilde{S}_i \geq \tilde{S}_j) = \begin{bmatrix} 1 & m_i \geq m_j \\ \frac{u_i - l_l}{(u_i - m_i) + (m_j - l_j)} & l_i \leq u_i \\ 0 & otherwise \end{bmatrix}$$

where $\tilde{S}_i$= (l_i, m_i, u_i) and $\tilde{S}_j$= (l_j, m_j, u_j) for i,j = 1…….n; i ≠ j

3. Compute priority vector W_i of the fuzzy comparison matrix $\tilde{A}$ as follows:

$$W_i = \frac{P\ (\tilde{S}_i \geq \tilde{S}_j \ \ j=1.........n; j \neq i)}{\sum_{k=1}^{n} P\ (\tilde{S}_k \geq \tilde{S}_j \ \ j=1.........n; j \neq k)}\ , \ i = 1.......... n$$

Table C-3 presents the relative weightage of the considered nine preference factors.

Table C-3: Calculated relative weightage

Preference factors	Relative weightage	Preference factors	Relative weightage
Transfer stations	0.41	Transmission lines	0.05
Urban	0.17	Substation	0.05
Rivers	0.12	Land cover	0.03
Roads	0.07	Slope	0.03
Rail	0.07		

Appendix D: Location-Allocation Solver in ArcGIS

The location-allocation solver in the ArcGIS generates an origin-destination matrix of the shortest path cost using Dijkstra's algorithm between all facilities and sources (transfer stations) in the network (ESRI, 2019). This solver creates a set of semi-randomized solutions that is refined by a vertex substitutional heuristic (Teitz and Bart, 1968). In order to determine the best solution global near-optimal solution, the greedy randomized adaptive search procedure (GRASP) metaheuristic, described by Gendreau and Potvin (2010), was applied. The following simplistic implementation of GRASP would generate a semi-randomized starting solution set (ESRI, 2020):

1. Generate an empty list of facilities.

2. For each facility not in the list, determine how advantageous it is to add this facility to the current list in the solution set and then prioritize facilities from the most advantageous to the least advantageous.

3. Randomly pick a facility from the top X percent of facilities (X is determined by how many times we have called the GRASP routine).

4. Add this facility to the list of facilities in the solution set.

5. If the solution set is not full, go to step 2.

Appendix E: Sample of raster file

The following figure is an example of raster file that shows the land cover view for the province of Alberta. Table E-1 presents the values used in legends that illustrated the type of the land area.

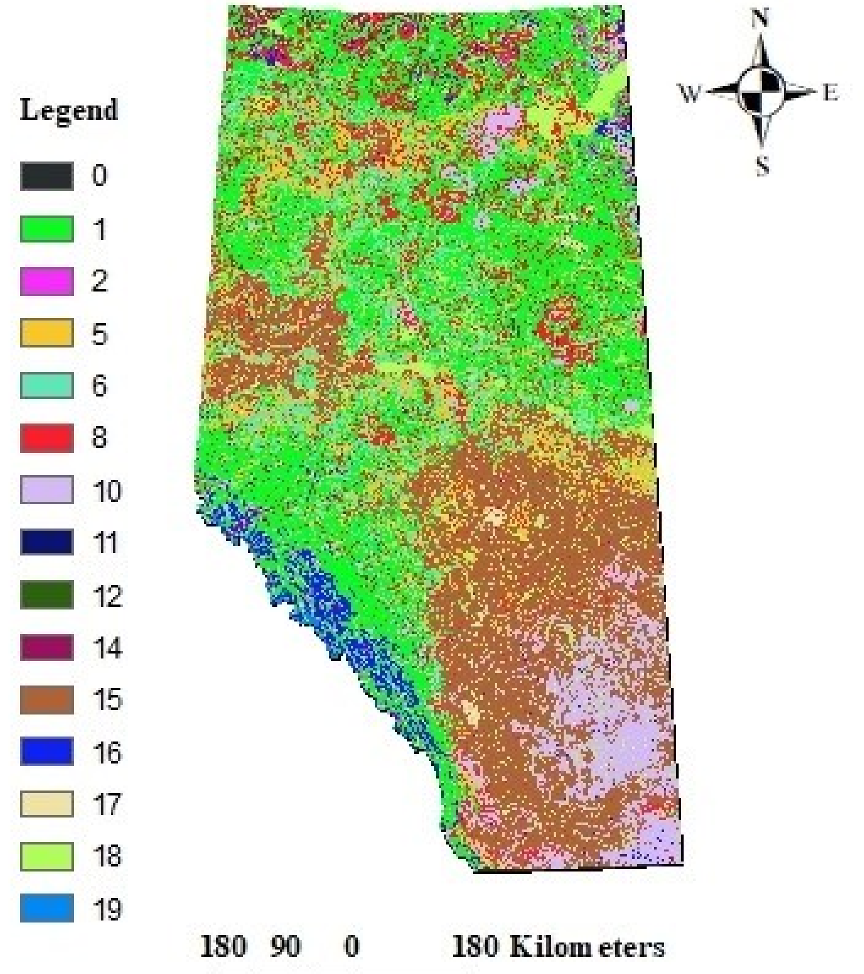

Figure D-1: Raster map of land cover shapefile of Alberta

Table E-1: Grading values for Land cover raster map

Values	Land type
0	Undefined area
1	Temperate or sub-polar needle leaf forest
2	Sub-polar taiga needle leaf forest
5	Temperate or sub-polar broadleaf deciduous forest
6	Mixed forest
8	Temperate or sub-polar shrub land
10	Temperate or sub-polar grassland
11	Sub-polar or polar shrub land-lichen-moss
12	Sub-polar or polar grassland-lichen-moss
13	Sub-polar or polar barren-lichen-moss
14	Wetland
15	Cropland
16	Barren lands
17	Urban
18	Water
19	Snow and Ice

Appendix F: Sample of a binary map

Figure F-1 is an example of binary map created for the urban area of Alberta. Similar to the binary function, cell values of ‘‘0’’ and “1” in the map indicate areas unsuitable and suitable, respectively, for locating W2VA facilities.

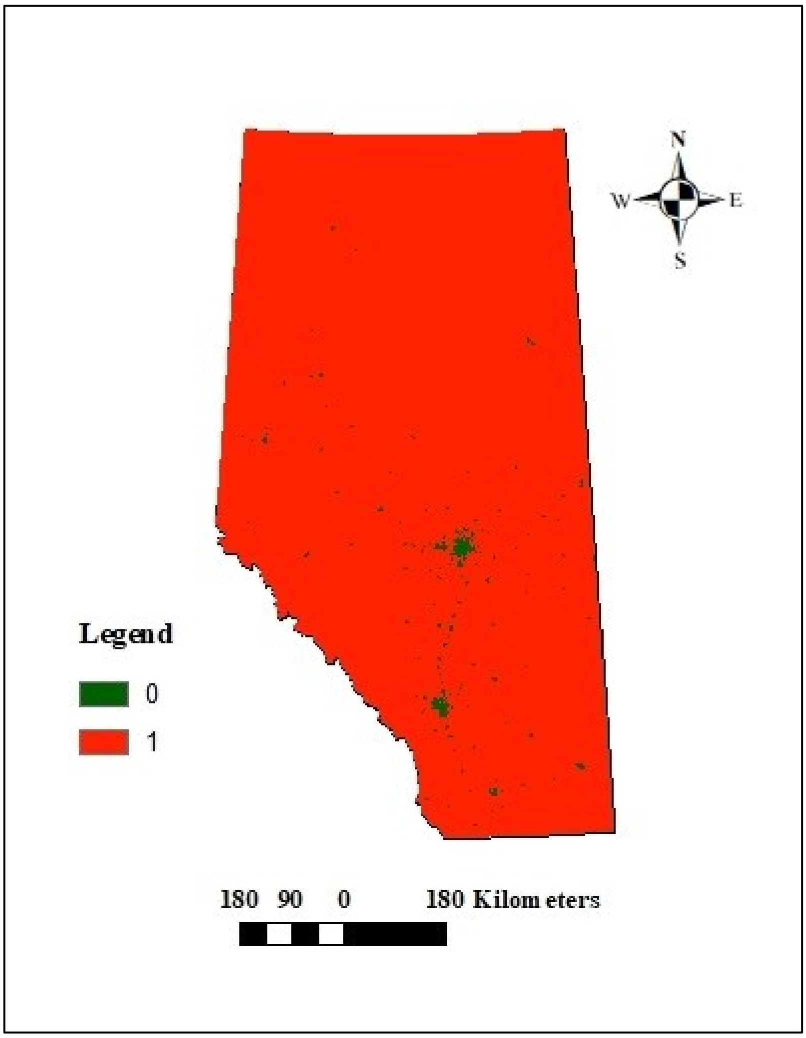

Figure F-1: Binary map for urban area shapefile