Optimal Siting of Solid Waste-to-Value-Added Facilities through a GIS-Based Assessment

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Abstract

Siting a solid waste conversion facility requires an assessment of solid waste availability as well as ensuring compliance with environmental, social, and economic factors. The main idea behind this study was to develop a methodology to locate suitable locations for waste conversion facilities considering waste availability as well as environmental and social constraints. A geographic information system (GIS) spatial analysis was used to identify the most suitable areas and to screen out unsuitable lands. The analytic hierarchy process (AHP) was used for a multi-criteria evaluation of relative preferences of different environmental and social factors. A case study was conducted for Alberta, a western province in Canada, by performing a province-wide waste availability assessment. The total available waste considered in this study was 4,077,514 tonnes/year for 19 census divisions collected from 79 landfills. Finally, a location-allocation analysis was performed to determine suitable locations for 10 waste conversion facilities across the province.

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Keywords

Waste conversion facility; geographic information system; location-allocation analysis; analytic hierarchy process

Nomenclature

1. Introduction

The management of municipal solid waste (MSW) is a big concern today for city authorities and planners because of increasing population, urbanization, and limited land space. MSW is also one of the most significant threats to the environmental health (Javaheri et al., 2006) since treatment and dumping of solid wastes are environmentally challenging procedures (Ojha et al., 2007). Such environmental challenges combined with political, social, economic, and land availability issues raise concerns over land management and evaluation techniques (Lein, 1990). In addition, increasing population leads to increases in fossil fuel consumption and corresponding greenhouse gas (GHG) emissions. Converting solid waste to energy or fuel is an environmentally preferable option to waste management that contributes to offsetting GHG emissions as well.

Before mid-1970s, most household garbage in the United States went to the dump, and currently many landfills have either reached or nearly reached their capacity (Palmer, 2011). In Canada, most of the waste ends up at landfills, 30% of whole landfills have either reached or surpassed their capacity in 2010 (PPP Canada, 2014). Landfills produce a sizable portion (about 25%) of Canada's methane emissions (Environment Canada, 2012). The concept of waste conversion facilities is receiving increased attention because of the depletion of landfills and restrictive environmental regulations to replace fossil fuels. However, MSW treatment plants are usually considered undesirable (Aragones-Beltran et al., 2010). Siting waste conversion facilities in optimal locations at optimal capacities is a complex task involving many social and environmental challenges. For example, social opposition due to community reactions, sometimes known as not-in-my-backyard (NIMBY), is one of the major challenges (Aragones-Beltran et al., 2010). Environmental challenges include odors, noise, and litter in the neighboring environment (Aragones-Beltran et al., 2010). Also, economic parameters (i.e., transportation cost) need to be considered during site selection.

The Geographical Information System (GIS) software ArcGIS 10 (Environmental Systems Research Institute - ESRI) is a great tool to analyze land use suitability, store and handle spatial data, and combine different types of numeric and descriptive values with spatial data (Al-hanbali et al., 2011). In a multi-criteria decision analysis (MCDA), several factors are considered and values are assigned to find the corresponding relative weighted values. An analytic hierarchy process (AHP) is a widely accepted MCDA method that applies a pairwise comparison of multiple criteria and a multi-level hierarchical structure to obtain the relative weight of each individual criterion. The integration of GIS features and AHP techniques (a GIS-based MCDA approach) uses spatial data and relative weighted criteria to produce more valuable spatial data (i.e., spatial data containing more information that can be further used) for critical decision making. These GIS-based MCDA approaches have been used for a number of studies for landfill siting (Delgado et al., 2008; Geneletti, 2010; Kontos et al., 2005; Nas et al., 2010; Sener et al., 2006; Sumathi et al., 2008; Wang et al., 2009; Sultana et al., 2012). Limited research has been conducted on GIS-based siting of solid waste conversion facilities (Aragones-Beltran et al., 2010; Tavares et al., 2011). Aragones-Beltran et al. (2010) applied the analytic network process (ANP) and used 21 economic, legal, and environmental criteria grouped into clusters for MSW plant site selection. Chiueh et al. (2008) and Chang et al. (2009) proposed GIS-based systems for allocating compensatory funds for existing solid waste incinerators; their research included environmental impact assessments. Tavares et al. (2011) presented a siting methodology incorporating GIS combined with AHP for a solid waste incineration plant. However, there is no study on solid waste conversion facility siting that conducts a detailed waste assessment and uses waste availability, existing landfill locations, and an actual road network. There is a need to develop a methodology that uses existing data to develop a sustainable waste management infrastructure for a particular region. This study is an effort to address these gaps. The overall objective of this research work is to develop a methodology to locate the waste conversion facilities considering existing landfill locations, waste availability, and real road networks. The specific objectives include:

- Development of a framework to assess the optimal location of waste to added-value facilities using a range of social and environmental factors;
- Integrate GIS-AHP for the development of the framework;
- Conduct a location-allocation analysis to select the ten most suitable waste conversion facility sites in the province of Alberta, Canada.

This paper has five sections. Section 1 provides the background, research objectives, motivation, and overview of the rest of the paper. Section2 describes the methodology of this study. The methodology is subdivided into three subsections that describe three types of analysis: constraint analysis, preference analysis, and location-allocation analysis. Section3 discusses the study area specifics of this research. This section lists and describes the constraint criteria and preference parameters used in this study. Section4 discusses the results found from this study and finally section 5 provides a conclusion that states where this methodology can be used and provides recommendations for future work.

In this paper, the terms "waste-to-value-added facilities" and "waste conversion facilities" have been used interchangeably. Examples of these facilities include waste-to-biofuel facilities, waste-to-electricity facilities, and composting and anaerobic digestion facilities. This study did not consider incineration technology; hence, the waste-to-value added facility does not include incineration plants.

2. Methodology

In this study, a GIS-AHP integrated approach was used to find suitable locations for waste conversion facilities. Geospatial information for this analysis was collected in both vector and raster format from several sources including Geobase Portal (Geobase Portal, 2013) and AltaLIS (AltaLIS, 2013). A two-step approach was used to create a land suitability map. In the first step, a constraint analysis, areas considered unsuitable based on social and environmental constraints were screened out of the study area. Then a preference analysis was conducted to find out the relative preference of different regions of the study area based on economic, safety, and environmental factors. Figure 1 shows the overall methodology. All maps (e.g., Fig. 5) were converted to raster maps with a 30m x 30m cell size, with each cell containing an interpretable value. The relative preference of different regions was combined with the constraint analysis data to find the land suitability model (LSM). This map was later used in location-allocation analysis to determine specific locations for waste conversion facilities using a real road network.

2.1. Constraint Analysis

In this work, a constraint analysis was performed to screen out unsuitable areas. In order to screen out unsuitable areas for waste conversion facilities, some environmental and social factors (referred to hereafter as constraints) were considered. An exclusion zone was created around each of the constraints by creating a buffer[2] with an extent equal to the minimum site development distance from the corresponding constraint. A binary map was developed for each constraint, with values of "0" given to the exclusion zone and "1" outside the exclusion zone. All these binary maps were combined to produce the final constraint map. In the final constraint map, cells with the value "0" represent unsuitable locations and those with the value "1" represent places suitable for waste conversion facilities. The value of the i^{th} cell of the final constraint map is calculated as follows:

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

where $C_{E,i}$ is the Boolean[3] (0,1) cell value of the i^{th} cell of the final constraint map, $C_{i,k}$ is the Boolean cell value of i^{th} cell in the k^{th} constraint grid layer, and n is the number of constraints considered in the study. The multiplication of all the constraint grid layers results in the final constraint map. A value of "0" in a cell in any of the constraint grid layers results in a value of "0" for the corresponding cell of the final constraint map. Cells with a value of "1" in each of the constraint grid layers result in a value of "1" for the corresponding cells of the final constraint map. Figure 1 (a) gives a brief overview of the constraint analysis.

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[2] A buffer is a zone around a feature (i.e., point, line or polygon) at a specified distance.

[3] A Boolean expression shows a value in a true or false (logical) condition (ESRI, 2016)

Figure 1: **(a) Constraint analysis overview, (b) Preference analysis overview**

2.2. Preference Analysis

A preference analysis shows relative preference for particular regions of a study area. Some factors (mentioned in section 3.3) were considered in order to identify the most preferable sites for maximum energy and economic benefits. These factors were identified based on previous research (Eskandari et al., 2012; Ma et al., 2005; Sultana and Kumar, 2012) and personal communications with Alberta Environment personnel (Page, 2013). For almost all of these factors, multiple buffers were generated around the corresponding factor. Each of the buffer rings was then assigned a grading value[4]. Since factors are not of equal importance, the analytic hierarchy process (AHP) was used to assign appropriate weights to each factor. For the i[th] cell of the final preference map, its value was calculated as:

$$P_{i,f} = \sum_{j=1}^{m} w_j P_{i,j} \;; \qquad 0 \le w_j \le 1 \qquad (2)$$

where $P_{i,f}$ is the value of i[th] cell of the final preference map, $P_{i,j}$ is the value of i[th] cell for j[th] preference factor, m is the number of preference factors considered for this study, and w_j is the weight assigned to the j[th] preference factor. Figure 1(b) gives a brief overview of the preference analysis.

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[4] Grading values are used to classify any feature. Usually a higher grading value represents greater importance and lower grading value less importance.

A land suitability map is created by using the final constraint map from a constraint analysis and the final preference map from a preference analysis. The suitability index (SI)[5] is accordingly calculated using Eq. 3.

$$SI_i = C_{i,j} \times P_{i,j} \quad (3)$$

2.3. Location-Allocation Analysis

A location-allocation analysis is an ArcGIS Network Analyst extension, useful for selecting optimal locations for a given number of facilities from a set of candidate locations. In this study, the "Minimize Weighted Impedance (P-Median)[6]" option was used with Alberta's road network dataset to select 10 optimum facility locations in such a way that the total sum of weighted distances between each facility and waste transfer stations was minimized.

The ArcGIS location-allocation solver calculates the shortest path between all facilities and demand point locations using an actual road network (ESRI, 2015). It then generates an origin-destination matrix of these costs and processes it using Hillsman editing[7] (Hillsman, 1984). A near-optimal solution is obtained through a combination of semi-randomized initial solutions, a vertex substitution heuristic, and a refining metaheuristic (Varnamkhasti, 2012).

[5] The suitability index is the number that is used in a land suitability map (LSM) to indicate how suitable the location is. The higher the suitability index, the more suitable the location.

[6] Facilities are located such that the sum of all weighted costs between demand points and solution facilities is minimized

[7] Hillsman editing is a process that enables an overall solver heuristic to solve a variety of different problems.

3. Case Study: Province of Alberta

3.1. Study area and solid waste characteristics

The province of Alberta covers an area of 661,185 square kilometers with a total population of 3,699,939 (Government of Alberta, 2012). In Alberta, waste disposal from residential and non-residential sources was 970,422 tonnes and 2,947,070 tonnes, respectively, in 2010 (Statistics Canada, 2010). Table 1 shows the waste composition and components for Alberta.

Table 1: Waste composition in Alberta (Alberta Environment, 2007; City of Edmonton, 2010)

Since a portion of the total waste generated in Alberta goes to recycling and composting facilities, this study uses "waste by disposal data" instead of "waste by generation data" to find out waste availability for waste-to-energy facilities. Although significant efforts are made to reduce, reuse, and recycle waste, landfilling still remains the most common method for waste disposal in Alberta (Government of Alberta, 2014). There are four types of landfills in Alberta: hazardous waste landfill (class I), non-hazardous waste landfill (class II), inert waste landfill (class III), and industrial landfill (Alberta Environment and Parks, 2015; Page, 2013). Landfill data were collected from Alberta Environment (Page, 2013) and landfill managers.

Figure 2 shows the waste availability at Alberta landfills generated through ArcGIS using the longitude, latitudes, and waste availability (tonnes). The figure includes both residential and non-residential waste. Some industrial landfill operators were unwilling to share their landfill data, and real measured data were not available for some other landfills. Since this study aimed at siting waste conversion facilities for all of Alberta, it was important to take all available waste into consideration; hence it was necessary to estimate the missing data. Waste availability data were assumed for some of the class II landfills with no measured data based on the per capita of the nearest landfill (see section 3.3 for details on this estimation).

Figure 2: Waste availability at Alberta landfills

Of the total estimated waste, 66% is from class II and class III landfills and 34% is from industrial landfills. Waste availability at class II, class III, and industrial landfills is shown in Table 2.

Table 2: Waste availability at different types of landfills in Alberta

3.2. Waste transportation framework

Figure 3 depicts anticipated and proposed waste transportation frameworks considered in this study for use in waste-to-energy facilities in Alberta.

Figure 3: Waste transportation framework

In this framework, waste is sorted at transfer stations. The recyclable portion goes to recycling facilities, waste with high organic content goes to composting facilities, waste with very low energy content goes to landfills, and waste with moderate and high energy content goes to waste-to-energy facilities. After waste is treated at waste conversion facilities, ash goes to the landfills. Few transfer sites in Alberta are equipped with waste sorting facilities.

3.3. Transfer stations

A solid waste transfer station receives waste material from a community and the waste is consolidated, tranferred to a large vehicle, and transported to a distant waste disposal facility. In Alberta, transfer stations are typically used to collect and transport waste economically to landfills, increase collection efficiency, provide convenient drop-off locations, and decrease traffic volume at landfills (Solid Waste Association of North America, 2008). A general rule of thumb is that transfer stations are more economical if the hauling distance is greater than 35 km (Solid Waste Association of North America, 2008). However, according to a break-even analysis conducted in 2010, transfer stations are required within a radius of 40 km from the potential waste-to-energy facility (Southern Alberta Energy from Waste Alliance, 2012).

Since, in the anticipated waste transportation framework, waste is transported from a transfer station to waste-to-energy facilities, it is critical to know how much waste is available at the transfer stations. In Alberta's current waste management system, waste availability is not measured accurately at transfer sites. For this study, waste disposal at each census division (CD) was estimated based on the total waste available inside the CD's landfills, and waste availability per unit area was then calculated by dividing the total waste by the area of the census division. Areas served by each transfer site were calculated by dividing the whole area into proximal zones by obtaining Thiessen polygons (i.e., zones representing an area where any location within the zone is closer to its associated transfer station than any other transfer stations) around the transfer sites. Waste availability at each transfer station was estimated by multiplying the area served by the corresponding transfer site and waste availability per unit area of the corresponding census division. Figure 4 shows the location and estimated solid waste availability at existing waste transfer sites.

Figure 4: Waste availability at different transfer stations in Alberta

3.4. Constraint Criteria

A waste conversion facility should not be sited within a certain distance of waterbodies, wetlands, airports, environmentally sensitive areas, and industrial zones for environmental regulations; it cannot be sited near to rural and urban areas, parks because of social issues and it cannot be sited close to gas pipelines, transmission lines, power plants, and land surface gradients for safety concerns. The factors and corresponding distances considered in this study for the constraint analysis are as follows.

i) Rivers, lakes, and other water bodies (areas within 300 m were screened out) (Government of Alberta, 2010)
ii) Rural and urban areas (areas within 1 km were screened out) (Eskandari et al., 2012; Ma et al., 2005)
iii) Airports and heliports (areas within 8 km were screened out) (Southern Alberta Energy from Waste Alliance, 2012; Solid Waste Association of North America, 2008)
iv) Industrial and mining zones (areas within 1 km were screened out) (Sultana and Kumar, 2012)
v) Environmentally sensitive areas (ESA) (flood plains, conservation areas, habitat sites) (areas within 1 km were screened out) (Eskandari et al., 2012)
vi) Natural gas pipelines (areas within 100 m were screened out) (Sultana and Kumar, 2012; Ma et al., 2005)
vii) Park and recreational areas (areas within 500 m were screened out) (Sultana and Kumar, 2012)
viii) Wetlands (areas within 200 m were screened out) (Sultana and Kumar, 2012)
ix) Highways (areas within 300 m were screened out) (Solid Waste Association of North America, 2008)
x) Power plants and substations (areas within 100 m were screened out) (Sultana and Kumar, 2012)

xi) Transmission lines (areas within 100 m were screened out) (Sultana and Kumar, 2012)

xii) Land surface gradient (areas with slopes larger than 15% were screened out) (Sultana and Kumar, 2012)

In the constraint analysis, buffer zones were created for each constraint, and areas inside the buffer zones were excluded from the study area. "Standards for Landfills in Alberta" (Government of Alberta, 2010), the *Alberta Transfer Station Technical Guidance Manual* (Solid Waste Association of North America, 2008), and other research on siting landfills were used to determine the buffer extents. These 12 constraint criteria and 8 preference factors (described in section 3.5) were selected based on our literature review and by consulting with experts from Alberta Environment (a ministry of Government of Alberta), different counties in Alberta (e.g., Parkland County, St. Paul County), and from Alberta Innovates – Energy and Environment Solutions. Constraint criteria and preference factors used in this study are globally usable since these parameters are common to almost all jurisdictions. However, the extent of buffers may differ in other jurisdictions, and other jurisdictions may need to consider some additional parameters depending on jurisdiction specifics.

3.5. Parameters for Preference Analysis

The following eight factors were considered in this study's preference analysis:

i) Waste availability and distance from transfer stations

ii) Distance from roads

iii) Distance from transmission lines

iv) Distance from substations

v) Water availability

vi) Distance from existing landfills

vii) Distance from urban areas

viii) Land cover

Among these eight factors, waste availability and distance from transfer stations, distance from existing landfills, distance from substations and water availability can be categorized as economic factors. Distance from roads has both economic and social aspects associated with it. Economic and safety related social concerns are related with distance from transmission lines. Distance from urban areas and land cover can be categorized as environmental factors.

3.5.1. Waste Availability and Distance from Transfer Stations

Waste transportation is a major criterion in waste conversion facility siting because of transportation costs and environmental problems (e.g., odour, nuisance). Thus it is essential to locate waste conversion facilities as close as possible to waste transfer sites. In this analysis, multiple buffer rings were created for each transfer station and grading values were assigned to each buffer with different distances as shown in Table 3.

Lands closer to transfer stations should get more preference due to lower transportation cost. On the other hand, transfer stations with higher waste availability should get further more preference compared to transfer stations with lower waste availability. Hence in this study transfer stations were categorized based on their waste availability and final grading values were calculated using the methodology stated below.

Transfer stations were classified in seven groups based on standard deviation. In this analysis, the mean, median, and standard deviation were 13,476 tonnes/year, 6,519 tonnes/year, and 25,036 tonnes/year, respectively. Moreover, ten equally distant buffer regions (0 – 15, 15 – 30, 30 – 45, 45 – 60, 60 – 75, 75 – 90, 90 – 105, 105 – 120, 120 – 135, 135 - 150 kilometers) around each transfer station were considered. The seven waste availability ranges together with the ten distance ranges were assigned values (see Table 3).

Table 3: Values assigned to waste availability and distance from transfer stations

Grading values for the surrounding regions of the transfer stations were calculated using equation 4:

$$\text{Grading values} = R_i \times D_j \div 7 \quad (4)$$

Buffer regions having values less than any integer were merged together till the grading value reached an integer. For example, the first four buffer regions (0 – 15, 15 – 30, 30 – 45, 45 – 60 kilometers) for 0 – 7,200 tonnes/year waste availability, had grading values of 1.43, 1.28, 1.14, and 1. These four regions were merged and assigned a grading value 1. Table 4 shows the grading values assigned to the buffers based on waste availability and transfer stations.

Table 4: Grading values assigned to buffers based on waste availability and distance (in kilometers) from transfer stations

Figure 5(a) shows maps with grading values based on waste availability and distance from transfer stations.

Figure 5: Maps showing grading values based on (a) waste availability (b) distance from roads (c) distance from transmission lines and (d) distance from substations

3.5.2. Distance from Roads

Distance from existing roads is an important factor in locating waste conversion facilities. A restricted buffer zone was considered in this study in order to minimize odour and view. Beyond this restricted buffer zone, the facility location must be close to a road network in order to reduce transportation costs. Multiple buffer rings were created around the roads, and grading values were assigned to these buffer rings in such a way that grading values increase with a decrease in the buffer ring distance from roads. Research by Al-hanbali et al. (2011), Kontos et al. (2005), and Sultana and Kumar (2012) was used to decide on the multiple buffer ring extents and the grading values for roads. Grading values for different areas based on their distance from roads are tabulated in Table 5.

Table 5: Grading values for preference parameters

Figure 5(b) shows the grading values assigned to different areas based on their distance from roads.

3.5.3. Distance from Transmission Lines and Substations

Research by Ma et al. (2005) and Sultana and Kumar (2012) was used to decide on the multiple buffer ring extents and the grading values for substations.

Grading values of places for distance from transmission lines are given in Table 5. Figure 5(c) shows the grading values assigned to different areas based on their distance from transmission lines. Beyond the restricted buffer zone (100 m buffer for substations), the closer the facilities are to substations the better, in order to save costs. Grading values of places for distance from substations are also given in Table 5. Figure 5(d) shows the grading values assigned to different areas based on their distance from substations.

3.5.4. Water Availability

In siting any waste-based facility, surface water contamination is a major consideration. Figure 6(a) shows the grading values assigned to different areas beyond the restricted buffer zone based on water availability at those areas. Water availability for all regions was classified into 10 classes using Jenk's natural break classification method (Environmental Systems Research Institute, Inc., 2017). Grading values (1-10) increase with increase in water availability.

Suitability grading values assigned to different zones based on water yield for those areas are shown in Table 5.

Figure 6(a) shows the grading values assigned to different areas based on their water availability.

Figure 6: Maps showing grading values based on (a) water availability (b) distance from existing landfills (c) distance from urban areas (d) land cover

3.5.5. Distance from Existing Landfills

There is always a portion of waste that cannot be treated thermally or biologically and thus needs to be landfilled. Moreover, for gasification facilities, ash needs to be disposed at the landfills also. Hence the distance from existing landfills is an important factor in locating waste conversion facilities. Multiple buffer rings were created around existing landfills, and grading values were assigned to these buffer rings such that grading values increase with a decrease in the buffer ring distance from landfills. Grading values for different areas based on their distance from landfills are tabulated in Table 5.

Figure 6(b) shows the grading values assigned to different areas based on their distance from landfills. Lower distance from facility location to existing landfill indicates lower transportation cost for ash or unsuitable waste transportation. Hence regions closer to the existing landfills were assigned with higher grading values.

3.5.6. Distance from Urban Areas

Multiple buffer rings were created around urban areas, and grading values were assigned to these buffer rings such that grading values increase as buffer rings increase in distance from urban areas. Research by Al-hanbali et al. (2011), Kontos et al. (2005), and Sultana and Kumar (2012) was used to decide on the multiple buffer ring extents and the grading values for urban areas. These grading values, along with the corresponding distances, are given in Table 5. Figure 6(c) shows the grading values assigned to different areas based on their distance from urban areas. For waste management facilities, the preference for suitable sites increases as the distance from urban areas increases. Hence lands closer to urban areas were assigned lower grading values and higher grading values were assigned to farther regions.

3.5.7. Land Cover

Figure 6(d) shows the grading values assigned to different areas based on types of land cover (e.g., agricultural land, forest areas, grassland, etc.). Earlier work done by the Alberta Biodiversity Monitoring Institute (2014) and Sultana and Kumar (2012) was used to decide on the classification of land cover types and the grading values for these classes of land covers. Grading values for different types of land cover are given in Table 5.

3.6. Analytic Hierarchy Process (AHP)

After defining parameters for preference analysis and assigning grading values to the corresponding study area, a weightage factor was calculated for each of the eight parameters using the analytic hierarchy process (AHP). Through this method a weightage factor from a pairwise comparison can be derived. Paired elements are compared, and each element is assigned a value on a 9-point scale derived from Saaty (Saaty, 2002). The fundamental scale of relative importance is shown in Table 6.

Table 6: The fundamental scale of relative importance in AHP, based loosely on Saaty's definitions (Sultana and Kumar, 2012; Ma et al., 2005)

The first step is to make a hierarchy of the influencing factors that provides an overall view of the complex relationship between the factors. After defining the structure, for each pair of criteria, rating on the basis of relative priority is done by assigning a weight between "1" (equal importance) and "9" (extremely more important). A $n \times n$ matrix "A" is developed where $a_{i,j}$ is the extent of preferring factor i to factor j and $a_{j,i} = \frac{1}{a_{i,j}}$. Then the sum of each column in the matrix is calculated and each matrix element is divided by its corresponding column sum. Finally, relative weight is calculated by taking the average across each row.

The final steps of the AHP are to calculate the consistency ratio (CR) and to check the consistency of the pairwise comparison. The consistency ratio is calculated using the following mathematical relation:

$$CR = \frac{CI}{RI} \tag{5}$$

where CR is consistency ratio, RI is mean/average consistency index, and CI is consistency index. The consistency index is calculated using the following relation:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

where n is order of matrix and λ_{max} is maximum eigenvalue of the matrix.

The pairwise comparison matrix and weights of preference factors for this case study are given in Table 7.

Table 7: Pairwise comparison matrix and weights of preference factors using the AHP

4. Results and Discussion

Figures 7(a) and 7(b) show the result of constraint and preference analysis, respectively. In this study, the constraint analysis screened out 45.7% of the total study area, thereby reducing it to 54.3%. Banff National Park and Wood Buffalo National Park are the dominant limiting factors in southwest and northeast Alberta in the constraint analysis. Other critical constraint criteria include environmentally sensitive areas and industrial and mining zones. The distance from the waste disposal area and the amount of waste availability are the dominant preference factors in the preference analysis. Superposing the raster layers from the constraint and preference analyses yields a final siting suitability map (shown in Fig. 7(c)).

Figure 7: (a) Final constraint map (b) Final preference map (c) Final land suitability map (d) Result of location-allocation analysis

The most suitable areas (SI = 7 and SI = 6) are found mostly in CD - 7, CD - 8, and CD – 10. Considering social, environmental, and economic conditions, facilities should be built in areas with higher SI values. Hence, areas with SI = 6 and 7 and larger than 10 acres (Lynch, 2014) were considered as candidate sites for facility site selection. Location-allocation analysis was performed to select 10 optimal sites from the candidate sites using the “Minimized Weighted Impedance” method. Figure 7(d) shows the locations of selected sites and corresponding waste transfer sites. Table 8 shows the longitude, latitude, county location, and nearest road for the selected sites.

Table 8: Locations of selected sites for waste conversion facility

Since population density and urbanization are comparatively lower in northwest Alberta than other jurisdictions in the province, only two sites (Sites 1 and 3) are located in northwest Alberta to serve the mostly rural areas. Although Wood Buffalo National Park is a critical limiting factor in northeast Alberta for waste conversion facility siting, available industrial and residential waste in that region and distance optimization between facility and existing waste disposal regions prompt the siting of Site 2 in northeast Alberta. The locations of Sites 4, 5 and 6 are largely attributed to the short distance from a road network, easier access to transmission lines, and proximity to substations. High population density and higher urbanization in the central and southern Alberta regions are the key attributing factors for Sites 7, 8, 9, and 10.

5. Conclusions

Siting a new MSW conversion facility is a highly complicated task involving decisions based on environmental, social, technical, and economical issues. The methodology outlined in this paper is a GIS-based approach to locate suitable sites for waste conversion facilities. Suitability indices were generated through a multi-criteria decision making analysis combined with a GIS. These indices provide information on site suitability taking into account environmental components, location of waste, and amount of waste available. A GIS spatial analysis was done in two steps. First, 45.7% of the area was screened out by a constraint analysis that considered 12 constraints and second, an AHP was used to calculate the weightage of different factors. The suitability analysis was followed by a location-allocation analysis which was conducted to select 10 locations for waste conversion facilities. Consequently this approach may provide with an indication for switching to waste conversion technologies from landfilling through future economic feasibility studies for many international regimes. Therefore this methodology can be adopted to analyze environmental and economic aspects of a region's waste management and accordingly can contribute to cleaner production related policy adoption.

This GIS-aided siting method is flexible in terms of criteria (both constraint and preference) determination. This methodology can be expanded to include more criteria and thereby uncertainty can be reduced.

The method presented in this paper can serve as an efficient tool for decision makers and planners in siting a waste conversion facility. Optimal plant capacity and technology selection also have important roles when making the final decision for any waste conversion facility. Moreover, since the final decision for siting a waste conversion facility also depends on public opinion and political decisions, participation from the local community is mandatory while for this process.

Acknowledgements

This study was carried out with the financial support of Alberta Innovates - Energy and Environment Solutions, the NSERC/Cenovus/Alberta Innovates Associate Industrial Research Chair Program in Energy and Environmental Systems Engineering and Cenovus Energy Endowed Chair Program in Environmental Engineering (Grant No. IRCPJ 436795 & 436794 - 2011). The authors are grateful to Xiaomei Li, Surindar Singh, and Natasha Page for their input to this study, and to Astrid Blodgett for editing.

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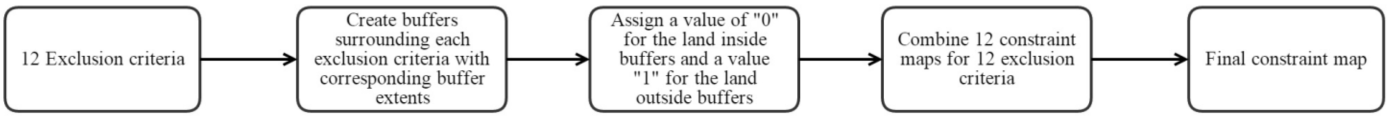
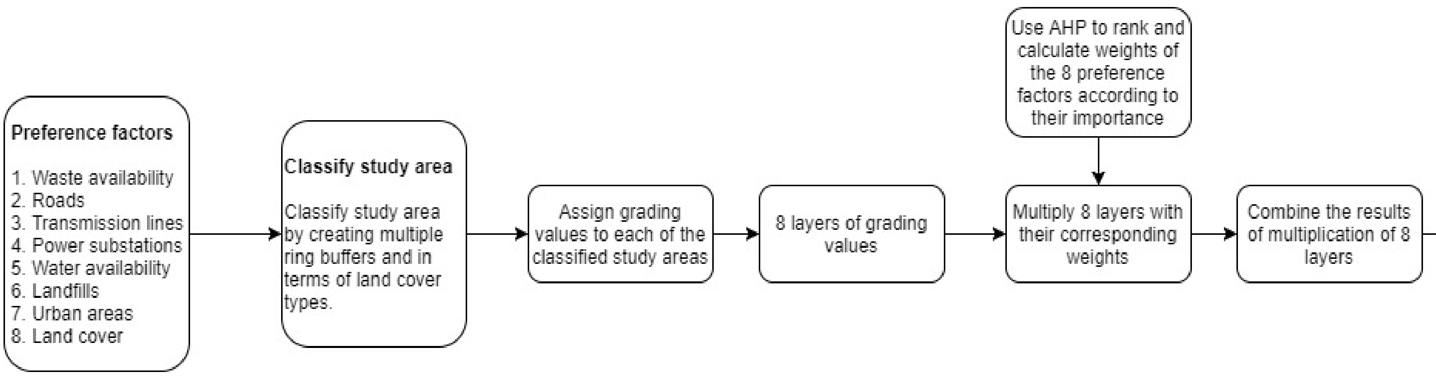


(a)



(b)

Figure 1: **(a) Constraint analysis overview, (b) Preference analysis overview**

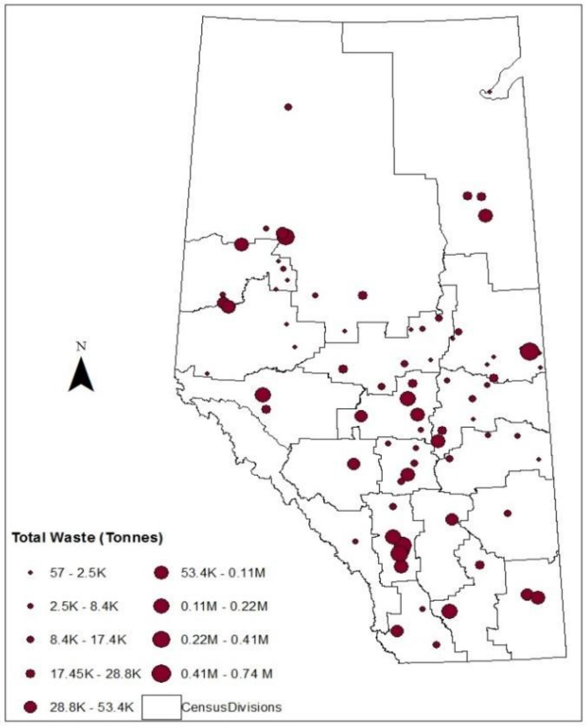


Figure 2: Waste availability at Alberta landfills

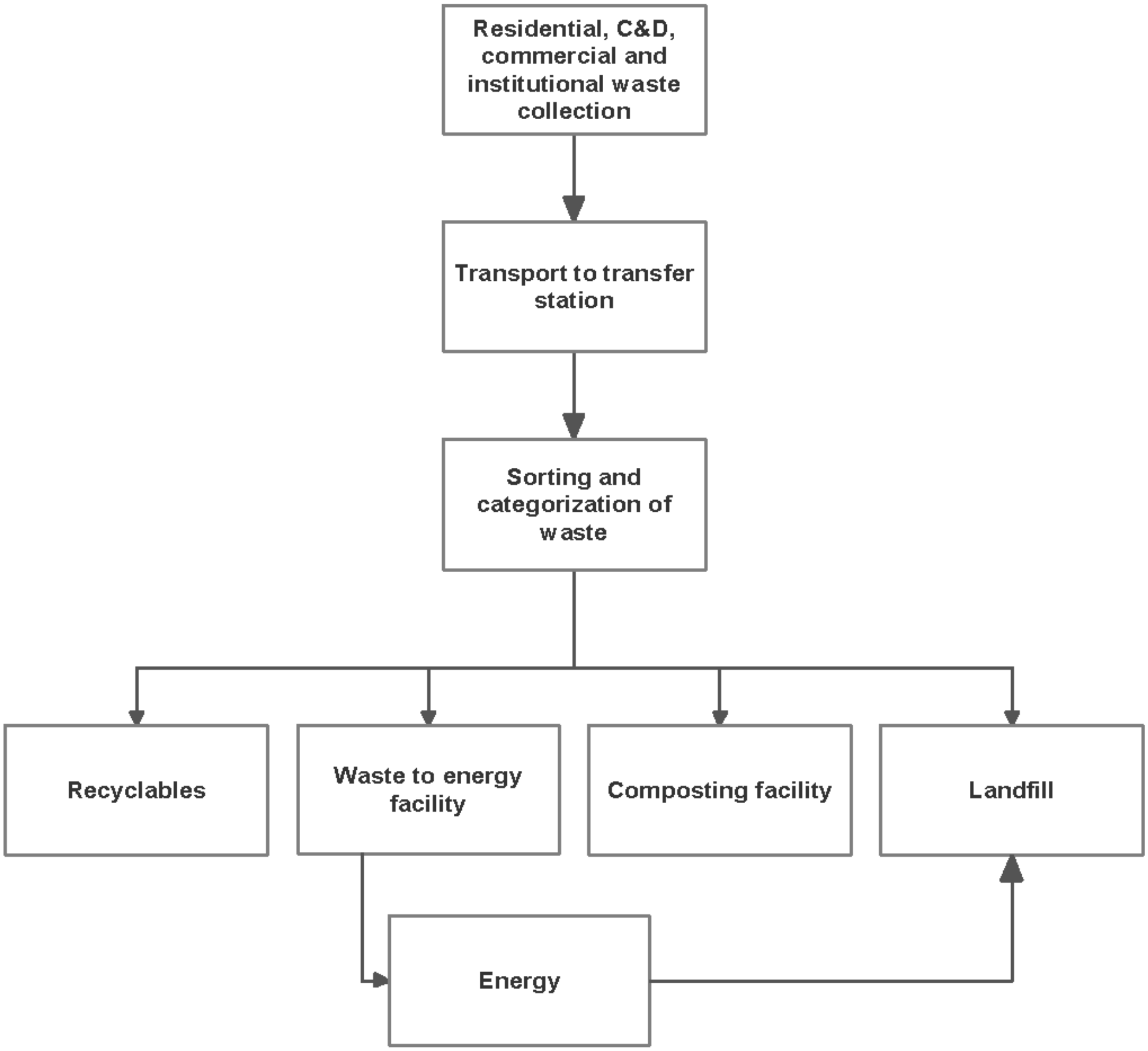


Figure 3: Waste transportation framework

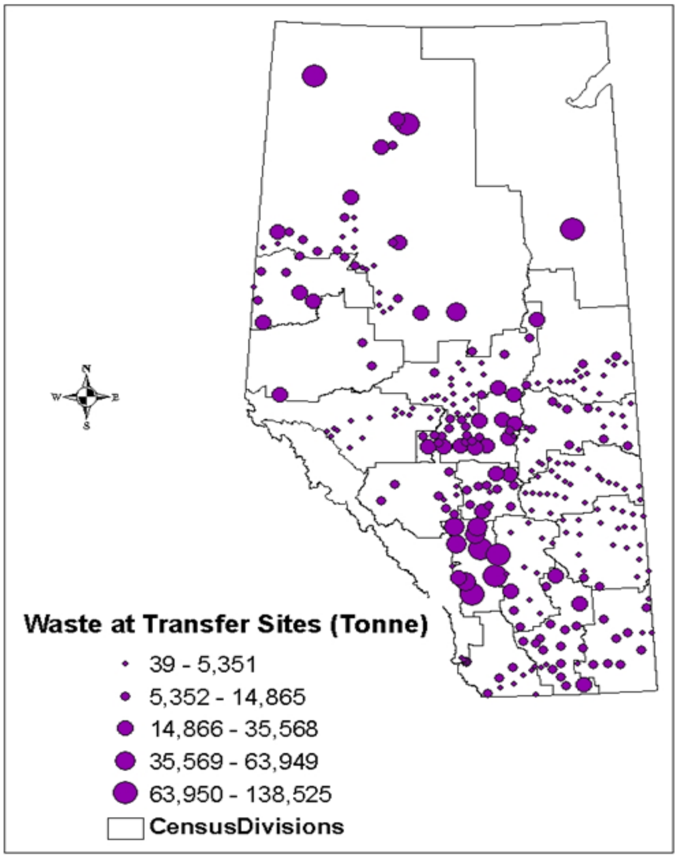


Figure 4: Waste availability at different transfer stations in Alberta

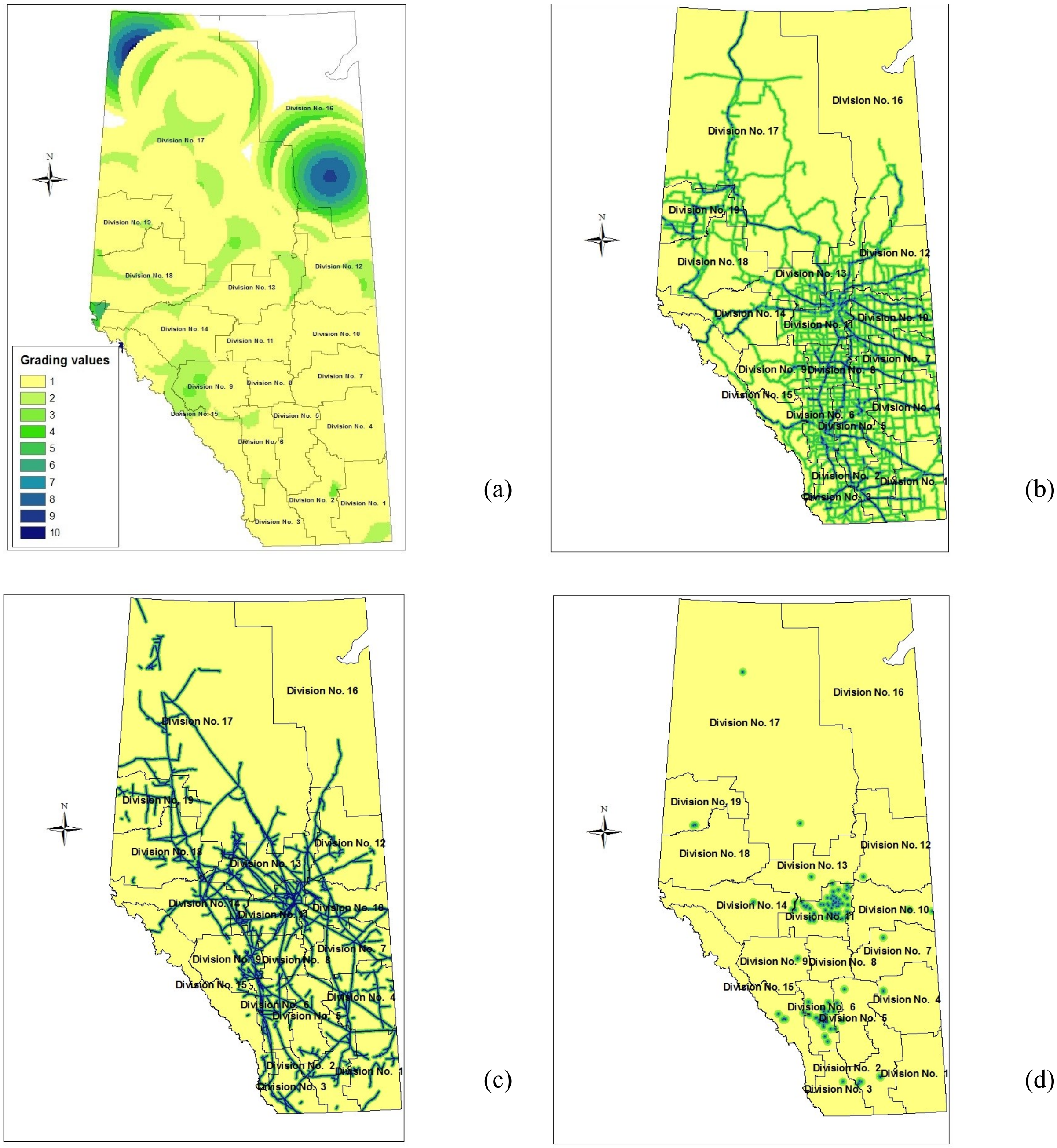
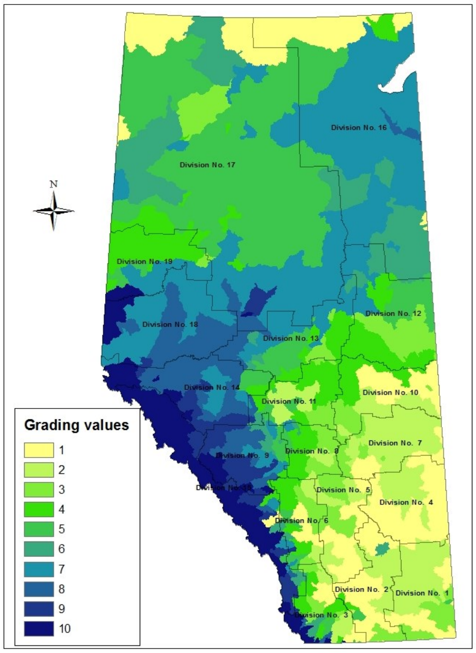
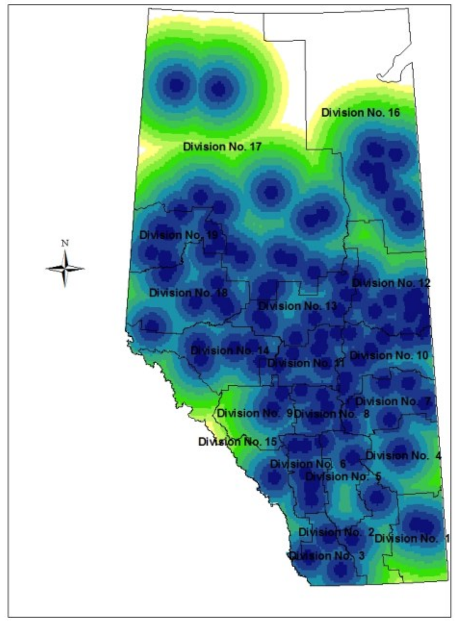


Figure 5: Maps showing grading values based on (a) waste availability (b) distance from roads (c) distance from transmission lines and (d) distance from substations



(a)



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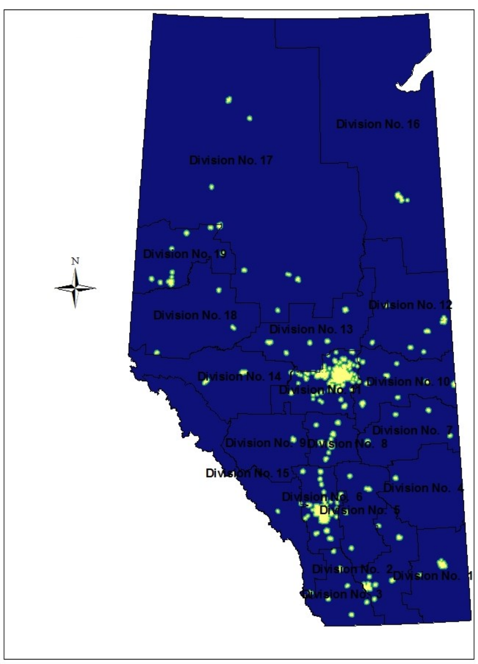
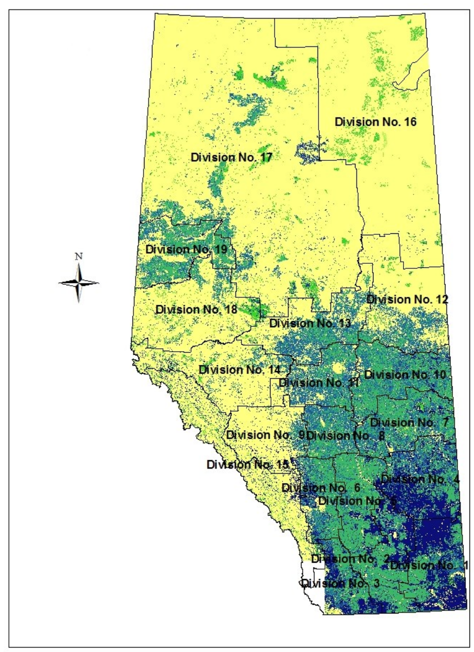


(c)



(d)

Figure 6: Maps showing grading values based on (a) water availability (b) distance from existing landfills (c) distance from urban areas (d) land cover

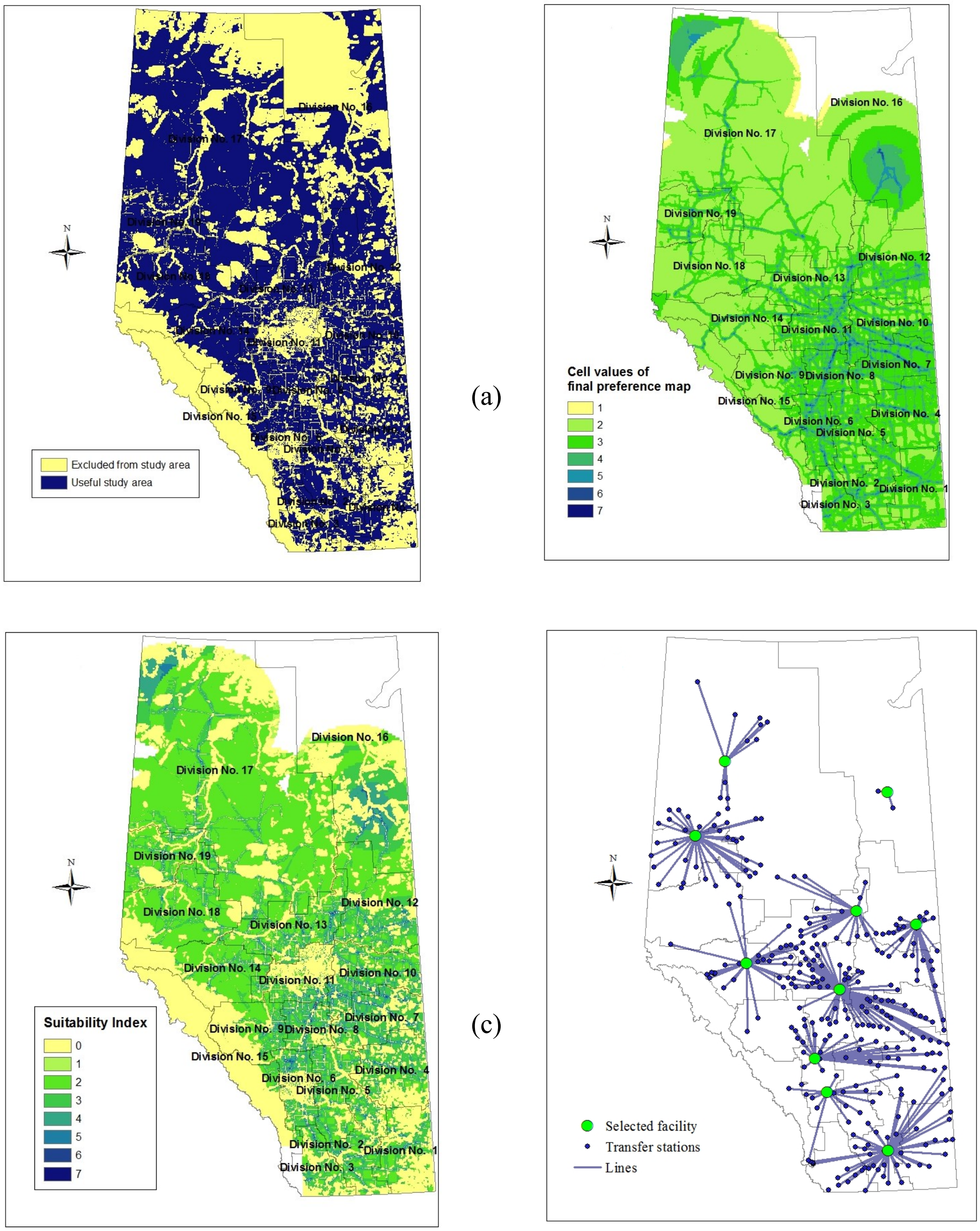


Figure 7: (a) Final constraint map (b) Final preference map (c) Final land suitability map (d) Result of location-allocation analysis

Nomenclature

MSW	Municipal solid waste
GIS	Geographic information system
MCDA	Multi-criteria decision analysis
ESRI	Environmental Systems Research Institute
SI	Suitability index
CD	Census division
AHP	Analytic hierarchy process
ANP	Analytic network process
GHG	Greenhouse gas
LSM	Land suitability model
R_i	Assigned values based on waste availability
D_j	Assigned values based on distance
C&D	Construction and demolition
CR	Consistency ratio
RI	Mean/average consistency index
CI	Consistency index
n	Order of matrix
λ_{max}	Maximum eigenvalue of the matrix

Table 1: Waste composition in Alberta (Alberta Environment, 2007; City of Edmonton, 2010)

Residential Waste (Edmonton)	**Percent**	**ICI Waste (Alberta)**	**Percent**	**C&D waste (Alberta)**	**Percent**
Paper & Cardboard	17	Paper	29.7	Paper	14
Food Waste	23	Hazardous Waste	1.7	Asphalt	4.5
Other Organics	9	Organics	30	Drywall	9.5
Yard Waste	29	Wood	6.4	Wood	26.5
Metal & Aluminium	3	Ferrous	4.1	Ferrous	2.1
Glass	2	Glass	1.9	Roofing	11.5
Plastics	7	Plastics	10.4	Brick-Stone	3.0
Textiles	3	Textiles & Rubber	4.1	Concrete	9
Other Wastes	7	Other Wastes	8.1	Other Wastes	13
		Non-Ferrous	0.6	Non-Ferrous	6.9
		Renovation	3.1		

Table 2: Waste availability at different types of landfills in Alberta

Type of landfill	**Waste (Tonne/year)**
Waste from industrial landfills	1,371,708
Waste from class II and class III landfills	2,705,806
Total waste considered	4,077,514

Table 3: Values assigned to waste availability and distance from transfer stations

Waste availability (tonnes/year)	**Assigned value based on waste availability (R_i), i = 1 – 7**	**Distance from transfer stations (kilometers)**	**Assigned value based on distance (D_j), j = 1 – 10**
0 – 7,200	1	0 – 15	10
7,200 – 20,000	2	15 – 30	9
20,000 – 32,000	3	30 – 45	8
32,000 – 45,000	4	45 – 60	7
45,000 – 57,000	5	60 – 75	6
57,000 – 70,000	6	75 – 90	5
70,000 – 200,000	7	90 – 105	4
		105 – 120	3
		120 – 135	2
		135 – 150	1

Table 4: Grading values assigned to buffers based on waste availability and distance (in kilometers) from transfer stations

Grading values Waste availability (tonnes/year)	1	2	3	4	5	6	7	8
0 - 7,200	0 – 60							
7,200 – 20,000	60 – 120	15 – 60	0 – 15					
20,000 – 32,000	90 – 120	60 - 90	15 – 60	0 – 15				
32,000 – 45,000	105 – 135	90 – 105	60 – 90	45 – 60	15 – 45	0 – 15		
45,000 – 57,000	120 – 150	105 – 120	75 – 105	60 – 75	45 – 60	15 – 45	0 – 15	
57,000 – 70,000	120 – 135	105 – 120	90 – 105	75 – 90	60 – 75	45 – 60	15 – 45	0 – 15
70,000 – 200,000	135 – 150	120 – 135	105 – 120	90 – 105	75 – 90	60 – 75	45 – 60	30 - 45

Table 5: Grading values for preference parameters

Grading values / Preference factors	1	2	3	4	5	6	7	8	9
Roads (meters)	>2000	Equal intervals within the range							
Transmission lines (meters)	>5000	Equal intervals within the range							
Substations (meters)	>5000	Equal intervals within the range							
Water availability ($dm^3/km^2/yr$)	0	0-13	13-23	23-45	45-71	70-98	98-147	147-193	1
Distance from existing landfills (kilometers)	Equal intervals within the range of 15-150								
Distance from urban areas (meters)	<1000	Equal intervals within the range							
Land cover	Mixed forest	Rock/rubble	-	-	Roads, railways	Agricultural land	Shrubland	Developed land	F l

Table 6: The fundamental scale of relative importance in AHP, based loosely on Saaty's definitions (Sultana and Kumar, 2012; Ma et al., 2005)

Definition	Relative importance
Equal importance	1
More important	3
Moderately more important	5
Considerably more important	7
Of greatest importance	9
Intermediate values to reflect compromise	2, 4, 6, 8

Table 7: Pairwise comparison matrix and weights of preference factors using the AHP

Preference factors	Waste availability	Roads	Transmission	Substation	Water	Landfills	Urban	Land cover	Weight
Waste availability	1	2	3	4	5	6	8	9	0.33
Roads	0.5	1	2	3	4	5	6	8	0.23
Transmission	0.33	0.50	1.00	2.00	3	4	5	6	0.16
Substation	0.25	0.33	0.50	1.00	2	3	4	5	0.11
Water	0.20	0.25	0.33	0.50	1	2	3	4	0.07
Landfills	0.17	0.20	0.25	0.33	0.5	1	2	3	0.05
Urban	0.13	0.17	0.20	0.25	0.33	0.50	1	2	0.03
Land cover	0.11	0.13	0.17	0.20	0.25	0.33	0.5	1	0.02

Table 8: Locations of selected sites for waste conversion facility

Sites	Longitude	Latitude	Nearest roads	County location
1	-117.510	57.602	HWY 35	County of Northern Lights
2	-111.629	57.104	HWY 63	Wood Buffalo
3	-118.462	56.076	HWY 64A	Municipal District of Fairview no. 136
4	-112.789	54.602	HWY 63, HWY 663	Athabasca County
5	-110.773	54.290	HWY 660, HWY 41	Municipal District of Bonnyville no. 87
6	-116.540	53.573	HWY 16	Yellowhead County
7	-113.431	53.047	HWY 2A	County of Wetaskiwin no. 10
8	-114.262	51.670	HWY 582	Mountain View County
9	-113.891	51.005	84 ST SE	Rocky View County
10	-112.036	49.798	HWY 3	Municipal District of Taber