An evaluation of the temporal and spatial evolution of waste facilities using a simplified spatial distance analytical framework

Original research paper

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ABSTRACT:

This study proposed a simplified GIS-based decision support tool to examine the temporal and spatial evolution of waste facilities at a regional level. The key objective is to examine the geospatial distribution of landfills and transfer stations in Saskatchewan, Canada, from 2018 to 2020 based on changes in Euclidean distance computed by both the Central Feature (CF) and median center (MdC) spatial statistical tools. Both the CF and MdC results suggest that transfer stations in 2020 were located significantly closer to communities, and an improved level of landfill regionalization is observed. Smoother Landfill and Transfer Station radial curves are generally observed using the MdC tool. About 47.1% of the divisions are classified as challenging areas using the CF method, whereas only 41.1% of the divisions are classified as challenging areas using the MdC method. Six divisions (35.3%) are considered as appropriately managed by both CF and MdC methods. On the contrary, 23.5% of all divisions are suggested by both methods as challenging areas. Most divisions with an improving placement of waste facilities were located near the Canada-US border. The presences of major cities and total division population appear not key factors affecting the evolution of waste facility siting.

Keywords: Spatial statistics; Central Feature; Median Center; Geographical Information System; Strategical siting of waste facilities; Landfills and transfer stations

1. INTRODUCTION & LITERATURE REVIEW

1.1 – Background

Proper management of municipal solid waste (MSW) is an overwhelming concern around the globe (Yaashikaa et al., 2020; Di Maria et al., 2021). The mammoth amount of waste produced is a massive challenge for any waste management system due to human population and economic growth (Kim et al., 2013; Ajibade et al., 2019; Khajevand and Tehrani, 2019). MSW management issues mostly originated from rapid urbanization, inefficient management systems, and inadequate financial funding (Eskandari et al., 2015; Guo et al., 2021; Tsai et al., 2021). With a land area nearly 10 million km^2, Canada is the second largest country on the planet. According to Statistics Canada, Canadians send the majority of their MSW produced for permanent land disposal via landfills (Statistics Canada, 2020). In 2018, approximately 25.7 million tonnes of solid waste was disposed in Canadian landfills (Statistics Canada, 2020). The daily per capita generation rate is about 1.94 kg/day in Canada, which is about 30% higher than the global average of 1.2 kg/day (Kaza et al., 2018; Assuah & Sinclair, 2021). High MSW generation rates together with the heavy reliance on landfill disposal represents a pressing environmental burden to Canadians since both infrastructure and resources to efficiently manage MSW are lacking, particularly on many First Nations communities in Canada (Assuah & Sinclair, 2021; Karimi et al. 2022a). Anaerobic degradation of organic fraction of MSW such as food waste contributes to greenhouse gas emissions (Hannibal and Vedlitz 2018; Skeldon et al. 2018; Johansson 2021) and leachate production (Fallah et al. 2019; Pan et al. 2019b). Despite the immense number of opportunities to improve the Canadian MSW management sector, little published information is available about these potential improvements (Bolton and Curtis, 1990; Lakhan, 2015; Pan et al., 2019a).

1.2 – Literature review

While most recent studies on Canadian waste management have focused on the most populated province of Ontario (Baxter et al., 2016; Lakhan, 2016; Chowdhury et al., 2017; Karimi et al., 2021a), sparsely populated provinces, rural areas, and northern regions have received much less attention. Given the vast land area, heterogeneous climatic conditions, changing natural resources and economic opportunities, it is not uncommon for people to choose to live in clustered areas within the province. For example, about 90% of Saskatchewan's total population lives in the southern part of the province (Government of Saskatchewan, 2017), making design and operation of a province-wide effective MSW management system challenging and expensive for the policy makers (Kabir et al. 2022). The dependency on landfill disposal as the primary waste treatment process is more pronounced in the Canadian prairie provinces of Saskatchewan and Manitoba (Bruce et al., 2016; Wang et al., 2016; Karimi et al., 2020). Waste diversion and recycling programs have been wildly adopted in these two Canadian prairie provinces, but with varied degrees of success (Wang et al., 2016; Pan et al., 2019a; Bolingbroke et al., 2021). Lessons learnt from traditional MSW management studies focusing on urban areas and cities are less applicable to rural areas (Ghosh & Ng, 2021), and a local jurisdiction's decisions on the design and operation of a MSW system often impacts neighboring jurisdictions due to the interconnectivity of the municipalities (Sarra et al., 2019). As such, more data-driven studies at a regional level are needed to derive evidence-based MSW policy and strategical siting of waste facilities in the Canadian prairies (Richter et al. 2019b). Regional analysis is increasingly popular in environmental policy studies (Agovino et al. 2016; Gløersen et al. 2019; Tilt et al. 2022).

Transportation and transfer of municipal solid waste are inherently costly and energy intensive due to NIMBYism. Richter et al. (2021a, 2021b, 2021c) examined Canadian waste management systems in various municipalities and concluded that waste regions are difficult to compare directly due to the orographic, morphological, and territorial differences, which tend to affect the operation and performance of their respective waste management systems. Unlike most city-based waste studies, advanced spatial analytical tools such as Geographic Information Systems (GIS) and remote sensing (RS) techniques are typically used for MSW management studies in rural and remote regions (Khan et al., 2018; Richter et al., 2021c, 2021d). For example, GISs have been commonly applied for landfill siting (Moeinaddini et al., 2010; Karimi et al., 2020; Richter et al., 2021b) and other applications (Yadav et al. 2020; Slavík et al. 2021). Various analytical approaches such as overlay analysis, buffer analysis, and multi-criteria decision analysis have been successfully implemented in GIS studies (Kamdar et al., 2019; Richter et al., 2019; Karimi et al., 2021b). Gorsevski et al. (2012) utilized satellite imagery to extract elevation, slope, and urban area layers to evaluate landfill sites in Macedonia. Khan et al. (2018) sited waste conversion facilities in Alberta, Canada by integrating a GIS and an analytic hierarchy process technique. Richter et al. (2019a, 2019b) combined RS and vector data using a GIS to examine the suitability of landfill sites and applied Thiessen polygons to study their areas of influence. Karimi et al. (2020) utilized nighttime light imagery, land surface temperature, and Thiessen polygons to evaluate potential landfill sites in Saskatchewan, Canada. Occasional cloud coverage and lower image resolution of civilian satellite imagery are known hindrances of RS techniques (Karimi et al., 2021a). Moreover, expert opinions are typically required for the analytic hierarchy process and multi-criteria decision analysis used in many GIS-based waste studies (Geneletti, 2010; Gorsevski et al., 2012), and inconsistencies among experts are not uncommon.

Centroidal Voronoi Tessellation (CVT) has been explored by researchers to optimize optimal partitions (Freeman et al., 2014; Di et al., 2020; Huang et al., 2020). Richter et al. (2019a, 2021a, 2021d) recently developed an original data-driven analytical framework using geometric centroids to construct Thiessen polygons for optimization of Canadian waste management regions (Richter et al., 2021a, 2021d). Specifically, standard deviations of landfill counts, populated places, and road length were minimized to determine optimized tessellations in Saskatchewan and Nova Scotia (Richter et al., 2019a). Richter et al. (2021d) further proposed an alternative CVT algorithm using the Central Feature (CF) tool and suggested that the optimization associated with CF-derived seed points is generally more representative in their study.

1.3 – Study objectives, novelty, and contributions

The current study proposed a simplified data-driven GIS-based technique to examine the spatial distribution of waste facilities at a regional level. The study objectives are to (i) examine the geospatial distribution of landfills and transfer stations in Saskatchewan, Canada, from 2018 to 2020 based on changes in Euclidean distance computed by both the Central Feature (CF) and median center (MdC) spatial statistical tools, and (ii) map, analyze, and interpret the resulting ratings with respect to the temporal evolution of the waste facility locations in Saskatchewan.

The design and operation of MSW management systems in rural areas with scarce populations are often neglected in literature and are less well understood (Ghosh & Ng, 2021). Unlike most GIS-based waste studies focusing on a metropolitan area or a city (Forouzesh et al., 2021; Karimi et al., 2021a; Torkayesh et al., 2021), this study analyzes the temporal and spatial evolution of landfills and transfer stations at a regional level. The aggregation of spatial statistic tools to evaluate temporal changes of the waste facility's strategical locations is original. Furthermore, both CF and MdC spatial statistical tools have been utilized in the overall assessment. It is hypothesized that the combination of the CF and MdC tools will help to provide a more comprehensive assessment of the changes in the locations of waste facilities in Saskatchewan. The proposed analytical approach is also of interested to waste policy makers.

2. MATERIALS AND METHODOLOGY

2.1 – Study Area and study period

Saskatchewan, located in the heart of Canadian prairies, has traditionally lower waste diversion rates than the national average (Pan et al., 2019a, Bolingbroke et al., 2021). However, Saskatchewan saw a rapid increase of 15% in waste diversion from 2016 to 2020, second only to Quebec with a 16% increase (Statistics Canada, 2020). In addition to a stronger province-wide waste recycling program, Saskatchewan is moving towards landfill regionalization (Richter et al., 2021b) and has closed many of its landfills. Saskatchewan witnessed a 54% reduction in the number of landfills and a 55% increase in the number of transfer stations in the past few years (Ghosh & Ng, 2021). In this study, the temporal changes on the geospatial distribution of landfills (LF) and transfer stations (TS) in Saskatchewan during a two-year period (2018 - 2020) are examined using the proposed simplified analytical framework. MSW collection and transportation is one of the most expensive functional elements (Vu et al., 2018; 2020; Peng et al. 2023), and strategically located waste facilities help to minimize system cost. In this study, LFs are permanent disposal sites for MSW, and TSs are temporary MSW storage facilities used to improve MSW transportation efficiency (Ağaçsapan and Çabukb 2020).

Saskatchewan is shown in red in the embedded map in Table 1. Saskatchewan has over 650,000 km^2 of land area and shares its north, east, south, and west borders with the Northwest Territories, Manitoba, the United States, and Alberta, respectively. Saskatchewan's total population grew steadily between the census year of 2016 and an estimate 2020 (Statistics Canada, 2021b). Federal census subdivisions (hereby known as "divisions") are used by the Federal government for statistical data collection and analysis (Statistics Canada, 2011). There are a total of 18 divisions in Saskatchewan, with the majority of the inhabitants residing in the first 17 divisions within southern Saskatchewan.

Table 1: The Canadian province of Saskatchewan and related statistics.

Item	Values
Total Area	651,000 km^2
Total population	1,098,400 (2016 census) 1,177,800 (2020 estimate)
Number of Census divisions	18
Land area	318,300 km^2 (Divisions 1-17) 270,000 km^2 (Division 18 only)

The characteristics of the 17 divisions are shown in Table 2. Divisions 11, 6, and 15 are the most populated divisions. The population densities of the divisions ranged from 0.51 to 18.17 people/km^2. On average, there are 9.5 towns and cities in a division, and about 5,700 people per town or city. In this study, 10 divisions (#1, 2, 3, 4, 5, 8, 9, 13, 14, & 17) are termed as external divisions, with at least one neighboring border with other jurisdictions, and 7 divisions (#6, 7, 10, 11, 12, 15, & 16) are considered as internal divisions, which fall completely within the province.

2.2 – Data acquisition and sources

All major shapefiles used in the study were downloaded from the provincial government’s open data portals (Government of Saskatchewan, 2021). The Geospatial distributions of LFs and TSs were obtained from the Saskatchewan Geohub (Saskatchewan Solid Waste Management, 2021). Saskatchewan’s census subdivision boundaries were obtained from the 2016 Census boundary files (Statistics Canada, 2016). GIS shapefiles for locations including towns and cities (T/C) in Saskatchewan were obtained from OpenStreetMap (2021). The most recent 2021 dataset for major T/Cs is used, and no significant changes during the 2-year study period are assumed. The summary of the sources of all input parameters is tabulated in Table 3.

Table 2: Characteristics of the 17 divisions in Saskatchewan, Canada

Census Division	Population (2016 data)	Land area (km^2)	Pop density (ppl/km^2)	Number of major towns or cities (T/C)	Number of people per T/C	Internal or External division
1	31,800	15,000	2.12	12	2,650	External
2	22,850	16,850	1.36	5	4,570	External
3	12,600	18,550	0.68	7	1,800	External
4	10,850	21,400	0.51	3	3,620	External
5	31,750	14,800	2.15	16	1,980	External
6	262,850	17,550	14.98	17	15,460	Internal
7	47,200	18,850	2.50	4	11,800	Internal
8	30,700	22,250	1.38	8	3,840	External
9	35,650	15,300	2.33	10	3,570	External
10	16,550	12,200	1.36	10	1,660	Internal
11	303,400	16,700	18.17	17	17,850	Internal
12	24,000	13,900	1.73	7	3,430	Internal
13	23,200	17,300	1.34	7	3,310	External
14	36,000	33,800	1.07	9	4,000	External
15	85,900	19,600	4.38	15	5,730	Internal
16	38,000	21,800	1.74	8	4,750	Internal
17	47,900	22,450	2.13	7	6,840	External
Average	***62,424***	***18,724***	***3.52***	***9.5***	***5,697***	***N/A***

Table 3: Summary of vector data set

Vector Data	Feature Type	References
Landfills (LF)	Point	Government of Saskatchewan, 2018, 2020
Transfer stations (TS)	Point	Government of Saskatchewan, 2018, 2020
Major towns/cities (T/C)	Point	OpenStreetMap, 2021
Census divisions	Polygon	Statistics Canada, 2016
Saskatchewan boundary	Polygon	Statistics Canada, 2016

2.3 – Geospatial analysis and workflow

Geospatial analysis is conducted using ArcGIS. The general workflow of the study is shown in Figure 1. Details on the input tessellations are first collected, verified, and processed. Two distinct GIS spatial statistical tools known as CF and MdC are then used to identify the representative locations of LFs, TSs, and T/Cs in Saskatchewan in 2018 and 2020. As further discussed in Sections 2.3.1 and 2.3.2, CF selects the most central point from a group of existing points, whereas MdC selects a theoretical median point from the group. Euclidean distances between the representative locations of the waste facilities (LFs and TSs) and the T/Cs (the communities) are then computed in all cases. In this study, the change in distance is defined as the changes of Euclidean distance between CF (or MdC) of the waste facilities to the CF (or MdC) of the major T/Cs during the two-year period. Temporal and spatial and changes using CF and MdC are examined using a radar chart. Both CF and MdC results are then combined to develop an overall rating for the strategic placement of waste facilities in Saskatchewan. Since travel distances are directly related to system cost, knowledge on the spatial and temporal distributions of the waste facilities helps facilitate data-driven waste policy that are more cost-effective and environmentally sustainable.

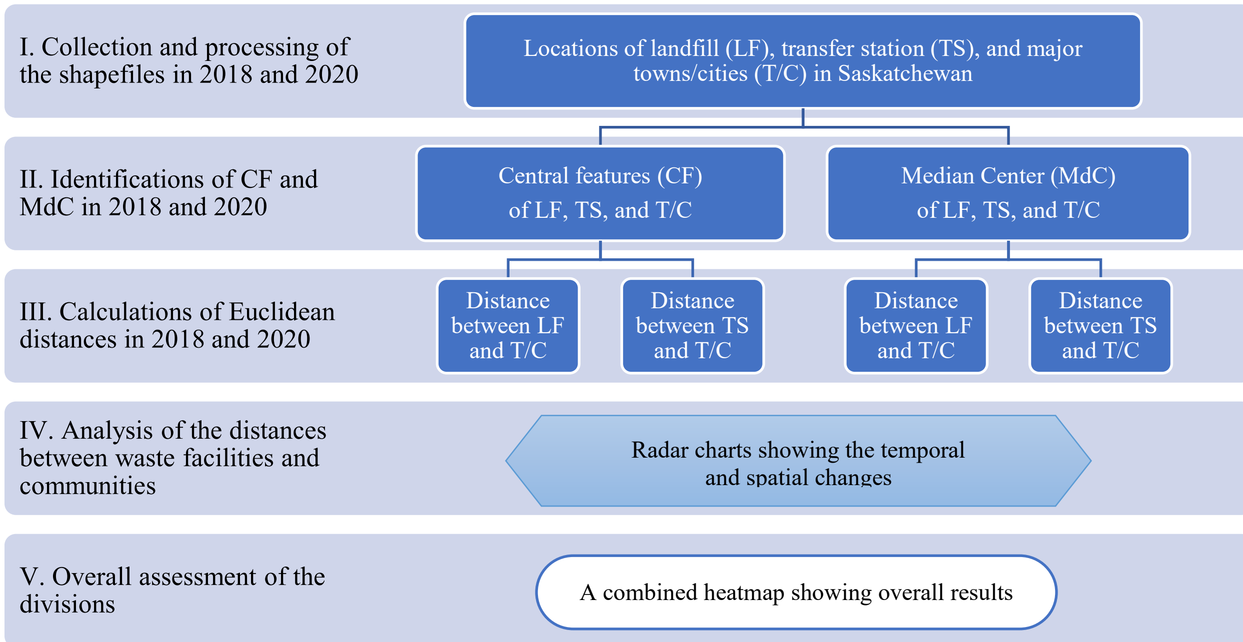

Figure 1: Workflow of the study.

It should be noted that Saskatchewan's division 18 (northern Saskatchewan) is excluded in this study. The proposed analytical framework examines the changes in Euclidean distance between the waste facilities and major T/Cs over a span of two years. In 2018, division 18 had zero transfer stations. Thus, neither of the spatial statistical tools can be applied nor the changes in distance can be computed. Although division 18 (representing about 45% of the total land area of the province, Table 1) is excluded, the division is scarcely populated and has the lowest population density among the divisions (Ghosh & Ng, 2021). It contributes little to the overall design and operation of a province-wide MSW management system.

2.3.1 – Central feature

CF is the spatial statistics feature which characterizes the most centrally located feature in a point, line, or polygon feature class (Esri, 2021a). The CF tool has been commonly considered in distance minimization problems (Esri, 2021a) and has been successfully applied in waste management regionalization problem (Richter et al. 2021d). Figure 2a shows the geospatial distribution of major towns and cities in Saskatchewan (black stars), which receive regular MSW collection and disposal services. More towns and cities are located within southern Saskatchewan (Figure 2). For example, only a single major town is located in division 18 in the northernmost division despite its size. On the contrary, 10 T/Cs are located in the tenth division and 17 T/Cs are located in the sixth division. Unlike MdC, the CF tool selects a pre-existing point in the feature input layer as the output. As shown in Figures 2b and 2c, the location of the CF (yellow square) coincides with a pre-existing major T/Cs (black star) located centrally. This property is unique to the CF tool, making it more intuitive from a practical viewpoint.

2.3.2 – Median center

MdC is the spatial statistics feature that identifies the location to minimize the overall Euclidean distance to the features in a dataset (Esri, 2021b). Figure 2b and 2c show the MdCs (green circles) in divisions 10 and 6, respectively. Unlike the CF, the MdC is purely mathematically constructed, and the coincidence of a pre-existing feature is not required. Euclidean distance is a tool which describes, in a cartesian grid, each cell's relationship to a source or group of sources based on a straight-line distance (Esri, 2021c). The MdC or $d^a{}_i$ is calculated through iterations, where at each step 'a' in the algorithm, a candidate point (X^a, Y^a) is considered, and processed to minimize the Euclidean distance 'd' to all features 'i' in the dataset (Esri, 2021c). Mathematically, it can be expressed by equation 1 (Esri, 2021d).

$$d_i^a = \sqrt{(X_i - X^a)^2 + (Y_i - Y^a)^2} \qquad [1]$$

MdC should not be confused with mean center. An edge which MdC has over mean center is while the latter provides a point which is an average value of X and Y coordinates for the involved feature centroids, MdC uses an algorithm which iteratively search the minimum overall Euclidean distance, making it less sensitive to outliers. Thus, MdC was chosen over mean center tool in this study. Depending on the spatial distributions of the points of interest, the MdC and CF can be very similar (Figure 2b), or quite different (Figure 2c).

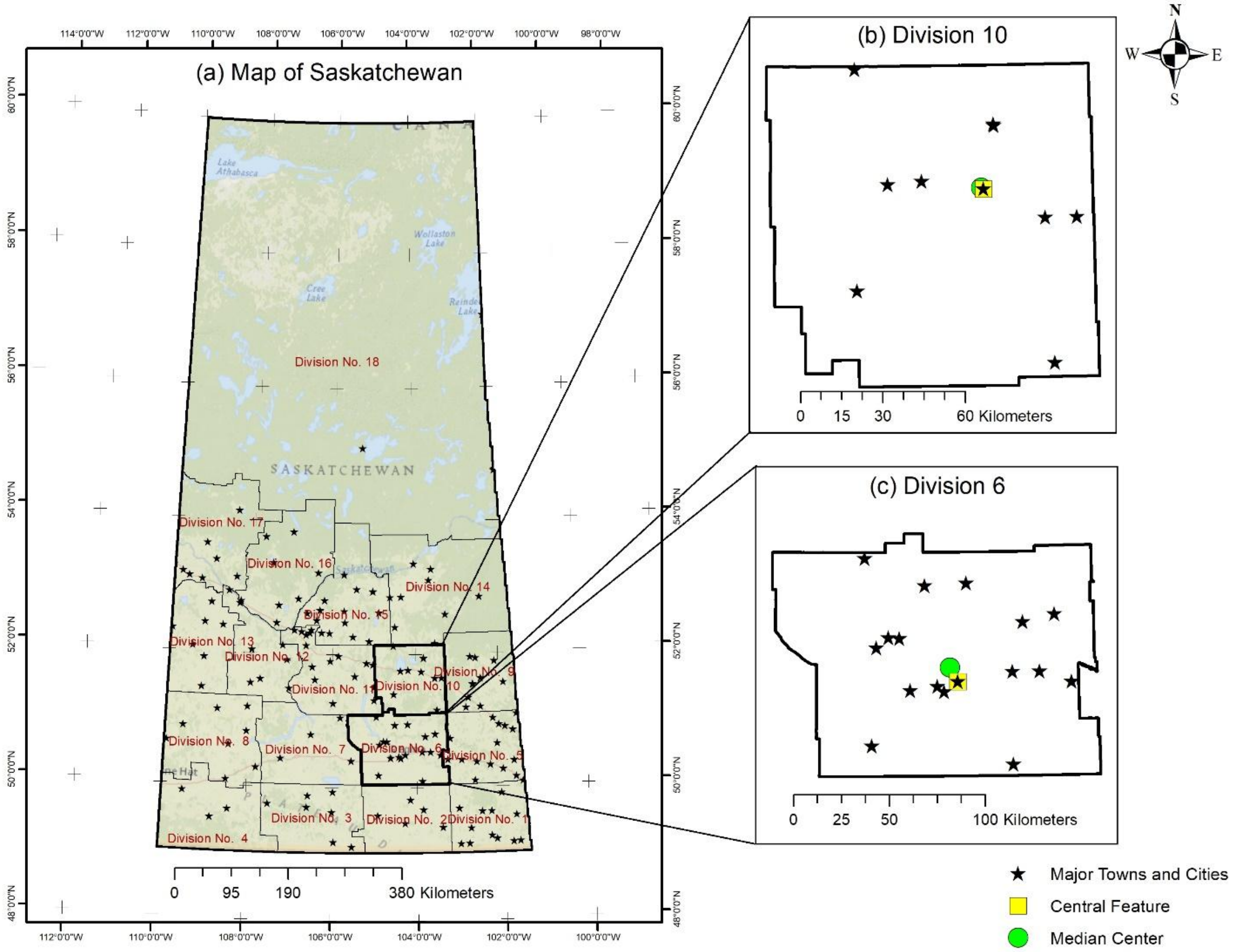

Figure 2: (a) Major towns/cities in 18 divisions of Saskatchewan; (b) central feature and median center of major towns/cities in Division 10, and (c) central feature and median center of major towns/cities in Division 6.

3. RESULTS & DISCUSSION

3.1 Central Feature

Figure 3 shows the changes in Euclidean distances between CF of the waste facilities to the CF of the major T/Cs in the province, for all 17 divisions during the 2-year period. A positive change means increasing average distance between waste facilities and communities, and a negative change means a closer proximity between waste facilities and communities.

The changes in Euclidean distance for LFs (shown by green solid line) show significant variations between divisions, ranging from -39.6 km (division 13) to +38.0 km (division 8). The TSs (shown by orange dashed line) also show a similar range of variations, ranging from -67.8 km (division 4) to +9.5 km (division 7). The differences in distance ranges suggest that Saskatchewan transfer stations in 2020 are located significantly closer to major T/Cs as compared to 2018. A closer look at Figure 3 reveals that the area encompassed by the solid green line is larger than that of the broken orange line (Figure 3), suggesting more LFs were generally moved further away from T/Cs in 2020. The results generally suggest an improved level of landfill regionalization in the province, consistent results are reported in Ghosh & Ng (2021). However, the level of landfill regionalization is not consistent among the divisions, reflecting the diverse needs and preferences of the local residents.

Transfer stations are commonly used to improve system efficiency of a MSW collection system (Ağaçsapan and Çabukb, 2020; Lou et al. 2020). TSs are also used in Saskatchewan due to increasingly strict provincial regulations regarding landfill design and operation, driving up local landfill construction and environmental costs and leading to landfill regionalization. Ideally, the changes in distances for LFs and TSs should have compensated for one another, i.e., an increasing distance for LFs should have been balanced by a reducing distance for TSs and vice versa. These opposing trends are indeed observed in 52.9% of the 17 divisions (divisions 1, 2, 3, 4, 8, 9, 11, 13, and 16). For example, division 1 experienced similar ranges but opposite trends in distances between LFs and TSs. Between 2018 and 2020, landfills are on average about 5km closer to the communities in division 1, while the transfer stations are on average 5km further away. On the other hand, division 8 saw on average a 38km increase in distance between landfills and communities, while the transfer stations were on average 10km closer. Given the similarities of function between these two waste facilities, an opposing trend is more desirable, suggesting more efficient use of waste facilities in 2020.

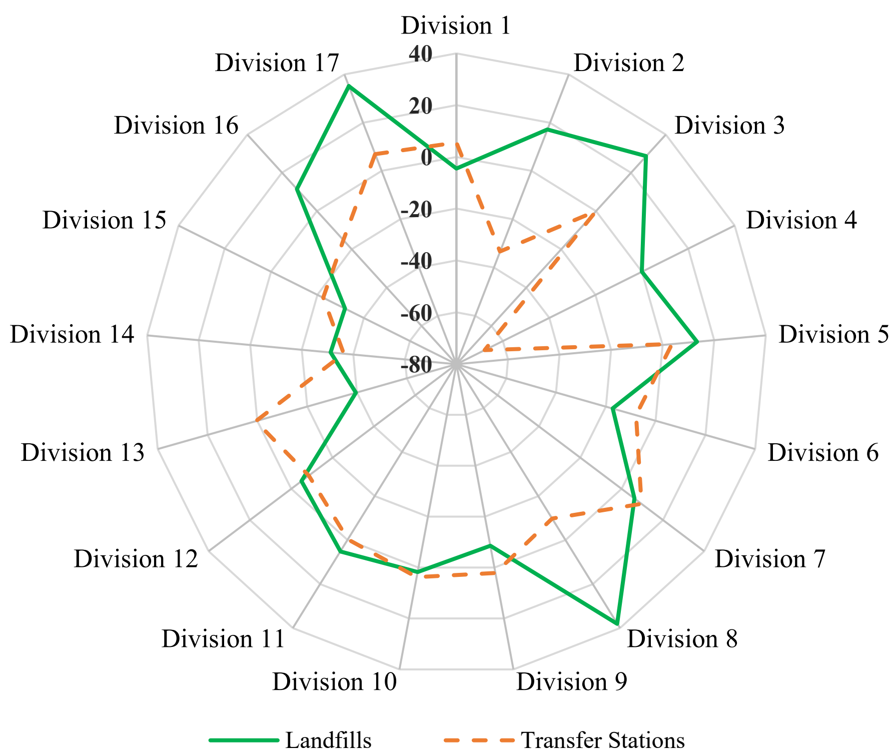

Figure 3: Changes in Euclidean distance between central feature of landfills and transfer stations and major towns/cities (2018 and 2020)

Figure 3 shows that about 23.5% of divisions (divisions 5, 7, 10, and 17), waste facilities generally went further away from communities in 2020. This is represented by positive changes of Euclidean distance in both LF and TS. The results suggested accessibility to MSW services in these four divisions is generally reduced in 2020. As discussed in the subsequent paragraph, all of these are internal divisions which do not share inter-provincial borders with Alberta and Manitoba, or international borders with the United States. The reason behind the reduced accessibility to MSW facilities in divisions #5, 7, 10, 17 in 2020 is not clear. However, it appears the reduced accessibility trend is not related to differences in population densities and the average size of the T/C. For example, the population densities of the 4 divisions ranged from 1.36 to 2.50 people per km^2, on par with other divisions (Table 2). Population by T/C in the 4 divisions appear on both sides of the average, ranging from 1,655 to 11,800 people per town/city.

In divisions 6, 12, 14, and 15, the opposite trend is observed. Overall MSW service accessibility improved in these 4 divisions (23.5% of divisions), as both landfills and transfer stations were now closer to communities. It is interesting to note that divisions 6 and 15 are the second and third most populated divisions, with 223,850 and 85,900 habitants, respectively (Table 2). The results suggested that in general more residents have been benefited from the improved accessibility in 2020. This finding is important to the waste policy makers for prioritization of waste management resources. However, more analysis is needed to fully assess the true efficiency of the waste facilities.

In Canada, MSW transportation across the inter-provincial and international borders is not uncommon, as waste is often treated as a resource or good under trade agreements. Given that the waste management sector is a lucrative industry with a global market size valued at $1,612 billion in 2020 (Pawar and Sawant, 2021), one would expect the different geospatial distribution of waste facilities between internal and external divisions in Saskatchewan to better capitalize on the profits of MSW importation. However, no obvious geospatial pattern is observed between internal and external divisions. For example, external divisions 5 and 17 and internal divisions 7 and 10 experienced similar positive changes in distances (Figure 3). The results suggest the current geospatial distributions of Saskatchewan MSW facilities failed to take full advantage of the potential market of MSW importation. Strategically placement of waste facilities is recommended in the 10 external divisions (Table 2) from an economical perspective. According to Pawar and Sawant (2021), the global waste management market size is expected to reach over $2,480 billion by 2030.

3.2 Median Center

Figure 4 shows the changes in Euclidean distances using MdC tool. Similar trends are seen between the CF (Figure 3) and MdC (Figure 4) spatial statistics, but subtle differences are also observed. Specifically, smoother LF and TS curves are observed in Figure 4 as there are less abrupt changes among divisions using the MdC tool. This is probably due to the fact that the MdC is mathematically constructed with no additional physical spatial constraint.

The changes in Euclidean distance for landfills ranged from -20.1 km (division 15) to +38.9 km (division 8). The transfer stations show a slightly larger range of variations, ranging from -60.5 km (division 4) to +17.9 km (division 14). Similar to CF, the MdC results suggest that Saskatchewan transfer stations in 2020 were generally located closer to the communities. The area encompassed by the solid green line is again larger than that of the broken orange line (Figure 4), suggesting an improved level of landfill regionalization in the province.

Compensating trends of the LFs and TSs are observed in 58.8% of the 17 divisions (divisions 1, 2, 3, 4, 5, 7, 8, 11, 12, and 14), suggesting a more efficient use of the waste facilities in 2020. These divisions are considered as optimized, as each community is served by a landfill or transfer station, but not both. Seven out of ten of these divisions are external divisions (Table 2), however, no definite conclusion can be made regarding the role of border sharing on the strategically siting of waste facilities in Saskatchewan. As discussed in Section 3.1, more waste facilities are recommended in the external divisions for waste importation.

According to MdC spatial statistics, Division 17 is the only division which experienced positive changes in Euclidean distances for both LFs and TSs. This reduced accessibility of waste facilities appears not to have originated from population density (2.13 ppl/km^2) or the size of T/C (6,840 people per town) in the division. More waste facilities are recommended in division 17.

Negative changes in Euclidean distances are observed in 35.3% of the divisions (#6, 9, 10, 13, 15, and 16), suggesting shorter average distances between waste facilities and communities and therefore improved accessibility. Since divisions 6 and 15 are the second and third most populated divisions (Table 2), the results suggested that a higher proportion of residents benefited from the improved accessibility in 2020. Improvement in MSW service accessibility is desirable, however, the efficiency of a MSW system should be carefully assessed (Bolingbroke et al. 2021).

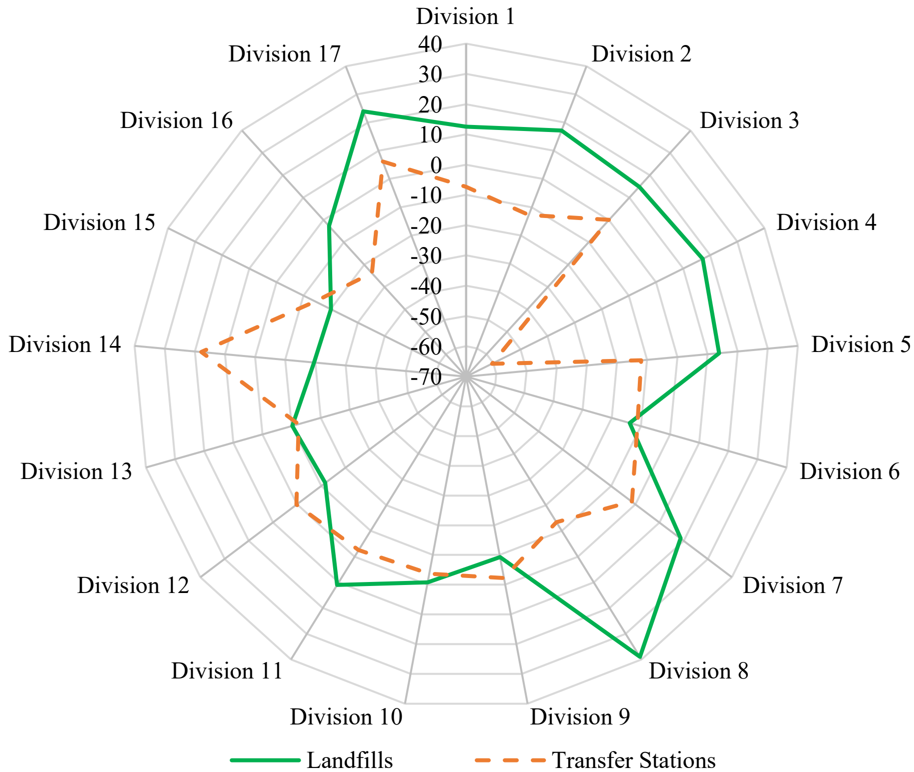

Figure 4: Changes in Euclidean distance between median center of landfills and transfer stations and major towns/cities (2018 and 2020)

3.3 – Overall Ranking utilizing CF and MdC

It appears both spatial statistical tools (CF and MdC) are capable of systematic capturing the temporal and spatial changes of the waste facilities in Saskatchewan from 2018 to 2020. As such, the overall assessment is produced by combining the results from both spatial statistical tools. Figure 5 separately shows the assessments of the changes in strategical locations of the waste facilities using CF and MdC during the study period. Divisions in green are deemed appropriately managed since opposing changes in Euclidean distance are detected from the waste facilities during the study period. The waste facilities in red divisions are believed to be strategically sited because landfills and transfer stations generally do not exist within a close proximity. The presence of an operational landfill makes a transfer station in proximity obsolete, and vice versa. Red divisions represent divisions with similar changes (positive or negative) in Euclidean distances during the study period. If both landfills and transfer stations are moved closer to communities, the efficiency of these waste facilities should be quantified. If both landfills and transfer stations are moved further away from the communities, accessibility to MSW services in the division is considered to be negatively impacted. Red divisions are considered as challenging areas and more work is recommended on the strategically planning of future waste facilities. A total of 8 (47.1%) divisions are classified as challenging areas using CF, whereas 7 divisions (41.1%) are classified as challenging areas by the MdC method.

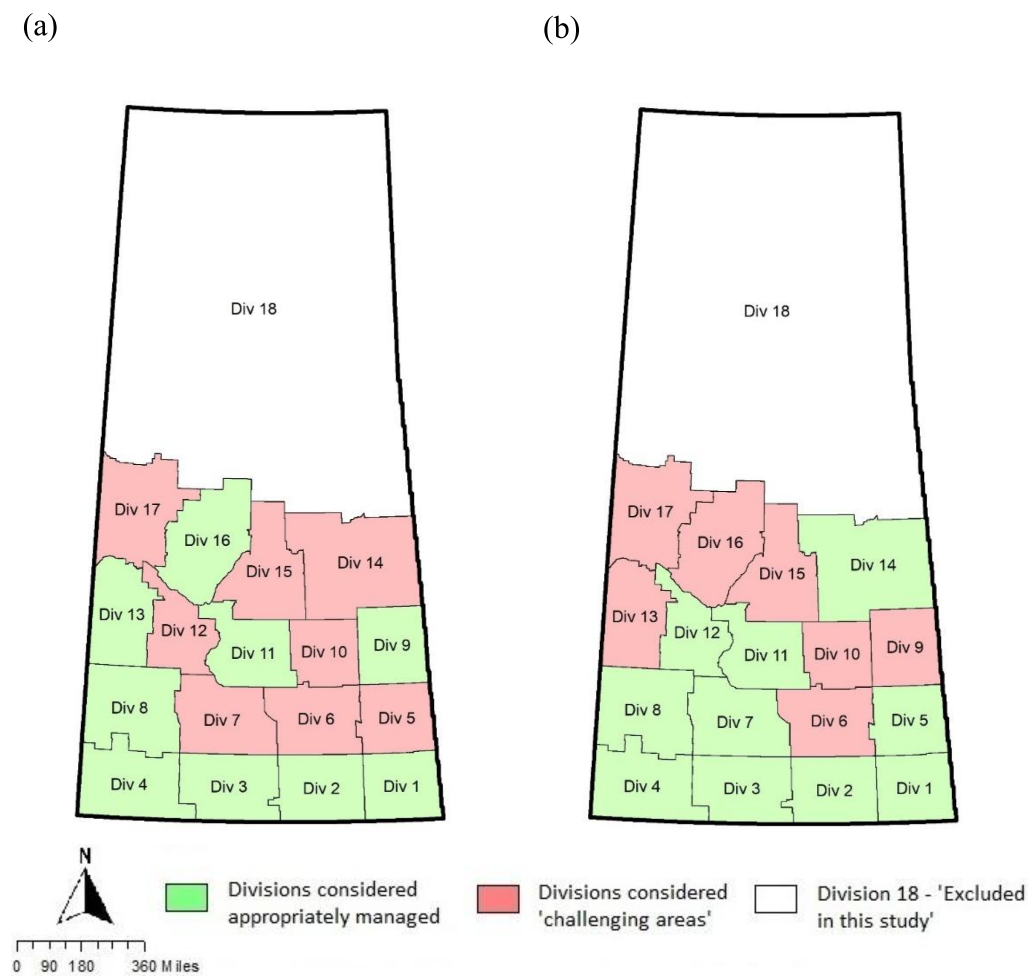

Figure 5: Temporal evolution of the spatial distribution of waste facilities using the (a) central feature method, (b) median center method.

Figure 6 graphically shows the overall heat map in Saskatchewan, superimposing maps in Figures 5a and 5b. A total of 6 divisions (divisions # 1, 2, 3, 4, 8, and 11), or 35.3% of all divisions, are considered as "appropriately managed" during the study period by both CF and MdC methods. On the contrary, divisions 6, 10, 15, and 17 are the divisions which are suggested by both methods as challenging areas, representing 23.5% of all divisions. The siting of waste facilities in these four divisions should be fully assessed, or relevant waste policy should be implemented. Divisions 5, 7, 9, 12, 13, 14, and 16 are the divisions which deserve a closer look once the challenging areas have been fully rectified.

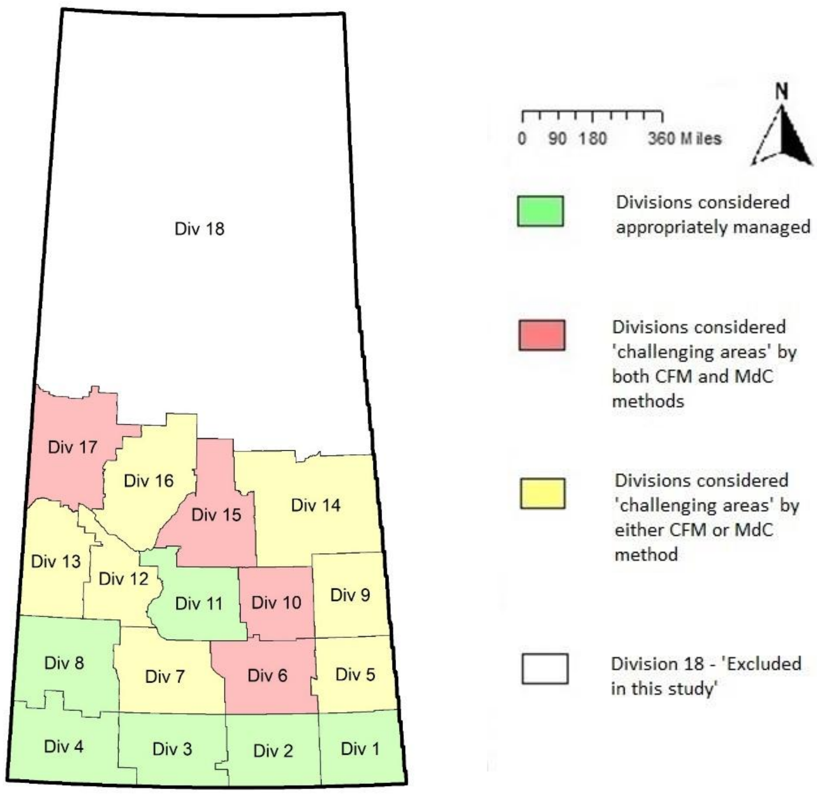

Figure 6: Overall ratings on the placement of landfills and transfer stations during 2018 and 2020

It appears that most divisions with appropriately placed waste facilities are located near the US-Canada border (divisions 1-4). The two most populated cities in Saskatchewan, Saskatoon and Regina, located in divisions 11 and 6, respectively, have completely opposite ratings (Figure 6). Similarly, division 11 (the most populated division) and division 4 (the least populated division) are both appropriately managed. It can be concluded that the presences of major cities and division population are not key factors affecting the evolution of waste facility siting during the study period. A closer look at the land area, population density, and the size of T/C (Table 2) reveals no observable relationships with the ratings. The results highlighted the complex nature of waste management systems and the intercorrelations between various socio-economic factors on strategical waste facilities siting. As discussed in Section 3.4, a GIS-based analytical framework is developed as a screening tool to systematically assess the temporal and spatial evolution of waste facilities in a region. The proposed decision support tool is useful to evaluate the waste facility distribution in a given jurisdiction, however it should not be confused with a definite and sole assessment tool on the effectiveness of waste facilities placement.

3.4 – Advantages and limitations

The proposed analytical framework examines the temporal and spatial and evolution of waste facilities at a regional level and is easy to implement by policy makers. No subjective expert opinions are required. One of the limitations of this simplified analytical framework is the use of Euclidean distance, a tool which measures distance in straight-line. Thus, existing road network, geographical features, individual T/C population, and changes in elevation are not directly addressed, making it more suitable in sparsely populated rural regions and grasslands with plain and flat landscapes such as Saskatchewan. A weighting system can however be added to the analytical framework for mountainous regions with heterogeneous geographical features, or regions with low-capacity waste facilities. Only spatial location of the towns and cities are considered in this study, and the physical footprint of the communities is not directly taken into account. The proposed method is more appropriate for a study at regional level; for city-based studies, the actual footprint of the cities should be explicitly considered. In addition, environmental, social, and economic aspects of the waste facilities must be comprehensively examined for a complete assessment of the strategical siting of waste facilities.

Given the continuous population growth in rural regions, many Canadian local governments began to consider regional development policies (Richter and Ng 2018). The results of this study highlight various conflicting factors of system cost and environmental impacts on waste regionalization for the policy makers. The success of a MSW management regionalization plan relates directly to the spatial distributions of residents and servicing waste facilities, as well as the economies of scale. Since waste management plans and contributing factors are site-specific, system optimization are strongly recommended (Karimi et al. 2022b; 2022c).

4. CONCLUSIONS

A simplified GIS-based analytical framework is proposed to examine the temporal and spatial distribution of waste facilities at regional level. The study objectives are to examine geospatial distribution of LFs and TSs in Saskatchewan during the two-year study period using both CF and MdC spatial statistics. Ratings are computed from the changes in Euclidean distances between the waste facilities and communities. The temporal changes of the waste facilities in Saskatchewan are graphically assessed using maps. Strategic siting of waste facilities in rural areas is often neglected and less well understood in the literature. The aggregation of both CF and MdC spatial statistical tools to evaluate the evolution of the temporal and spatial changes of waste facilities is original.

Both the CF and MdC results suggest that Saskatchewan transfer stations in 2020 were located significantly closer to communities compared to two years ago and landfills were moved further away from communities in 2020. The results suggest an improved level of landfill regionalization in the province. However, the level of landfill regionalization is not consistent among the divisions. Smoother LF and TS radial curves are observed using the MdC tool, probably due to the lack of physical constraints associated with the spatial statistic. About 47.1% of the divisions are classified as challenging areas using the CF method, whereas only 41.1% of the divisions are classified as challenging areas using the MdC method.

It appears that the combination of the CF and MdC tools provides a more comprehensive assessment on the changes in locations of waste facilities in Saskatchewan. A total of 6 divisions (divisions # 1, 2, 3, 4, 8, and 11), or 35.3% of all divisions, are considered as appropriately managed by both CF and MdC methods. On the contrary, 23.5% of all divisions are suggested by both methods as challenging areas. It appears that most divisions with an improving placement of waste facilities were located near the Canada-US border. It can be concluded that the presences of major cities and total division population are not key factors affecting the evolution of waste facility siting during the study period. A closer look at the land area, population density, and the average size of T/C reveals no observable relationships with the overall ratings. The results highlight the complex nature of waste management systems for the policy makers. The simplified analytical framework is intended for a systematic assessment of the temporal and spatial evolution of waste facilities in a region. The decision support tool should not be used as a definite assessment tool for the effectiveness of waste facilities placement.

List of acronyms

- CF: Central feature
- CVT: Centroidal Voronoi Tessellation
- GIS: Geographical Information System
- MdC: Median center
- MSW: Municipal solid waste
- RS: Remote sensing
- LF: Landfill
- TS: Transfer station
- T/C: Town or city

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Data Availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.