



Integrating Geographic Information System network analysis and nighttime light satellite imagery to optimize landfill regionalization on a regional level

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Abstract

More than half of financial resources allocated for municipal solid waste management are typically spent on waste collection and transportation. An optimized landfill siting and waste collection system can save fuel costs, reduce collection truck emissions, and provide higher accessibility with lower traffic impacts. In this study, a data-driven analytical framework is developed to optimize population coverage by landfills using network analysis and satellite imagery. Two scenarios, SC1 and SC2, with different truck travel times were used to simulate generation-site–disposal-site distances in three Canadian provinces. Under status quo conditions, Landfill Regionalization Index (LFRI) ranging from 0 to 2 population centers per landfill in all three jurisdictions. LFRI consistently improved after optimization, with average LFRI ranging from 1.3 to 2.0 population centers per landfill. Lower average truck travel times and better coverage of the population centers are generally observed in the optimized systems. The proposed analytical method is found effective in improving landfill regionalization. Under SC1 and SC2, LFRI percentages of improvement ranging from 58.3% to 64.5% and 22.7% to 59.4%, respectively. Separation distance between the generation and disposal sites and truck capacity appear not a decisive factor in the optimization process. The proposed optimization framework is generally applicable to regions with different geographical and demographical attributes, and is particularly applicable in rural regions with sparsely located population centers.

Keywords Landfill Regionalization · Nighttime Light Satellite Imagery · GIS Network Analysis · Optimized Municipal Solid Waste Collection System · Canadian Northern and Rural Areas

Introduction & literature review

Municipal solid waste collection costs and impacts

Municipal solid waste (MSW) collection and transportation have been identified as a major share of operational costs in MSW management (Akhtar et al. 2017; Aliahmadi et al. 2020; Sanjeevi and Shahabudeen 2016), ranging from approximately 40% to 85% of total budgets in urban and rural areas (Behi et al. 2021; Richter et al. 2018; Yadav and Karmakar 2020). Thus, even a slight

enhancement in collection efficiency would result in significant savings (Erfani et al. 2017; Hannan et al. 2020; Rızvanoğlu et al. 2019). In addition, there are often environmental and social concerns associated with inefficient waste collection (Xue et al. 2015; Erfani et al. 2017). These concerns include but are not limited to increased greenhouse gas emission (Gilardino et al. 2017; Budzianowski 2016), elevated traffic congestion and fuel consumption (Erfani et al. 2017; Vu et al. 2018), extended nuisance including physical, chemical, and biological stressors in waste generation sites (Hannan et al. 2018; Hua et al. 2017), and lessened geographical coverage of populated regions (Akhtar et al. 2017). As a result, an effective MSW collection system with strategically sited landfills would be of practical importance to regulators and policymakers seeking ways to reduce operational costs while addressing environmental and social concerns (Hannan et al. 2018; Taşkın and Demir 2020).

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MSW collection system and landfill site selection

The literature shows that landfill siting and suitability analysis are mostly done using multicriteria decision-making tools (Karimi et al. 2020; Rahimi et al. 2020; Rezaeisabzevar et al. 2020), and network analysis and route optimization are not explicitly considered. On the other hand, the majority of waste collection studies focus on the conventional vehicle routing problem (VRP) as a proxy for optimization of MSW collection system (Aliahmadi et al. 2020; Reed et al. 2014; Hannan et al. 2018) with predetermined disposal sites. VRP defines the shortest path between waste generation points and waste facilities such as landfills (Reed et al. 2014; Vu et al. 2018). Different heuristic and meta-heuristic methods such as genetic algorithm (Viotti et al. 2003; Karadimas et al. 2007) and ant colony optimization (Islam and Rahman 2012; Liu and He 2012; Aksaraylı 2018) were successfully applied and reported. These algorithms provide suitable solutions for waste collection problems (Hannan et al. 2018), particularly with respect to a given city or urban area. However, population coverage of landfills (the number of population centers served by a landfill) is often not directly addressed in these city-focused waste collection studies. Ideally, both urban and rural areas should be incorporated into a regional setting in the establishment of a sustainable waste management system (Franco et al. 2021; Karimi et al. 2022b).

Given the size of rural areas, Geographical Information System (GIS) and Remote Sensing (RS) data are typically used to site regional landfills. GIS and RS data have been successfully utilized in dealing with different aspects of MSW management problems, including landfills regionalization (Richter et al. 2019b, 2021a, b), siting and suitability analysis (Richter et al. 2019a; Ajibade et al. 2019; Chabok et al. 2020), monitoring environmental anomalies in the vicinity of disposal sites (Karimi et al. 2021a, b, 2022a; Mahmood et al. 2017), and collection optimization methods (Vu et al. 2018; Rızvanoğlu et al. 2019; Yousefloo and Babazadeh 2020). The establishment of a MSW management system in urban and rural areas involves large geospatial areas and many spatial variables. This complexity can be easily dealt with using various GIS tools and assumptions (Aliahmadi et al. 2020). Route optimization models and network analysis datasets in GIS such as storage bin locations, demand points, waste facilities, road types, and speed limits are reported to be effective in a Singaporean study (Xue et al. 2015). In addition to enhancing the collection system with the VRP algorithm, GIS is able to evaluate different practical scenarios including shortening travel time and/or travel distance, incorporating specific locations along the route, designing different accumulated travel time for the collection fleet, and considering capacity constraints

for collection trucks (Huang and Lin 2015; Vu et al. 2018). Recently, Karimi et al. (2020) have integrated a multicriteria decision-making tool with GIS in a landfill site suitability study in Canada, utilizing constraints such as land surface temperature, slope, distance to water resources, presence of protected areas, airports, and urban zone.

Despite the popularity of GIS and RS data in waste studies, the literature shows that GIS network analysis is often not directly used to site landfills for optimization of population coverage (i.e., maximizing the number of population centers per landfill) at a regional level. An effective MSW collection system should be able to cover the majority of population centers within a jurisdiction, as they are the major generation points of waste (Erfani et al. 2017; Abdallah et al. 2019; Yousefloo and Babazadeh 2020). It is believed that the absence of properly located landfills within the MSW collection network increases the likelihood of illegal dumpsites (Glanville and Chang 2015; Mahmood et al. 2017; Richter et al. 2021c). This is particularly important in remote rural areas where population centers are less well defined than cities and urban centers, and can have significant environmental ramifications. For example, six first nation communities located in rural Alberta and Saskatchewan, Canada, identified illegal disposal sites as a significant threat to their drinking water resources (Patrick 2018). Furthermore, the absence of landfills in some rural regions of Canada results in frequent practices of open burning and accumulation of waste piles (Keske et al. 2018). Difficulties and challenges associated with MSW management in rural and remote areas have been reported in both developed countries (Lakhan 2015; Wagner and Arnold 2008) and developing countries (Han et al. 2018; Smith et al. 2014).

Most published studies focus on waste management system optimization within an urban area or a metropolis, where waste generation sites are well defined and geographically precise. However, the design of a full-scale waste management system containing both urban and rural areas is more challenging and is much less addressed in the literature (Ghosh and Ng 2021), probably due to the difficulties associated with identification of population centers and waste generation sites outside of the city boundary. In this study, identification of population centers is done by RS nighttime light satellite (NTL) data. NTL imagery can effectively detect population centers as well as anthropogenic activities that are associated with light at night (Zhao et al. 2017; Li et al. 2018; Zhao et al. 2019). For example, Wang et al. (2018) compared the NASA Black Marble NTL imagery before and after hurricanes in Puerto Rico, New York City, and northeastern New Jersey during 2017 and 2018 to examine how communities recovered after the power outage. Their results show that NASA Black Marble NTL imagery can be a suitable tool to monitor and detect areas where better service

and rescue would be needed (Wang et al. 2018). Enenkel et al. (2020) also used NASA Black Marble NTL images to analyze displacement in populated communities' shifting over time and to support humanitarian decision-making. Similarly, this study takes advantage of NASA Black Marble NTL imagery to identify population centers in rural regions.

Study objectives, novelties, and potential contributions

The overall goal of this work is to optimize population coverage by landfills using network analysis and satellite imagery. The specific objectives are to (i) develop a data-driven analytical framework to optimize population coverage by landfills using both NASA Black Marble nighttime light satellite imagery and GIS network analysis tools, and (ii) evaluate the proposed method against the status quo using a set of performance indicators across three Canadian provinces with large rural areas.

Unlike similar studies that improve MSW collection solely by identifying the shortest and the most cost-effective routes for linking population centers and landfills within a given urban center or metropolis (Reed et al. 2014; Hannan et al. 2018; Martins et al. 2015), the present study adopts a broader approach and improves MSW collection systems beyond the city boundary by optimizing both landfill population coverage (maximize population centers per landfill)

and collection truck traveling distances (minimize traveling cost). Incorporation of RS data such as NTL imagery in the network analysis tool makes it possible to optimize waste management systems at regional level consisting multiple urban centers and rural regions.

In addition to conventional performance indicators commonly adopted in GIS network analysis such as travel time and area coverage, an original landfill regionalization index (LFRI) is proposed in this study to evaluate the degree of regionalization before and after the optimization. Three Canadian provinces with a total area of $2.67 \times 10^6 \text{ km}^2$ were selected in the present work to demonstrate the potential benefits of the method at a regional level, and the proposed analytical framework is, however, applicable in any large rural regions with sparsely located population centers. Civilian-use satellite imagery is freely available globally, making the proposed data-driven framework versatile on the implementation of evidence-based waste management strategies.

Material & methods

A data-driven analytical framework for combining waste collection optimization and landfill siting is developed in the current study, and the overall workflow is illustrated in Fig. 1. sections “Region selection”, “Data processing and calculation”, and “Final mapping and assessment” discuss

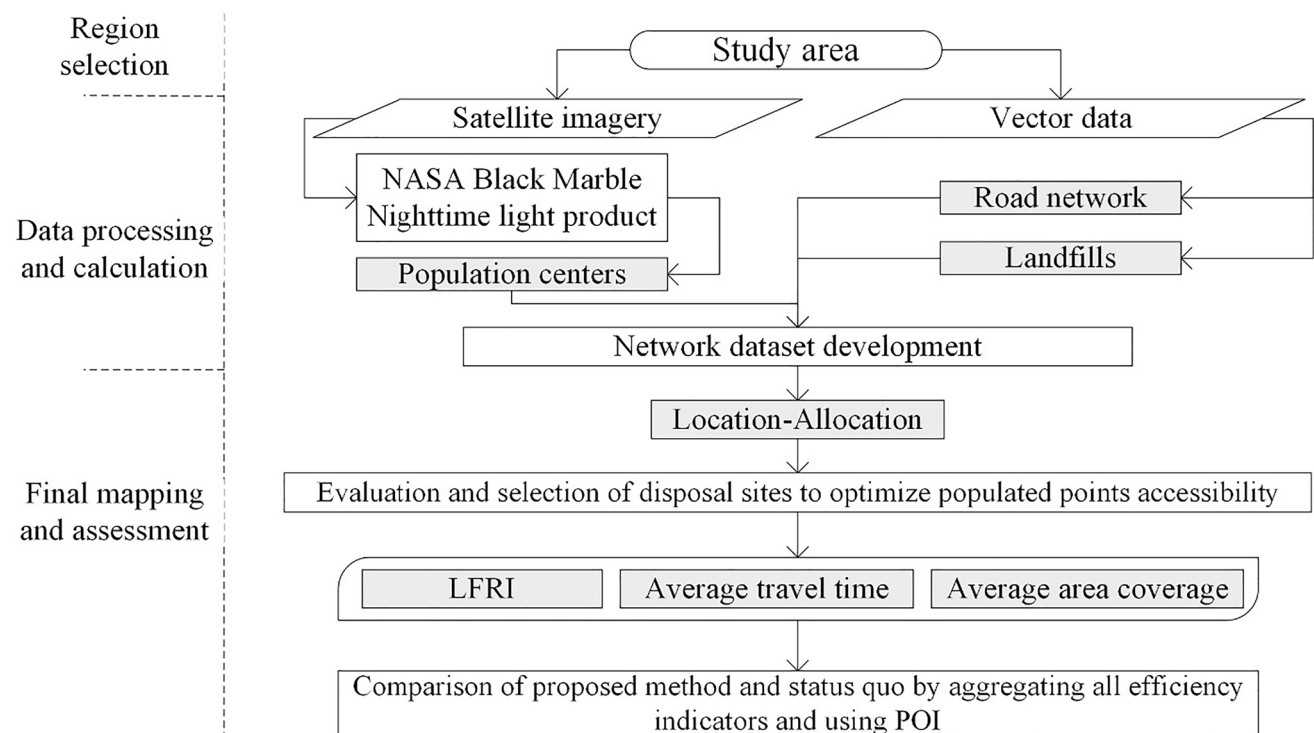


Fig. 1 Workflow of current study

the details and assumptions on region selection, data processing and calculation, and final mapping and assessment, respectively.

Region selection

Study area

The absence or inaccessibility of municipal landfills in the vicinity of population centers is causing serious health and environmental issues in the Canadian rural areas (Patrick 2018; Keske et al. 2018). This is especially important when some jurisdictions have started to close landfills and move toward landfill regionalization (Ghosh and Ng 2021; Richter et al. 2021a), making strategical landfill siting an urgent necessity. For example, Saskatchewan started to reduce the number of rural landfills (SARM 2017), without a comprehensive landfill selection and reduction plan.

Three Canadian provinces, namely Ontario (ON), Saskatchewan (SK), and British Columbia (BC) with areas of 1.08, 0.65, and 0.94×10^6 km², respectively, were selected in this study. Each province has a predominant presence of rural regions, especially in the North of 55th parallel. The selected provinces located in the Central and West Canada (Fig. 2), represent a broad demographical and geographical area. Only landfills that are located in the built network dataset were evaluated in this study because the performance

indicators (LFRI, travel time, and area coverage) can only be interpreted in the presence of a road network. In other words, smaller community disposal sites and unregulated dump sites are ignored in this study. Details of selected roads and landfills will be further discussed in “Data processing and calculation” section.

Data processing and calculation

Population centers and NTL imagery

Given the vast size of the study area (2.67×10^6 km²), NASA Black Marble NTL satellite imagery is used to identify the population centers. The imagery is derived from the Visible Infrared Imaging Radiometer Suite mounted on Suomi National Polar-orbiting Platform with a spatial resolution of 500×500 meter (Román et al. 2018). Black Marble NTL was originally developed by NASA to enhance cloud-free NTL image quality, eliminate stray light effects, and mitigate snow reflected lights (NASA 2021b; Román et al. 2018). The most recent annual product, 2016 NASA Black Marble NTL imagery, is used in the current study. Final NTL imagery can be built by mosaicking different tiles representing different regions of the globe (NASA 2021a).

Once the respective tiles are mosaicked into a single image, binary classification with equal intervals is used to separate brighter regions in the three provinces. Boundary

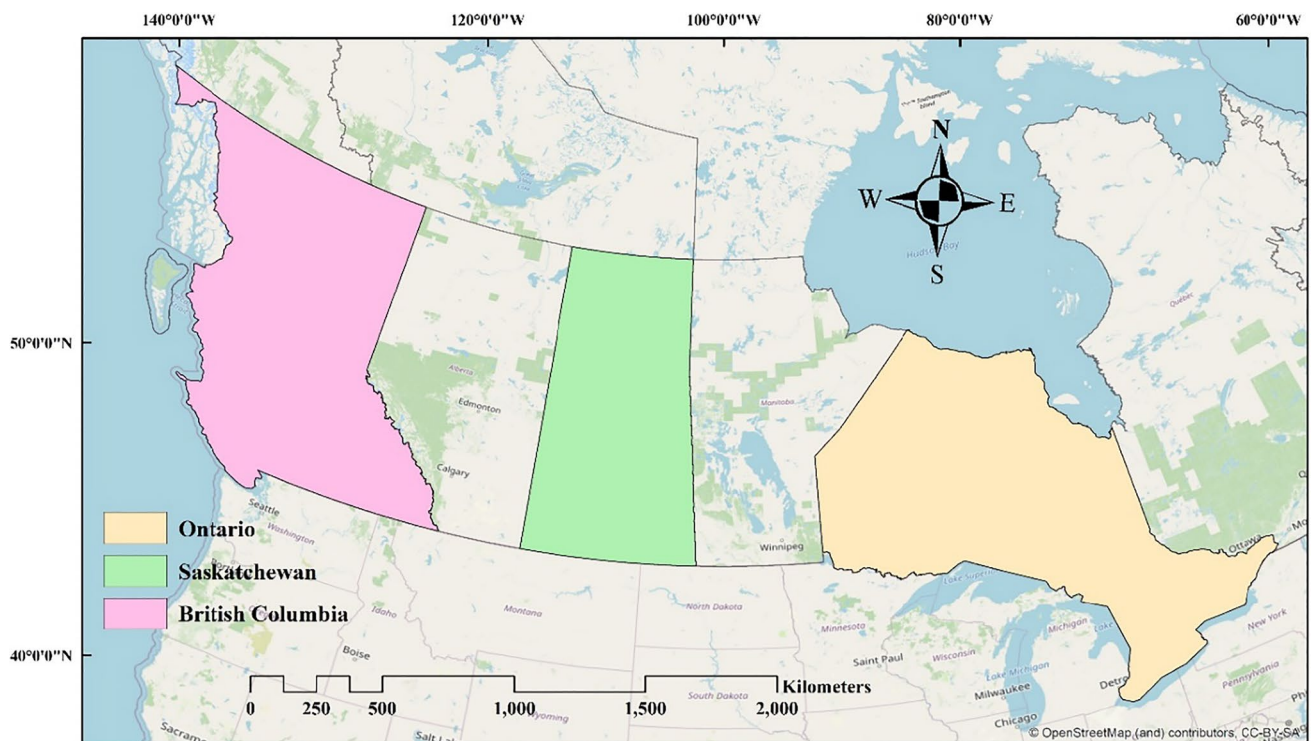


Fig. 2 Study area of three provinces representing central and western regions of Canada, Basemap acquired from ESRI (2021b)

clean and majority filters were then used to smoothen the selected class and eliminate island pixels (ESRI 2021a, b). The remaining brighter pixels, representing regions with higher anthropogenic activities, were converted to polygons. In other words, a single polygon is made from an aggregation of brighter pixels adjacent to each other. The centroids of the polygons, representing the population centers and locations with high anthropogenic activities, are identified and then used in the GIS network analysis. Karimi et al. (2020) used a similar approach to detect the population centers in a landfill site suitability study around Regina, Saskatchewan. A schematic map showing the different steps of population center extraction is shown in Fig. 3. The proposed analytical framework on the use of NTL to identify population centers enable us to study waste management systems outside of major urban centers. Details of landfills, road networks, and population centers are included in Table 1. Among the different parameters, the provincial area linear density is defined as the area occupied by a kilometer of the road network. As discussed further in “[Result and discussion](#)” section, a higher provincial area linear density implies lower vehicular accessibility.

Road networks and assumptions

The most recent 2016 Statistics Canada road network dataset includes the unique identifier, type, travel direction, rank, and class of streets (Statistics Canada 2021), and is adopted in the current study. All road types ranging from urban avenues and streets to express highways were included in the analysis. However, for simplicity and consistency between the three jurisdictions, only two speed limit classes were considered for the waste transportation trucks in the road networks. A top speed of 80 km/hr is assumed in all types of highways, and 50 km/hr is assumed in all urban roads (SGI 2021). The details on road surface, gradation, and specific traffic restrictions on speed limits, turns, intersection access, and day/night time zones are neither included in the Statistics Canada road network database nor considered in the current study. The total length of roads ranging from 202,670 to 369,070 km (Table 1).

Landfill database and assumptions

Status and location of waste facilities were acquired directly from the respective provincial government databases (Government of British Columbia 2021; Government of Ontario 2021; Government of Saskatchewan 2021). Only landfills are considered, and other standalone waste facilities such as waste transfer stations, recycling facilities, material recovery centers, and incinerators are not considered. As discussed

earlier, landfills located outside of the road network with no normal vehicular accessibility were also eliminated.

The total number of landfills within the road network ranged from 314 to 995 (Table 1). Historical records of the landfills in 2016 at the three jurisdictions are not available, and no changes of landfill location and status are assumed in the past 5 years.

Network dataset development and assumptions

In the current study, the network dataset is built from the road network shapefile (as discussed in “[Road networks and assumptions](#)” section) using ArcMap10.5 network analyst extension (ESRI 2021c). During network dataset construction, three types of network elements (edges, junctions, and turns) were created. Edges are the linking roads, junctions are the connecting points between different edges, and turns enable specific kinds of movements over two edges (ESRI 2021d). Due to undefined turns in the three provinces, global turns are assumed in the current study (ESRI 2021e).

Final mapping and assessment

Location allocation

Once the network dataset is built, the “location-allocation” tool in GIS Network Analyst is used to maximize population coverage surrounding neighboring landfills (Fig. 1). GIS Network Analyst is commonly adopted in location-allocation waste studies (Vu et al. 2018). Population centers and landfills in the three provinces are assigned as “demand points” and “facilities,” respectively. Waste collection trucks are required to transport waste from population centers to landfills within a specific time duration. For this purpose, typical hauling costs versus travel times are calculated and the point where direct hauling is no longer economically justified is estimated. The breakeven point is schematically shown in Fig. 4 (EPA 2016). Details and assumptions for breakeven calculations are shown in Supplementary Table S1 and Table S2, respectively. In this study, the average separation distances between the generation sites and the disposal sites are used to estimate the maximum travel times. These estimated times (33.6 minutes in SC1 and 77.4 minutes in SC2) are used as impedance cutoffs for GIS location-allocation analysis.

Performance indicators: LFRI, travel time, and area coverage

Regarding location-allocation optimization, a suitable solution can be attained once a higher number of population centers are served by a lower number of landfills.

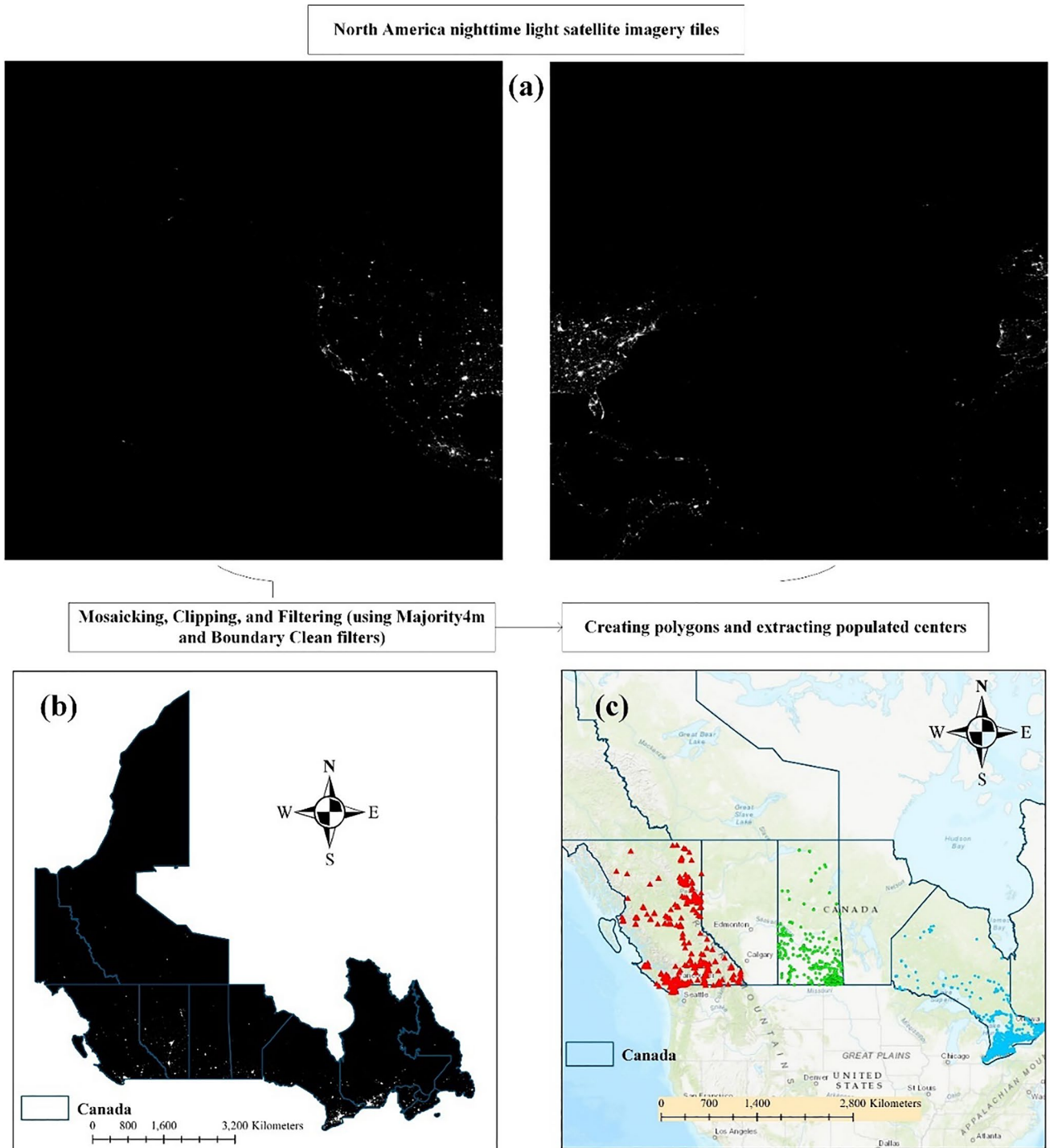


Fig. 3 Extraction of population centers from NASA Black Marble satellite imagery including **a)** aggregation of two NASA Black Marble NTL imageries in 2016, **b)** extraction of clipped, mosaicked,

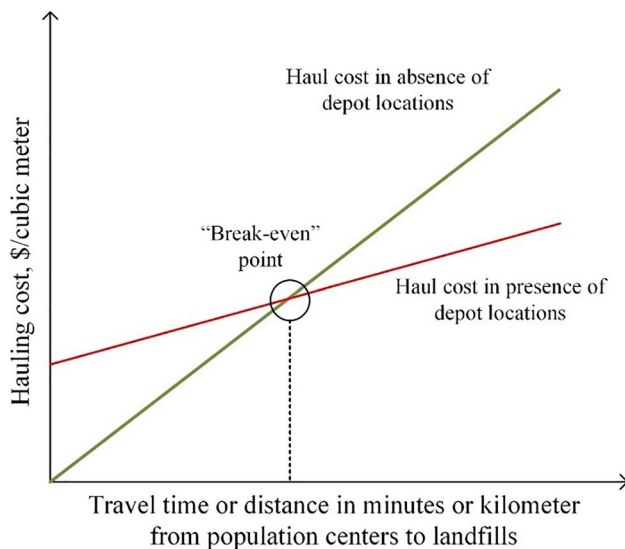
and postprocessed NTL imagery and polygons in Canada, **c)** conversion of NTL imagery to population centers in the three provinces. Basemap acquired from ESRI (2021c)

Therefore, a performance indicator known as landfill regionalization index (LFRI) is proposed (Eq. 1). This index depicts how many population centers are served by the landfills, and the average LFRI is reported for each jurisdiction. The subscript *s* refers to the status quo

condition, and the subscript *p* refers to the optimized solution determined by the proposed method. A larger LFRI generally means better utilization of landfills within a jurisdiction; therefore, the more regionalized or strategically located the facilities.

Table 1 General specification of the three Canadian provinces in 2016

	British Columbia (BC)	Saskatchewan (SK)	Ontario (ON)
Total area (km ²)	944,740	651,040	1,076,400
Number of detected population centers within the road network	355	314	995
Number of landfills within the road network	482	118	191
Total length of roads (km)	202,670	369,070	317,306
Landfill linear density ($\times 10^{-4}$ km ⁻¹)	23.78	3.19	6.02
Landfill per capita ($\times 10^{-5}$)	9.3	10	1.29
Provincial area linear density (km ² /km)	5.28	1.76	2.96

**Fig. 4** Haul costs lines in the absence or presence of depot locations, transfer stations, and their intersection as “breakeven” point. Assumed values and calculations are shown in Tables S1 and S2.

$$LFRI_{s \text{ or } p} = \frac{\text{Number of population centers covered}_{s \text{ or } p}}{\text{Number of landfills}_{s \text{ or } p}} \quad (1)$$

The waste collection time is another common performance indicator for an effective waste management system (Akhtar et al. 2017; Hannan et al. 2018; Vu et al. 2018) and is adopted in the present study. Travel times from population centers to landfills are computed for both status quo and the optimized conditions using attribute tables for all collection routes in ArcGIS10.5. Travel time is calculated assuming free-flowing traffic and idealized driving conditions, using the two assigned speed classes discussed in “Road networks and assumptions” section.

Accessibility of waste facilities appears to be an important issue in regionalization of Canadian waste management system (Ghosh and Ng 2021; Karimi et al. 2022b). A larger area coverage of a landfill helps reduce illegal disposal sites by providing accessibility to neighboring populations

(Patrick 2018; Keske et al. 2018; Quesada-Ruiz et al. 2019; Karimi et al. 2022a). In this regard, area coverage for landfills is estimated using the “service area” tool in GIS Network Analyst. As discussed in “Location allocation” section, 33.6 and 77.4 minutes are used as impedance cutoffs for SC1 and SC2, respectively.

Comparison of proposed method and status quo by aggregating all indicators

Once all three indicators (LFRI, travel time, and area coverage) were computed for both SC1 and SC2, a user-defined parameter percentage of improvement (POI) is calculated comparing status quo and proposed solution (Eq. 2).

$$POI = \frac{\text{Average result from proposed method} - \text{Average results from status quo}}{\text{Average result from proposed method}} \times 100\% \quad (2)$$

For travel time, the respective POI is calculated by switching “Status quo” and “Proposed method” in Eq. 2, since the shorter travel time represents an improvement in the proposed method. Overall improvement was then calculated by averaging the POI in the three indicators as shown in Eq. 3. Caution should be used when interpreting overall POI shown in Eq. 3. Since the three dimensionless ratios measure different spatiotemporal parameters, the combined ratios should be interpreted qualitatively and not quantitatively. The overall POI is intended for comparison between the status quo and optimized solution only.

$$\text{Overall POI} = \frac{1}{3} (POI_{LFRI} + POI_{travel \ time} + POI_{area \ coverage}) \quad (3)$$

Results and discussion

The three performance indicators

The LFRI for both scenarios are shown in Fig. 5a. The central bar of the box plot and the cross symbol represent

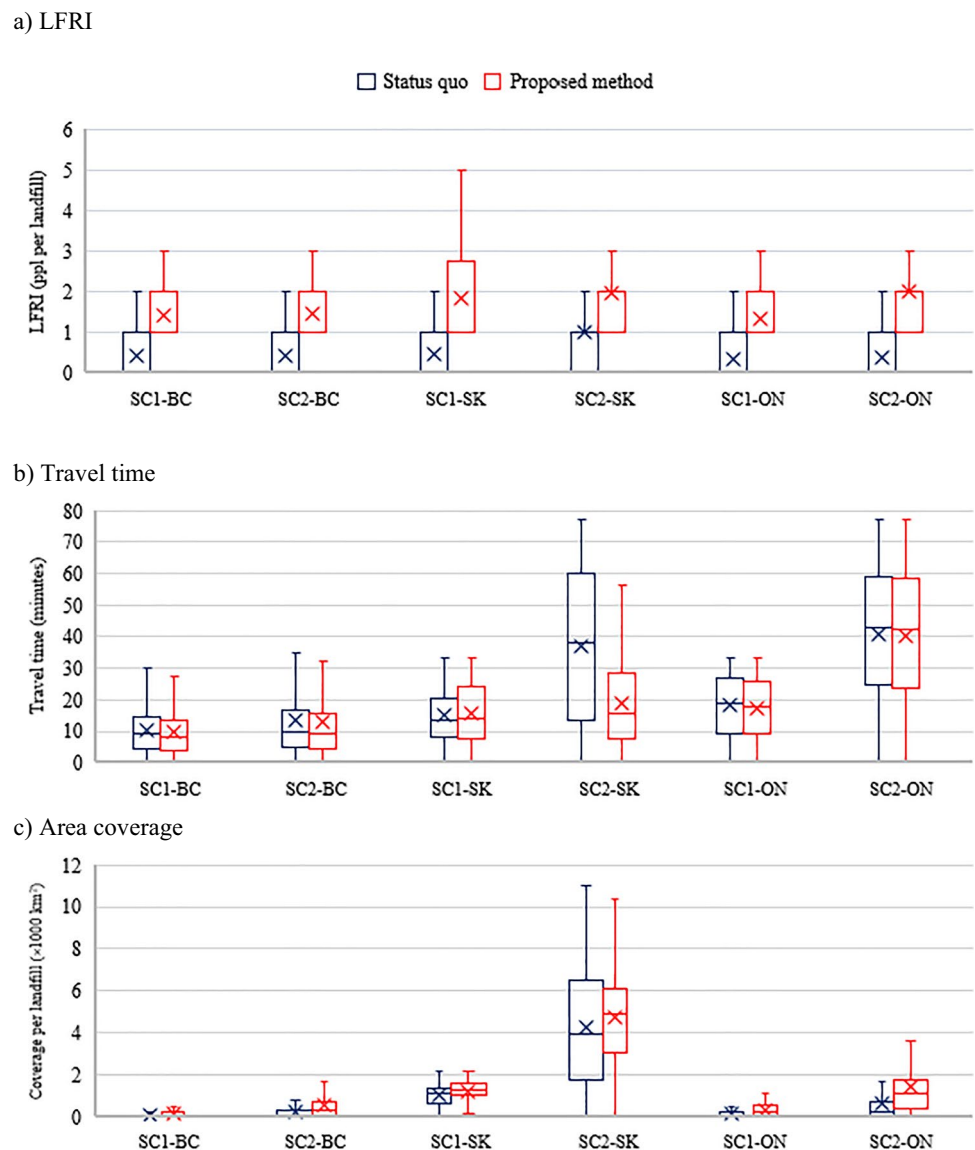
the median and mean, respectively. The bottom and top edges of the box represent the first and third quartile (25th and 75th percentile) of each group. Whiskers represent the maximum and minimum values. The LFRI are heavily skewed, and both the medians and the first quartiles are equal to zero under status quo conditions in all cases (blue boxes, Fig. 5a). Therefore, a quarter of landfills considered in the present study do not even cover a single population center in both SC1 and SC2, suggesting ineffective landfill siting. Under status quo conditions, the LFRI ranges from 0 to 2 population centers per landfill in all three jurisdictions, with an average of less than 1. Unlike others, the average status quo LFRI in Saskatchewan under SC2 is close to 1 population center per landfill and is higher than almost 75% of landfills within that group. The results show that Saskatchewan landfills are located slightly better compared to other provinces. The skewed LFRI in SC2-SK is

probably due to the close proximity between landfills and population centers. For example, several Saskatchewan landfills covered up to 5 population centers in SC2.

The red boxes in Fig. 5a show the optimized LFRI using the proposed method. The absence of lower whiskers in the boxplots indicate that both lowest and the first quartile are located at 1 population center per landfill. In other words, at least a quarter of landfills cover 1 population center in all cases. A higher variability is observed in SC1-SK. Specifically, the upper 25% of landfills in Saskatchewan under SC1 cover around 3 to 5 population centers after optimization, suggesting better landfill regionalization.

Red boxes are all above blue boxes in Fig. 5a, and LFRI improved consistently after optimization, with average LFRI ranging from 1.3 to 2.0 population centers per landfill. As discussed in “Performance indicators: LFRI, travel time, and area coverage” section, a larger LFRI represents

Fig. 5 Comparing status quo and proposed method with regard to a) LFRI, b) travel time, c) area coverage for both SC1 and SC2



better utilization of landfills, and a higher degree of landfill regionalization. The results in Fig. 5a suggest that the status quo conditions in the three provinces are all subpar, and the proposed analytical method can enhance landfill regionalization. The level of LFRI improvement in all provinces are similar, suggesting landfill regionalization might not be significantly affected by differences in geographical and demographical attributes (Table 1). Moreover, the spreads of LFRI are similar between SC1 and SC2 in a given jurisdiction, suggesting that the size of collection trucks is not a decisive factor in optimizing the population coverage. For example, the spread of LFRIs in British Columbia between SC1 and SC2 are almost identical, despite the differences in separation distances between waste generation and disposal sites. This is probably due to the abundance of landfills within the road network in BC (landfill linear density = $23.78 \times 10^{-4} \text{ km}^{-1}$, Table 1).

Travel time from population centers to landfills is shown in Fig. 5b. Unlike the LFRI where all landfills are included (including landfills with zero coverage), travel time is only defined for landfills that are linked to a specific population center. Thus, higher consistencies are observed on average travel time between status quo (blue cross symbols) and the proposed method (red cross symbols). In general, the average truck travel time associated with the optimized system is similar or lower than the status quo condition. The most noticeable improvement is observed in SC2-SK, with an average travel time below 20 minutes after optimization. As shown in Table 1, Saskatchewan has the smallest landfill linear density ($3.19 \times 10^{-4} \text{ km}^{-1}$) and the highest number of landfills per capita (10.0×10^{-5}) among the three jurisdictions, suggesting sparsely distributed low-density population centers within the road network. It appears that rural regions with sparsely located towns in Saskatchewan are a good candidate for optimization. Lower population density and the absence of multiple urban areas are reported as possible reasons for lower COVID-19 cases in Saskatchewan compared to other Canadian provinces in a study on waste disposal during the pandemic (Richter et al. 2021d).

On the other hand, relatively larger travel time differences are generally observed between the two scenarios. British Columbia has the least difference between SC1 and SC2 among the three provinces (Fig. 5b). The average travel time under SC1 is about 10 minutes and is increased to 13.4 minutes under SC2. British Columbia has the highest landfill linear density of $23.78 \times 10^{-4} \text{ km}^{-1}$ among the provinces (Table 1), indicating the abundance of landfills' presence within the road network. As such, the average travel time is much less sensitive to the differences in generation-site-disposal-site separation distance between the two scenarios.

An obvious twofold increase in average travel times can be seen between the scenarios in Ontario (Fig. 5b). With the least landfill per capita (1.29×10^{-5} , Table 1), the travel time

is very sensitive to the differences in generation-site-disposal-site separation distance. Lakhan (2015) studied recycling cost between urban and rural Ontario and also concluded that the recycling system in rural areas is more costly and far less efficient.

Figure 5c shows the differences in area coverage by landfill. Under both scenarios in all three jurisdictions, the optimized systems with strategically located landfills provided better coverage. Landfills with larger coverage of the populated centers are more efficient due to the economy of scale and provide better accessibility to users, helping to minimize potential illegal dumping sites. British Columbia has the least differences between the scenario, and Saskatchewan has the highest difference. Unlike other cases, over $4,000 \text{ km}^2$ average coverage per landfill is observed in SC2-SK (Fig. 5c). This is probably due to the sparsely located population centers and the well-established road network (provincial area linear density = $1.76 \text{ km}^2/\text{km}$, Table 1). It appears that intensified road network enables larger landfill coverage area. A comparison of the scales of the vertical axes in Fig. 5a, b, and c reveals that the area coverage is more sensitive to the differences in geographical and demographical attributes (Table 1). Results in Fig. 5c suggested that Saskatchewan landfills are generally more strategically located compared to other jurisdictions.

The percentage of improvement after optimization

It appears the proposed analytical method is effective in improving landfill regionalization. Under SC1, the largest POIs can be seen in the LFRI (Table 2a), ranging from 58.3% to 64.5%. A similar pattern is observed in SC2, with POIs of LFRI ranging from 22.7% to 59.4% (Table 2b). The results suggest that the optimization framework can enhance the level of landfill regionalization, making these waste facilities more efficient.

Compared to LFRI and area coverage, POI of travel time appears less sensitive to the optimization. Under SC1, POIs range from -4.8% in Saskatchewan to +8.4% in British Columbia (Table 2a). A negative POI in Saskatchewan means longer travel time after optimization (also shown in Fig. 5b), suggesting a high level of landfill regionalization at status quo (Fig. 5a). Saskatchewan is the only province showing conflicting travel times, with slightly worse travel time in SC1 (-4.8%) to significant improvement in SC2 (+49.3%). A closer look at Table 2 suggests Saskatchewan behaves slightly differently than its peers. Heterogeneous population distribution pattern and intensified road network might be the reasons for such volatility in truck travel times (Table 1).

POI of area coverage ranged from 18.1% in Saskatchewan to 51.5% in Ontario under SC1 (Table 2a). Similar trend is observed in Table 2b under SC2. Again, lowest

Table 2 Individual and overall POIs in the three Canadian provinces under (a) Scenario 1 and (b) Scenario 2

	(a) SC1			(b) SC2			
	BC	ON	SK	BC	ON	SK	
LFRI	61.8	64.5	58.3	LFRI	59.4	55.6	22.7
Travel time	8.4	3.6	-4.8	Travel time	4.0	1.3	49.3
Area coverage	47.2	51.5	18.1	Area coverage	53.0	53.9	10.3
Overall	39.1	39.8	23.9	Overall	38.8	36.9	27.4

POIs are observed in Saskatchewan, probably due to the presence of a well-established road network. Figure 5c reveals that Saskatchewan landfills have better coverage of population centers in status quo condition, making the optimization process less effective.

Overall POIs are arithmetic averages of the POIs, and the results should be interpreted qualitatively. Under SC1, the optimization yields very similar results in Ontario and British Columbia. The order is ON > BC > SK (Table 2a). Under SC2, the order is BC > ON > SK. In both cases, the levels of improvement in ON and BC are quite similar. Minor differences in the overall POI between SC1 (Table 2a) and SC2 (Table 2b) suggest that the separation distance between the generation and disposal sites is generally not a decisive factor in the optimization. The overall POIs for all provinces are all positive, suggesting that the proposed optimization framework is generally applicable to regions with different geographical and demographical attributes. Results suggested that the proposed LFRI is a sensitive performance indicator, and it may be considered in other waste management studies.

Limitations

In this study, population centers at regional level are identified by NTL images with a spatial resolution of 0.5 × 0.5 km, and imageries with higher aerial resolution (0.1 × 0.1 km of finer) can be used to improve result precision. Road surface attributes, gradation, and detailed traffic restrictions (such as abrupt changes of speed limits, day and night traffic zones) are not addressed in the current study. The type and operating costs of the collection and trailing trucks as well as the transfer stations are assumed constant in all provinces. MSW regulations and level of service are also assumed to be constant in three provinces for comparison purposes.

Conclusions

This study combined GIS network analysis and NTL imagery to develop an analytical framework for optimization of landfill regionalization. Unlike other waste collection

studies focus on the minimization of travel time and distance at city-level, the current study optimizes waste management system at regional level. The use of NTL allows identification of population centers in rural settings, specifically addressing the difficulties associated with waste management system development in Canadian northern and remote areas. An original performance indicator known as LFRI is used to evaluate the optimization.

Under status quo conditions, LFRI ranged from 0 to 2 population centers per landfill in all three jurisdictions, with an average of less than 1. Unlike others, Saskatchewan landfills are slightly better located compared to its counterparts. LFRI consistently improved after optimization, with average LFRI ranging from 1.3 to 2.0 population centers per landfill. Optimized landfills allow more efficient use of the sites and a higher degree of landfill regionalization.

Lower average truck travel times are generally observed in the optimized system. The travel time appears less sensitive to the differences in generation-site–disposal-site separation distance and truck capacity when landfills are abundant within a road network. In all cases, the optimized system provided better coverage. Landfills with larger coverage of the populated centers are more efficient due to economies of scale and provide better accessibility to users, thereby helping to minimize potential illegal dumping sites. It appears area coverage is more sensitive to the differences in geographical and demographical attributes, and intensified road network enables larger coverage area of population centers.

The proposed analytical method is effective in improving landfill regionalization. Under Scenario 1, POIs of LFRI ranging from 58.3% to 64.5%. A similar pattern is observed in SC2, with POIs of LFRI ranging from 22.7% to 59.4%. With the exception of SC1-SK, improvements on all performance indicators are observed. The levels of improvement in Ontario and British Columbia are quite similar. Minor differences of the overall POI between the scenarios suggest that the separation distance between the generation and disposal sites and truck capacity is generally not a decisive factor of the optimization. The overall POIs are positive in all jurisdictions, suggesting that the proposed optimization framework is applicable to regions with different geographical and demographical attributes. It is believed that the proposed framework and performance indicator will help to

establish a more data-driven MSW management system at regional scale.

Acronyms BC: British Columbia; GIS: Geographical Information System; LFRI: landfill regionalization index; MSW: Municipal solid waste; NTL: nighttime light; ON: Ontario; POI: Percentage of improvement; RS: Remote Sensing; SC1: Scenario 1; SC2: Scenario 2; SK: Saskatchewan; VRP: vehicle routing problem

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Author contributions Nima Karim contributed to the study conception. Study design was performed by Nima Karim and Kelvin Tsun Wai Ng. Data analysis and interpretations were performed by all authors. The first draft of the manuscript was written by Nima Karim and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability All data generated or analyzed during this study are included in this article.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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References

- Abdallah M, Adghim M, Maraqa M, Aldahab E (2019) Simulation and optimization of dynamic waste collection routes. *Waste Manag Res* 37:793–802. <https://doi.org/10.1177/0734242x19833152>
- Ajibade FO, Olajire OO, Ajibade TF, Nwogwu NA, Lasisi KH, Alo AB et al (2019) Combining multicriteria decision analysis with GIS for suitably siting landfills in a Nigerian state. *Environ Sustain Indic* 3-4:100010. <https://doi.org/10.1016/j.indic.2019.100010>
- Akhtar M, Hannan MA, Begum RA, Basri H, Scavino E (2017) Backtracking search algorithm in CVRP models for efficient solid waste collection and route optimization. *Waste Manag* 61:117–128. <https://doi.org/10.1016/j.wasman.2017.01.022>
- Aksaraylı OPA (2018) An Ant Colony Optimization Algorithm Approach for Solving Multi-objective Capacitated Vehicle Routing Problem. *Alp J* 6:37–48. <https://doi.org/10.17093/alphanumeric.366852>
- Aliahmadi SZ, Barzinpour F, Pishvae MS (2020) A fuzzy optimization approach to the capacitated node-routing problem for municipal solid waste collection with multiple tours: A case study. *Waste Manag Res: J Int Solid Wastes Public Cleans Assoc ISWA* 38:279–290. <https://doi.org/10.1177/0734242X19879754>
- Allen county (2021) A guide to truck trailers. Available at: <https://www.allencounty.us/homeland/images/lepc/docs/TruckTrailerGuide.pdf>. Accessed 26 Aug 2021
- Behi Z, Ng KTW, Richter A, Karimi N, Ghosh A, Zhang L (2021) Exploring the untapped potential of solar photovoltaic energy at a smart campus: Shadow and cloud analyses. *Energy Environ*. <https://doi.org/10.1177/0958305X211008998>
- Budzianowski WM (2016) A review of potential innovations for production, conditioning and utilization of biogas with multiple-criteria assessment. *Renew Sustain Energy Rev* 54:1148–1171. <https://doi.org/10.1016/j.rser.2015.10.054>
- Chabok M, Asakereh A, Bahrami H, Jaafarzadeh NO (2020) Selection of MSW landfill site by fuzzy-AHP approach combined with GIS: case study in Ahvaz, Iran. *Environ Monit Assess* 192:433. <https://doi.org/10.1007/s10661-020-08395-y>
- CSRD (2021) Landfill decommissioning cost assessment report, Columbia Shuswap Regional District, Golder Associates. Available at https://www.csr.d.bc.ca/sites/default/files/SolidWaste/191207897-005-L-Rev0-LF%20Decom%20Impact%20Assess%20010CT_20.pdf. Accessed 26 Aug 2021
- Enekel M, Shrestha RM, Stokes E, Román M, Wang Z, Espinosa MTM, Hajzmanova I, Ginnetti J, Vinck P (2020) Emergencies do not stop at night: Advanced analysis of displacement based on satellite-derived nighttime light observations. *IBM J Res Dev* 64:8:1–8:12. <https://doi.org/10.1147/JRD.2019.2954404>
- EPA (2016) Waste transfer stations: a manual for decision-making. <https://www.epa.gov/sites/production/files/2016-03/documents/r02002.pdf>. Accessed 26 Aug 2021
- Erfani SMH, Danesh S, Karrabi SM, Shad R (2017) A novel approach to find and optimize bin locations and collection routes using a geographic information system. *Waste Manag Res* 35:776–785. <https://doi.org/10.1177/0734242X17706753>
- ESRI (2021a) Boundary clean: filter application. <https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/boundary-clean.htm>. Accessed 6 June 2021
- ESRI (2021b) Majority: filter application. <https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/majority-filter.htm>. Accessed 6 June 2021
- ESRI (2021c) What is a network dataset?. <https://desktop.arcgis.com/en/arcmap/latest/manage-data/network-datasets/what-is-a-network-dataset.htm>. Accessed 20 Aug 2021
- ESRI, (2021d) Network Elements. <https://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/network-elements.htm>. Accessed 22 Aug 2021
- ESRI, (2021e) About global turns. <https://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/global-turns-about-global-turns.htm>. Accessed 22 June 2021
- Franco DGDB, Steiner MTA, Assef FM (2021) Optimization in waste landfilling partitioning in Paraná State, Brazil. *J Clean Prod* 283:125353. <https://doi.org/10.1016/j.jclepro.2020.125353>
- Ghosh A, Ng KTW (2021) Temporal and spatial distributions of waste facilities and solid waste management strategies in rural and urban Saskatchewan, Canada. *Sustainability* 13(12):6887. <https://doi.org/10.3390/su13126887>

- Gilardino A, Rojas J, Mattos H, Larrea-Gallegos G, Vázquez-Rowe I (2017) Combining operational research and Life Cycle Assessment to optimize municipal solid waste collection in a district in Lima (Peru). *J Clean Prod* 156:589–603. <https://doi.org/10.1016/j.jclepro.2017.04.005>
- Glanville K, Chang H (2015) Mapping illegal domestic waste disposal potential to support waste management efforts in Queensland, Australia. *Int J Geogr Inf Sci* 29:1042–1058. <https://doi.org/10.1080/13658816.2015.1008002>
- Government of British Columbia (2021) Contact details provided for environmental protection officers. <https://dir.gov.bc.ca/gtds.cgi?research=&updateRequest=&view=detailed&sortBy=name&for=people&attribute=display+name&matchMethod=is&searchString=Kirk+Phair&objectId=164495>. Accessed 1 June 2021
- Government of Ontario (2021) Ontario landfill sites map. <https://www.ontario.ca/page/large-landfill-sites-map>. Accessed 20 Aug 2021
- Government of Saskatchewan (2021) Landfill section. <https://www.saskatchewan.ca/government/directory?ou=672d0e8d-1935-4642-9e6c-c05e24c7eff7>. Accessed 2 June 2021
- Han Z, Liu Y, Zhong M, Shi G, Li Q, Zeng D, Zhang Y, Fei Y, Xie Y (2018) Influencing factors of domestic waste characteristics in rural areas of developing countries. *Waste Manag* 72:45–54. <https://doi.org/10.1016/j.wasman.2017.11.039>
- Hannan MA, Akhtar M, Begum RA, Basri H, Hussain A, Scavino E (2018) Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. *Waste Manag* 71:31–41. <https://doi.org/10.1016/j.wasman.2017.10.019>
- Hannan MA, Begum RA, Al-Shetwi AQ, Ker PJ, Al Mamun MA, Hussain A, Basri H, Mahlia TMI (2020) Waste collection route optimisation model for linking cost saving and emission reduction to achieve sustainable development goals. *Sustain Cities Soc* 62:102393. <https://doi.org/10.1016/j.scs.2020.102393>
- Heil (2021) Rear load garbage trucks. <https://www.heil.com/products/rear-loaders>. Accessed 26 Aug 2021
- Hua L, Shao G, Zhao J (2017) A concise review of ecological risk assessment for urban ecosystem application associated with rapid urbanization processes. *Int J Sustain Dev World Ecol* 24:248–261. <https://doi.org/10.1080/13504509.2016.1225269>
- Huang S, Lin P (2015) Vehicle routing–scheduling for municipal waste collection system under the “Keep Trash off the Ground” policy. *Omega* 55:24–37. <https://doi.org/10.1016/j.omega.2015.02.004>
- Islam R, Rahman MS (2012) An ant colony optimization algorithm for waste collection vehicle routing with time windows, driver rest period and multiple disposal facilities. In: 2012 International Conference on Informatics, Electronics & Vision (ICIEV). IEEE, Dhaka, pp 774–779. <https://doi.org/10.1109/ICIEV.2012.6317421>
- Karadimas NV, Papatzelou K, Loumos VG (2007) Genetic Algorithms for Municipal Solid Waste Collection and Routing Optimization. In: *Artificial Intelligence and Innovations: from Theory to Applications*. Springer, Boston, pp 223–231. https://doi.org/10.1007/978-0-387-74161-1_24
- Karimi N, Richter A, Ng KTW (2020) Siting and ranking municipal landfill sites in regional scale using nighttime satellite imagery. *J Environ Manag* 256:109942. <https://doi.org/10.1016/j.jenvman.2019.109942>
- Karimi N, Ng KTW, Richter A (2021a) Prediction of fugitive landfill gas hotspots using a random forest algorithm and Sentinel-2 data. *Sustain Cities Soc* 73:103097. <https://doi.org/10.1016/j.scs.2021.103097>
- Karimi N, Ng KTW, Richter A, Williams J, Ibrahim H (2021b) Thermal heterogeneity in the proximity of municipal solid waste landfills on forest and agricultural lands. *J Environ Manag* 287:112320. <https://doi.org/10.1016/j.jenvman.2021.112320>
- Karimi N, Ng KTW, Richter A (2022a) Development and application of an analytical framework for mapping probable illegal dumping sites using nighttime light imagery and various remote sensing indices. *Waste Manag* 143:195–205. <https://doi.org/10.1016/j.wasman.2022.02.031>
- Karimi N, Ng KTW, Richter A (2022b) Development of a regional solid waste management framework and its application to a prairie province in central Canada. *Sustain Cities Soc* 82:103904. <https://doi.org/10.1016/j.scs.2022.103904>
- Keske CM, Mills M, Godfrey T, Tanguay L, Dicker J (2018) Waste management in remote rural communities across the Canadian North: Challenges and opportunities. *Detritus* 2:63. <https://doi.org/10.31025/2611-4135/2018.13641>
- Lakhan C (2015) North of the 46° parallel: Obstacles and challenges to recycling in Ontario’s rural and northern communities. *Waste Manag* 44:216–226. <https://doi.org/10.1016/j.wasman.2015.06.044>
- Li X, Zhao L, Li D, Xu H (2018) Mapping Urban Extent Using Luojia 1-01 Nighttime Light Imagery. *Sensors* 18:3665. <https://doi.org/10.3390/s18113665>
- Liu J, He Y (2012) Ant Colony Algorithm for Waste Collection Vehicle Arc Routing Problem with Turn Constraints. In: 2012 Eighth International Conference on Computational Intelligence and Security. IEEE, Guangzhou, pp 35–39. <https://doi.org/10.1109/CIS.2012.16>
- Mahmood K, Batool A, Faizi F, Chaudhry MN, Ul-Haq Z, Rana AD, Tariq S (2017) Bio-thermal effects of open dumps on surroundings detected by remote sensing—Influence of geographical conditions. *Ecol Indic* 82:131–142. <https://doi.org/10.1016/j.ecolind.2017.06.042>
- Martins K, Mourão MC, Pinto LS (2015) A Routing and Waste Collection Case-Study. *Oper Res* 4:261–275. https://doi.org/10.1007/978-3-319-20328-7_15
- NASA (2021a) NASA black marble NTL imagery. <https://earthobservatory.nasa.gov/features/NightLights>. Accessed 6 Jul 2021
- NASA (2021b) NASA’s Black Marble imagery, Advances the science of earth at night. <https://blackmarble.gsfc.nasa.gov/>. Accessed 4 Jul 2021
- Patrick RJ (2018) Adapting to climate change through source water protection: case studies from Alberta and Saskatchewan, Canada. *The International Indigenous Policy Journal*, 9(3). <https://doi.org/10.18584/iipj.2018.9.3.1>
- Quesada-Ruiz LC, Rodríguez-Galiano V, Jordá-Borrell R (2019) Characterization and mapping of illegal landfill potential occurrence in the Canary Islands. *Waste Manag* 85:506–518. <https://doi.org/10.1016/j.wasman.2019.01.015>
- Rahimi S, Hafezalkotob A, Monavari SM, Hafezalkotob A, Rahimi R (2020) Sustainable landfill site selection for municipal solid waste based on a hybrid decision-making approach: Fuzzy group BWM-MULTIMOORA-GIS. *J Clean Prod* 248:119186. <https://doi.org/10.1016/j.jclepro.2019.119186>
- Reed M, Yiannakou A, Evering R (2014) An ant colony algorithm for the multi-compartment vehicle routing problem. *Appl Soft Comput* 15:169–176. <https://doi.org/10.1016/j.asoc.2013.10.017>
- Rezaeisabzevar Y, Bazargan A, Zohourian B (2020) Landfill site selection using multi criteria decision making: Influential factors for comparing locations. *J Environ Sci* 93:170–184. <https://doi.org/10.1016/j.jes.2020.02.030>
- Richter A, Ng KTW, Pan C (2018) Effects of percent operating expenditure on Canadian non-hazardous waste diversion. *Sustain Cities Soc* 38:420–428. <https://doi.org/10.1016/j.scs.2018.01.026>
- Richter A, Ng KTW, Karimi N (2019a) A data driven technique applying GIS, and remote sensing to rank locations for waste disposal site expansion. *Resour Conserv Recycl* 149:352–362. <https://doi.org/10.1016/j.resconrec.2019.06.013>
- Richter A, Ng KTW, Karimi N, Wu P, Kashani AH (2019b) Optimization of waste management regions using recursive Thiessen

- polygons. *J Clean Prod* 234:85–96. <https://doi.org/10.1016/j.jclepro.2019.06.178>
- Richter A, Ng KTW, Karimi N (2021a) Meshing Centroidal Voronoi Tessellation with spatial statistics to optimize waste management regions. *J Clean Prod* 295:126465. <https://doi.org/10.1016/j.jclepro.2021.126465>
- Richter A, Ng KTW, Karimi N (2021b) The role of compactness distribution on the development of regionalized waste management systems. *J Clean Prod* 296:126594. <https://doi.org/10.1016/j.jclepro.2021.126594>
- Richter A, Ng KTW, Karimi N, Chang W (2021c) Developing a novel proximity analysis approach for assessment of waste management cost efficiency in low population density regions. *Sustain Cities Soc* 65:102583. <https://doi.org/10.1016/j.scs.2020.102583>
- Richter A, Ng KTW, Vu HL, Kabir G (2021d) Waste disposal characteristics and data variability in a mid-sized Canadian city during COVID-19. *Waste Manag* 122:49–54. <https://doi.org/10.1016/j.wasman.2021.01.004>
- Rızvanoğlu O, Kaya S, Ulukavak M, Yeşilnacar Mİ (2019) Optimization of municipal solid waste collection and transportation routes, through linear programming and geographic information system: a case study from Şanlıurfa, Turkey. *Environ Monit Assess* 192:9. <https://doi.org/10.1007/s10661-019-7975-1>
- Román MO, Wang Z, Sun Q, Kalb V, Miller SD, Molthan A et al (2018) NASA's Black Marble nighttime lights product suite. *Remote Sens Environ* 210:113–143. <https://doi.org/10.1016/j.rse.2018.03.017>
- Sanjeevi V, Shahabudeen P (2016) Optimal routing for efficient municipal solid waste transportation by using ArcGIS application in Chennai, India. *Waste Manag Res* 34:11–21. <https://doi.org/10.1177/0734242x15607430>
- SARM (Saskatchewan Association of Rural Municipalities) (2017) Landfill report. <https://sarm.ca/advocacy/resolutions/resolution-full?id=1063>. Accessed 6 Jul 2021
- Saskatchewan Government Insurance (SGI) (2021) Speed limits, Saskatchewan driver's handbook. https://www.sgi.sk.ca/handbook/-/knowledge_base/drivers/speed. Accessed 1 Jul 2021
- Smith MT, Goebel JD, Blihnaut JN (2014) The financial and economic feasibility of rural household biodigesters for poor communities in South Africa. *Waste Manag* 34(2):352–362. <https://doi.org/10.1016/j.wasman.2013.10.042>
- Statistics Canada (2021) Road network file, catalogue no. 92-500-g. <https://www12.statcan.gc.ca/census-recensement/2011/geo/RNF-FRR/index-2011-eng.cfm?year=16>. Accessed 1 June 2021
- Taşkın A, Demir N (2020) Life cycle environmental and energy impact assessment of sustainable urban municipal solid waste collection and transportation strategies. *Sustain Cities Soc* 61:102339. <https://doi.org/10.1016/j.scs.2020.102339>
- Viotti P, Poletini A, Pomi R, Innocenti C (2003) Genetic algorithms as a promising tool for optimisation of the MSW collection routes. *Waste Manag Res* 21:292–298. <https://doi.org/10.1177/0734242X0302100402>
- Vu HL, Ng KTW, Bolingbroke D (2018) Parameter interrelationships in a dual phase GIS-based municipal solid waste collection model. *Waste Manag* 78:258–270. <https://doi.org/10.1016/j.wasman.2018.05.050>
- Wagner T, Arnold P (2008) A new model for solid waste management: an analysis of the Nova Scotia MSW strategy. *J Clean Prod* 16:410–421. <https://doi.org/10.1016/j.jclepro.2006.08.016>
- Wang Z, Román MO, Sun Q, Molthan AL, Schultz LA, Kalb VL (2018) Monitoring Disaster-Related Power Outages Using NASA Black Marble Nighttime Light Product. *ISPRS Int Arch Photogramm Remote Sens Spatial Inform Sci* 52-3:1853–1856. <https://doi.org/10.5194/isprs-archives-XLII-3-1853-2018>
- Xue W, Cao K, Li W (2015) Municipal solid waste collection optimization in Singapore. *Appl Geogr* 62:182–190. <https://doi.org/10.1016/j.apgeog.2015.04.002>
- Yadav V, Karmakar S (2020) Sustainable collection and transportation of municipal solid waste in urban centers. *Sustain Cities Soc* 53:101937. <https://doi.org/10.1016/j.scs.2019.101937>
- Yousefloo A, Babazadeh R (2020) Designing an integrated municipal solid waste management network: A case study. *J Clean Prod* 244:118824. <https://doi.org/10.1016/j.jclepro.2019.118824>
- Zhao M, Cheng W, Zhou C, Li M, Wang N, Liu Q (2017) GDP Spatialization and Economic Differences in South China Based on NPP-VIIRS Nighttime Light Imagery. *Remote Sens* 9:673. <https://doi.org/10.3390/rs9070673>
- Zhao M, Zhou Y, Li X, Cao W, He C, Yu B et al (2019) Applications of Satellite Remote Sensing of Nighttime Light Observations: Advances, Challenges, and Perspectives. *Remote Sens* 11:1971. <https://doi.org/10.3390/rs11171971>

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