

Consideration of wind as a criterion in Multi-criteria Decision Making for sustainable landfill siting

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ABSTRACT

Landfill site identification is a critical aspect of efficient solid waste management in urban areas, involving a multi-criteria approach to mitigate environmental degradation and risks to human health. Various studies have used multi-criteria decision making frameworks in combination with Geographical Information Systems to locate suitable landfill sites. However, the wind pattern which plays a significant role in dispersion of gases, odors and particulate matter, have frequently been undervalued or given minimal attention. The current study provides an original Geographical Information System-based approach that quantitatively incorporates wind speed, wind direction and calm days, in order to identify a suitable landfill site in Bhiwani city, Haryana, India. With the generation of nine grids covering the study area, the wind data were observed and analyzed for sixteen directions, subsequently integrated with other key criteria using weighted overlay in Arcmap software. With the least wind influence (6.98%) and least potential airborne pollutant dispersal to populated regions, Grid 6 was identified as the most suitable location for landfill establishment. The study demonstrates only the wind incorporation method and a wind driven map, not a final landfill site. As compared to prior studies where wind was considered qualitatively or neglected, the study illustrates that the proposed model quantitatively incorporates wind factors into a Multi-Criteria Decision Making approach, which offers a practical tool for decision makers and urban planners in similar environments.

Key words: *Landfill site selection, Geographic Information System, Multi-criteria decision-making, Solid waste management, Environmental modeling.*

Introduction

Landfill siting is an integral part of municipal solid waste management, as its location significantly influences possible impacts on environment and health risks to humans. The decomposition of municipal solid waste is a complex process that produces a mixture of various gases and odors, consisting of sulfur-containing substances, ammonia and volatile organic compounds (VOCs) that can have adverse impacts on population nearby. Considering such risks, the U. S. Environmental Protection

Agency regulates the emissions from landfills under the National Emission Standards for Hazardous Air Pollutants (NESHAP), which are listed in 40 Code of Federal Regulations (CFR), Part 63, Subpart AAAA (U.S. Environmental Protection Agency, 2024). Therefore, identifying an appropriate landfill site location is crucial to reduce adverse impacts and maintaining environmental sustainability.

In recent years, multi-criteria decision making (MCDM) methods in combination with Geographical Information System (GIS) have been widely used to optimize landfill site selection (Deswal and Laura,

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2018, Ali *et al.*, 2023). In circumstances where multiple criteria must be considered simultaneously, MCDM approaches are valuable tools for supporting decision-making and selecting the most suitable option (Majumder, 2015, Zandebasiri and Pourhashemi 2016). Decision-making for landfill site selection is typically a complex process involving socio-economic, environmental, and technological factors (Nazari *et al.*, 2011; Jamshidi *et al.*, 2015; Mardani *et al.*, 2017; Sonibare *et al.*, 2019). Various studies have assessed factors like distance from roads, residential areas; soil permeability, surface water bodies, slope, ground water table depth, and land use/land cover (Alavi *et al.*, 2013; Mussa and Suryabhadgavan, 2021; Guha *et al.*, 2023). Wind patterns, an important factor of odor and gas dispersion, have often been neglected or addressed only qualitatively in most landfill siting models, regardless of the fact that climatic factors are significant while evaluating environmental compatibility of landfill sites (Alavi *et al.*, 2012; Rezaeisabzevar *et al.*, 2020; Khanna and Chauhan, 2024;).

The main considerations for incorporating wind as a criterion in landfill site selection are environmental protection and safety to public health. A landfill site generates a foul smell or odor and liberates various gases, particulate matter, and pathogenic microbes; all these are influenced by wind, raising potential risk to the downwind population and environment (Shen *et al.*, 2020, Zewdie and Yeshanew, 2023). The above risks are influenced by several local factors, including:

- a) High organic matter in municipal solid waste
- b) High temperature
- c) High humidity and precipitation.
- d) The local wind conditions: Influence odors, gases and particulate matter to be blown from the dumpsite more frequently (Shen *et al.*, 2020, Srinivasan *et al.*, 2023)

In addition to these factors, the number of local calm days must also be considered when deciding the wind as criterion. The earlier researches have typically neglected wind related aspects from quantitative evaluation, or applied only to exclude general windward directions, without considering wind speed, wind direction, and calm days into main decision model (Shen *et al.*, 2020; Ahire *et al.*, 2021). The negligence of wind parameters from systematic incorporation in MCDM-GIS based framework indicates a significant gap, especially in urban areas where public health is potentially directly impacted

by downwind pollutant dispersion.

In order to address this gap, this study developed an original GIS-based index overlay model that integrates wind data, such as speed, direction and calm days, into a comprehensive MCDM framework for selecting landfill sites in Bhiwani city, Haryana, India. The results are intended to provide a feasible and reliable methodology for improving landfill siting decisions for urban areas with similar climatic and socio- environmental situations.

Methodology

Study area

Bhiwani city is located in Haryana state of India, lies at latitude of 28.78°N and longitude of 76.13°E was selected as the study area. The city has cool winters, hot summers, and variable wind patterns, associated with its semi-arid climate. According to projections derived from an earlier study (unpublished), the city is estimated to have population of 3,42,408 in 2035, producing approximately 160 tonnes of municipal solid waste per day (TPD), based on population growth rate stated by the Census 2011. Considering the future waste quantities, the landfill site suitability was evaluated for a ten year future prospective. The extent of the study area was established by extending it up to 5 km from the city's controlled area boundary, which was obtained from the master plan for 2025 (downloaded from Town and Country Planning Department, Haryana).

Criteria selection

Land use/land cover, soil permeability, ground water depth, road proximity, wind pattern, and slope were the six key criteria selected for the landfill site suitability analysis. These criteria were selected based on the literature review, expert consultation, and the availability of authentic data sources, and were derived from the author's earlier GIS-based landfill siting study (unpublished). These criteria are crucial to reduce potential threats to public health and the environment, while including socio-economic and environmental factors (Alavi *et al.*, 2012; Rezaeisabzevar *et al.*, 2020; Mussa and Suryabhadgavan, 2021; Guha *et al.*, 2023; Khanna and Chauhan, 2024).

The data sources for six criteria layers were:

- Land use/land cover (LULC): derived from False Color Composite (FCC) of Sentinel-2A im-

imagery (10m resolution), Copernicus Data Space Ecosystem, and using ArcMap software. Image acquisition date was 13 December, 2023.

- Soil permeability: field sampling at an interval of 1 km along major roads, up to 5 km beyond master plan boundary of study area.
- Ground water table depth: field data collected from local tube well owners.
- Road proximity: digitized from Sentinel-2A imagery and Google Earth mosaic, aligned with base map in ArcMap.
- Wind patterns: speed and direction were observed twice daily for one year, using a mobile application.
- Slope: derived from Copernicus GLO-30 DEM, European Space Agency (ESA) and extracted using ArcMap software.

Wind pattern visualization

The wind data was collected twice a day at fixed timings for one year. Wind data was observed for 16 directions: North (N), North-North-East (NNE), North-East (NE), East-North-East (ENE), East (E), East-South-East (ESE), South-East (SE), South-South-East (SSE), South (S), South-South-West (SSW), South-West (SW), West-South-West (WSW), West (W), West-North-West (WNW), North-West (NW) and North-North-West (NNW). The number of calm days (wind speed < 0.278 m/sec or 1 km/h) and the wind frequency (%) blowing in each direction, were calculated using formulas given below:

Wind % in a direction = (No. of observations in a direction / Total observations) × 100

Calm days percentage (%) = (No. of calm observations / Total observations) × 100

A wind rose diagram showing wind speed and prominent wind directions was generated based on

collected data using online wind rose generator tool. The visualization of wind rose provided an understanding of the directions that might have an impact on nearby areas. Encountering the challenges of integrating wind speed, direction, and calm days information into landfill site selection modeling, a grid-based technique was adopted to evaluate wind influence, quantitatively.

Grid formation in ArcMap for wind analysis

Defining the outer extent, which creates the boundary of the study area, is the first step towards integrating wind as a criterion in index overlay model to select a landfill site. In ArcMap software, the study area to be divided into nine equal grids (3 × 3), in this case, each measuring 9 km × 7km, having a raster cell size of 30 meters. Figure 1 illustrates the steps involved in grid generation for analysis.

Other criteria layers processing

ArcMap software was utilized to generate all thematic layers as raster datasets with a cell size of 30 meters.

Assigning weights to criteria and sub-criteria using Analytical Hierarchy Process (AHP)

A weighing strategy was designed based on author's earlier GIS-based landfill siting study (unpublished) and expert consultation in order to assign relative importance to each criterion in the index overlay model, which is expressed in the weights that have been assigned. In this case, the Weightage of wind as criteria depends upon the number of calm days. Here, the calculated percentage of calm days was used to decide the overall % influence of wind as a criterion. Wind is given higher Weightage when the calm days are also

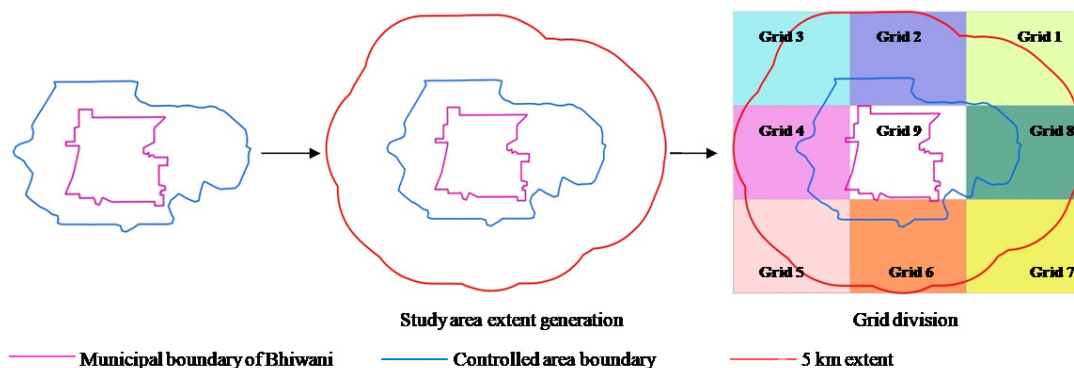


Fig. 1. Grid division of the study area for wind analysis

higher, since static air increases the potential for pollutant accumulation at local level. As a criterion, the weight assigned to the wind (7%) as an input data. The percentage influence of wind criterion was adopted from the detailed AHP-study by the authors. The relative Weightage of the wind sub-criteria depends upon the wind direction percentage blowing towards the city. This study emphasizes primarily on the quantification and incorporation of wind data into landfill site spatial modeling. The full multi-criteria decision making (MCDM) process, comprising Analytical Hierarchy Process (AHP) pair wise comparison, assigning weights, and consistency validation, is outside the scope of this paper, and has been described in a separate study by the authors.

Weighted overlay analysis in GIS environment

The study utilized weighted overlay analysis to assess wind influence throughout the study area. Wind rose data was overlaid with spatial grid zones to compute the wind direction percentages associated with each grid, assuring the uniformity with other thematic layers generated at 30 m resolution. The total percentage of wind influence across each grid was calculated by adding the wind frequencies of all directions impacting that specific grid. For example: Grid 1 had wind influence from directions-ENE, NE, and NNE with percentages of 3.63%, 1.60%, and 2.42%, respectively. The grid's overall wind influence was 7.65%. This strategy follows grid based wind frequency summation method applied in dispersion modeling (U.S. EPA, 2024).

The weighted overlay allowed the assigning of influence to wind as a criterion (7%), making the model more flexible to different sites. Moreover, the other thematic layers were generated for broader multi-criteria decision making (MCDM) procedure;

only the wind-based analysis is reported in the current analysis. A complete suitability map is not included in this paper, considering its primary goal incorporation of wind factor, which serves as an important step for larger landfill siting process.

Results and Discussion

Analysis of wind pattern

The findings of the wind data analysis for the study area showed that wind conditions were significantly calm, with majority of the observations had 1-2 km/h range. Calm days covered an extensive proportion i.e. 9.45% of the total observations, indicating limited potential for pollutant dispersal in the study area (Figure 2A). Following the directional pattern, it was demonstrated that the winds were primarily blew from west-northwest (WNW), north-west (NW), and west (W) directions (Figure 2B). The prevalence of calm days emphasized to a restricted pollutant dispersal chances, which is considered a crucial factor for landfill siting. In such stagnant circumstances, gaseous emissions and odors from a landfill may stay and accumulate, therefore increasing the potential of inconvenience and adverse impacts on nearby settlements.

Grid-based percentage of wind influence and priority ranking

Wind influence percentages showed variations across the nine grids of study area. Figure 3 illustrates the percentage of wind influence corresponding to each grid, generated from wind frequency and direction data. The percentage was higher in grids situated along the dominant wind directions, whereas grids situated distant from dominant wind directions showed lower influence.

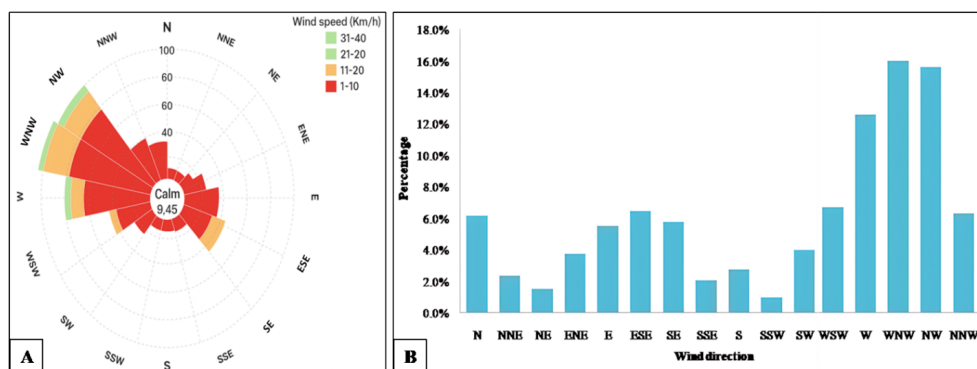


Fig. 2. (A) Wind rose of study area, (B) Directional wind analysis

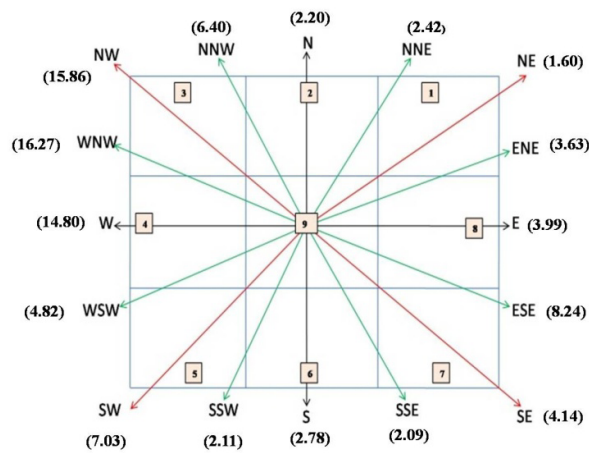


Fig. 3. Wind directions (%) influencing each grid of study area

Each grid was assigned a priority ranking based on the percentages of wind influence. Grid 6, with the lowest wind influence (6.98%), was given the first priority, indicating minimal potential of downwind dispersal of landfill related pollutants and odors. Grid 1, had 7.65 %, influence, was given second rank, followed by Grid 5 with 13.96%, at third priority. On the other hand, Grid 9 with 100% wind influence from all directions was accounted as unsuitable for landfill siting. The findings show that the dominant wind direction significantly affects the grids along their paths, whereas grids located opposite or perpendicular to the dominant wind experience reduced impact. Nevertheless, the present dump site in Bhiwani city, near Haluwas village is located in a zone that is 100% influenced by wind blowing towards the city from all directions. On the basis of wind analysis, the present dumpsite is placed in the least suitable zone, highlighting the significance of improved selection of the site considering wind-based parameters. Grid 3 and Grid 4, which were situated along the dominant wind directions, with higher wind percentages, were assigned lower priorities because of potential chances of pollutant transport towards populated areas.

Importance and contribution of integrating wind in MCDM models

The grid-based evaluation revealed that structured, quantitative integration of wind parameters such as wind speed, direction and calm days, significantly affects landfill siting decisions. The results showed that wind influence can be utilized to prioritize the

grids for landfill siting. Grid 6, with 6.98% influence of wind, was found to be the most suitable zone for reducing pollutant dispersion. The percentage of calm days was significant in assigning the percentage influence given to wind as a criterion (7%). This showed the necessity to consider stagnant wind, which causes pollutant accumulation risks.

The recent studies also highlighted the integration of wind as a significant factor. Asefa *et al.* (2021) found that in Harar city, Ethiopia, the predominant wind direction played a decisive role in landfill site selection, because downstream locations adjacent to settlements elevate odour and health concerns. Similarly, Srinivasan *et al.* (2023) employed wind analysis near a dumpsite to illustrate intensified downwind effects, further supporting the integration of wind in landfill site selection process. Neglecting wind parameters can lead to inappropriate landfill site selection and potentially enhanced risks to downwind populated areas. This study makes a significant contribution by demonstrating the wind influence percentages can be quantified into spatial grids, providing more accurate information to planners for landfill site selection. An important dimension is added by including calm days during assigning criterion Weightage, which addresses the potential risks of pollutant accumulation in these days, an aspect that was frequently neglected by prior studies.

The study emphasized on developing a method rather than sensitivity or comparative analysis. The outcomes were not compared with a model not including wind parameters. The adopted model was based on the wind data of one year and inter-annual variations may alter results in different climatic con-

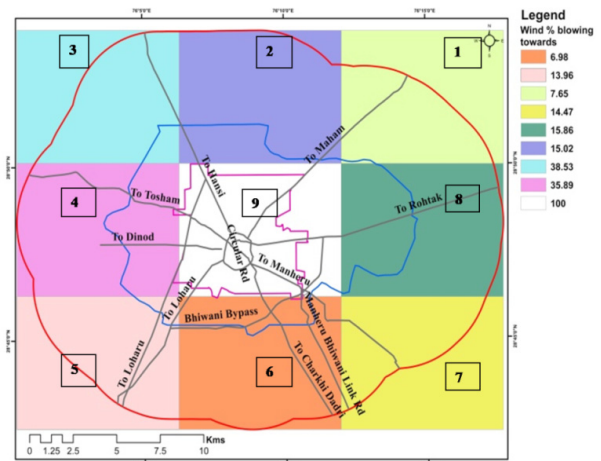


Fig. 4. Total wind percentages influencing each grid

ditions. Furthermore, no validation was conducted for air quality measurements, which is a crucial area for further research. Future research work may expand the model by including long-term meteorological datasets, analyzing seasonal variations of wind patterns, and correlating model results with actual air pollution data. These modifications would help to improve the utility of landfill siting model in urban areas.

Practical implications

The results provide an effective tool to urban planners and management authorities. Similar urban settlements with comparable climates can easily adopt the proposed grid-based wind integration methodology. The approach of including wind as a criterion for landfill siting decisions enhances environmental safety and contributes to greater public acceptance by addressing concerns over odor dispersion and quality of air. Additionally, the methodology is first study of its own kind to quantitatively include wind as a criterion for landfill site selection, and is replicable and compatible with GIS-MCDM frameworks used by urban planners and decision makers.

Conclusion

All over the world, the Geographic Information Systems are used effectively as a powerful tool in landfill site selection process. Its implementation becomes easy and fast when multi-criteria approach like analytical hierarchy process is used. The selection of landfill site becomes more accurate and environmentally compatible when wind pattern is taken into account. The study illustrated that percentage of calm days, wind direction and wind speed influence odor and pollutant dispersion to nearby communities. The GIS-based grid analysis of wind patterns in Bhiwani city revealed that integrating wind to multi-criteria decision making approach enhances the capability to locate sites that are socially and technically acceptable. This study underscores the necessity of incorporating wind criterion in MCDM frameworks for landfill site selection, thereby ensuring informed decision-making for sustainable municipal solid waste management. Protecting public health and the environment was the primary focus of the study by adopting a new methodology to integrate wind factor for landfill site selection procedure, which can be implemented to site a landfill in

urban areas.

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Conflict of interest-The authors declare that there is no conflict of interest.

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