Assessing Wind Direction Divergence in Relation to Urban Areas: A GIS Methodological Framework

Avaliação da Divergência da Direção do Vento em Relação às Áreas Urbanas: Um Arcabouço Metodológico com SIG

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Abstract

This study presents a methodology within a Geographic Information System (GIS) environment to evaluate the divergence of wind direction in relation to urban areas, with the objective of supporting the location of odor-generating facilities. The approach was organized into three main stages: obtaining the prevailing wind direction from interpolated raster data; calculating the orientation of each pixel relative to the nearest urban area; and comparing these directions through a function that computes the smallest angular difference adjusted within the range of 0° to 180°. The analysis produced a raster dataset that allows the identification of areas of greater convergence, where potential impacts on urban zones are more significant, and areas of greater divergence, more suitable for the location of facilities. The color-scale representation facilitated visual interpretation, distinguishing unfavorable and favorable regions for the location of odor-generating facilities. The approach demonstrates practical applicability for guiding the location of wastewater treatment plants, landfills, and industries, contributing to the mitigation of environmental and social impacts and providing support for sustainable urban planning policies.
Keywords:
Urban Planning, Odor Dispersion, Spatial Analysis, Environmental Impacts.

Resumo

Este estudo apresenta uma metodologia em ambiente de Sistemas de Informação Geográfica (SIG) para avaliar a divergência da direção do vento em relação às áreas urbanas, com o objetivo de subsidiar a locação de empreendimentos geradores de odores. A proposta foi organizada em três etapas principais: obtenção da direção predominante dos ventos a partir de dados interpolados em formato raster; cálculo da orientação de cada pixel em relação à área urbana mais próxima; e comparação entre essas direções, por meio de função que calcula a menor diferença angular ajustada no intervalo de 0° a 180°. A análise gerou um dado matricial que permite identificar áreas de maior convergência, nas quais os impactos potenciais sobre zonas urbanas são mais significativos,

e áreas de maior divergência, mais adequadas para instalação de empreendimentos. A representação em escala de cores facilitou a interpretação visual, distinguindo regiões desfavoráveis e favoráveis para instalação de empreendimentos que geram odor. A abordagem demonstra aplicabilidade prática para orientar a localização de estações de tratamento de esgoto, aterros sanitários e indústrias, contribuindo para a mitigação de impactos ambientais e sociais e oferecendo subsídios para políticas de planejamento urbano sustentável.
Palavras-chave:
Planejamento urbano, Dispersão de odores, Análise espacial, Impactos ambientais.

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I. INTRODUCTION

Urban air quality can be severely compromised by unpleasant odors, directly affecting the health and well-being of city inhabitants (Lewkowska et al., 2016; Canha et al., 2022). Wind direction relative to urban areas is an important criterion for the location of odor-generating facilities, since proper orientation can minimize olfactory impacts on residential and commercial zones (Sorte et al., 2019; Luckert et al., 2023). Types of facilities that frequently generate unpleasant odors and therefore must consider wind direction when being located include certain types of industries, tanneries, wastewater treatment plants (WWTPs), and sanitary landfills (Amkieh, 2020; Moumane; Al Karkouri; Batchi, 2025). By placing such facilities so that prevailing winds carry odors away from inhabited zones, it is possible to significantly reduce public discomfort, avoid health problems, and improve social acceptance of the enterprise.

The issue of unpleasant odors in urban areas, especially in residential zones, is regarded as a serious concern in cities. It negatively affects human health and well-being (Eltarkawe; Miller, 2019), and these areas are often devalued (Li; Li, 2018). Although strategies may be sought to minimize olfactory impacts, there is a lack of specific and effective methods to calculate wind direction divergence in relation to urban areas using Geographic Information System (GIS) tools. This methodological gap prevents an efficient assessment of best siting practices for such facilities, even though GIS is frequently used for this purpose (Shahmoradi; Isalou, 2013; Ribeiro et al., 2018; Hosseinzadeh; Momeni; Bagheri, 2024; Moumane; Al Karkouri; Batchi, 2025).

Studies have modeled wind direction divergence around geographic targets (such as urban areas, water bodies, or sensitive zones) using various approaches (Wong et al., 2010; Bernard et al., 2023). Statistical methods quantify directional wind variability from observations (e.g., Silva et al., 2016), while deterministic (or hybrid) models simulate how terrain and buildings deflect atmospheric flow, often integrating spatial data in GIS to represent local characteristics (Bernard et al., 2023). The input data for these models range from weather station records and local sensor networks to global climate reanalyses such as ERA5 (C3S, 2017), which cover

large regions but require downscaling - a refinement process that adapts regional-scale information to reflect more detailed variations in heterogeneous local environments (Alkhalidi et al., 2025).

This study aims to present a methodology for obtaining wind direction divergence in relation to urban areas in a raster dataset for use within a GIS environment. This approach seeks to fill a gap in the literature by providing a more precise and practical method for analyzing wind direction, contributing to improved urban and environmental management.

II. Materiais e Métodos

The calculation of wind direction divergence in relation to urban areas was based on the following steps: obtaining the prevailing wind direction; obtaining the orientation of pixels relative to the nearest urban area; and comparing the prevailing wind direction with the orientation of pixels in relation to the nearest urban area. This process makes it possible to identify areas where wind divergence is greater, indicating sites that are more suitable for the installation of odor-generating facilities, thereby minimizing impacts on the population.

Prevailing Wind Direction

Wind data were obtained from the annual prevailing wind direction map of Brazil (Amarante et al., 2001). This product is available so that the entire national territory has a wind rose representation approximately every 200 km. For use in GIS, the center of each wind rose was vectorized as a point, and the prevailing direction in degrees (0–360°) was recorded as an attribute.

The circular nature of the variable makes direct interpolation in degrees unfeasible due to the discontinuity in the vicinity of 0° to 360°. To circumvent this effect, we converted each direction θ (in radians) into linear components of the unit circle (Eq. 1 and 2). These components now represent two continuous scalar fields, suitable for usual spatial interpolation methods.

$$x = \cos(\theta) \qquad \text{Eq. 1}$$
$$y = \sin(\theta) \qquad \text{Eq. 2}$$

Where x represents the component on the horizontal axis (east–west) of the unit vector; $\cos(\theta)$ is the cosine function applied to the angle θ of the prevailing wind direction; y is the component on the vertical axis (north–south) of the unit vector; and $\sin(\theta)$ is the sine function applied to the angle θ.

These two scalar fields (x and y) were interpolated separately in SAGA GIS using the Multilevel B-Spline interpolator (Lee; Wolberg; Shin, 1997), which is suitable for scattered data. This algorithm was chosen because it produces a smooth surface without unnecessary complexity for the purpose of the study. The procedure was

carried out in geographic coordinates, with a pixel size of 0.006 degrees chosen arbitrarily. After interpolation, the estimated fields $\hat{x}$ and $\hat{y}$ were recombined to reconstruct the prevailing wind direction (Eq. 3):

$$\theta_{wind} = \left(arctan2(\hat{y}, \hat{x}) \cdot \frac{180}{\pi} + 360 \right) mod\ 360 \qquad \text{Eq. 3}$$

Where $\hat{x}$ represents the interpolated raster of the cosine of the angle; $\hat{y}$ is the interpolated raster of the sine of the angle; *arctan2* is the two-variable arctangent function, which returns the angle in radians; the factor $\frac{180}{\pi}$ converts radians to degrees; and *mod360* adjusts the wind direction orientation (θ_{wind}) to the range of 0 to 360. The final raster represents the spatial surface of the prevailing wind direction for each pixel.

Direction of Pixels in Relation to the Nearest Urban Area

The wind direction raster dataset was imported into the QGIS GIS software, and each pixel was converted into a point vector dataset, preserving wind direction orientation (in degrees) in the attribute table. Additionally, the land use and land cover raster dataset from the MapBiomas Project, Collection 10, corresponding to the most recent year (Souza Júnior et al., 2020), was used. From this collection, the urban area class was extracted and converted into a polygon vector format.

Using the "Distance to Nearest Hub" tool, line vectors were generated by connecting each point from the wind direction pixel layer (as the source layer) to the nearest urban area polygon (as the destination layer). This procedure preserved, in the line layer, the same identifier (ID) as the original point layer (source).

Subsequently, the line directions were calculated, representing the orientation from each point to the nearest urban area polygon. By concatenating the data using the same identifier, it was possible to obtain one column with the wind direction and another column with the pixel orientation relative to the nearest urban area.

Calculation of Wind Direction Divergence in Relation to Urban Areas

Finally, a function was developed to compare the values of the wind direction column with the direction of each pixel relative to the nearest urban area. This function calculates the absolute angular difference between the two directions and compares this difference with a predefined limit, always returning the smallest angle between them. This is useful for measuring the discrepancy between two angular directions, ensuring that the result lies within the range of 0° to 180°.

For example, if the prevailing wind direction is 10° and the direction of the pixel relative to the nearest urban area is 350°, the absolute difference between these angles is calculated as 340°. Since this difference is greater than 180°, the adjustment "360 − 340" is applied, resulting in 20°. Therefore, the smallest angular difference between 10° and 350° is 20°.

In another example, suppose the prevailing wind direction is 45° and the direction of the pixel relative to the nearest urban area is 100°. As this difference is less than or equal to 180°, no further adjustment is needed, and the smallest angular difference between 45° and 100° is 55°.

The difference between the prevailing wind direction (θ_{wind}) and the direction of a location relative to the nearest urban area (θ_{urb}) can be mathematically represented (Eq. 4).

$$\Delta D = \min(|\theta_{vento} - \theta_{urb}|, 360° - |\theta_{vento} - \theta_{urb}|) \qquad \text{Eq. 4}$$

Where θ_{wind} corresponds to the wind direction angle and θ_{urb} to the direction of the pixel relative to the nearest reference urban area. This formulation ensures that the angular difference ΔD represents the adjusted angular difference, guaranteeing that the resulting value always falls within the range of 0 to 180 degrees.

Since the data are in vector format, they were rasterized based on the attribute table column using the reference raster of prevailing wind direction. The nearest neighbor method is suggested on the same grid and pixel size as the reference raster of prevailing wind direction to avoid modifications or interpolations of the original values that could generate new results.

The wind direction divergence data were also compared with historical wind data obtained from climatological stations, considering a climatological average from 1990 to 2020, represented in a wind rose chart (IEM, 2025). This comparison allowed the assessment of the interpolated pattern against long-term observations.

III. RESULTS

From the interpolation of prevailing wind direction data provided by Amarante et al. (2001), a raster dataset was obtained with angular values for each pixel adjusted to the range of 0° to 360°, with North defined as 0° and progression in a clockwise direction (Figure 1).

The spatial extent shown corresponds to a portion of Brazilian territory (Figure 1) that includes the states of the Southeast region, as well as Goiás, Paraná, and southern Bahia. In this area, the prevailing wind direction is predominantly toward the East (E), followed by the Northeast (NE) and Southeast (SE). This pattern reflects the regional variability of the wind regime and its continuous spatial organization in the generated raster (Figure 1).

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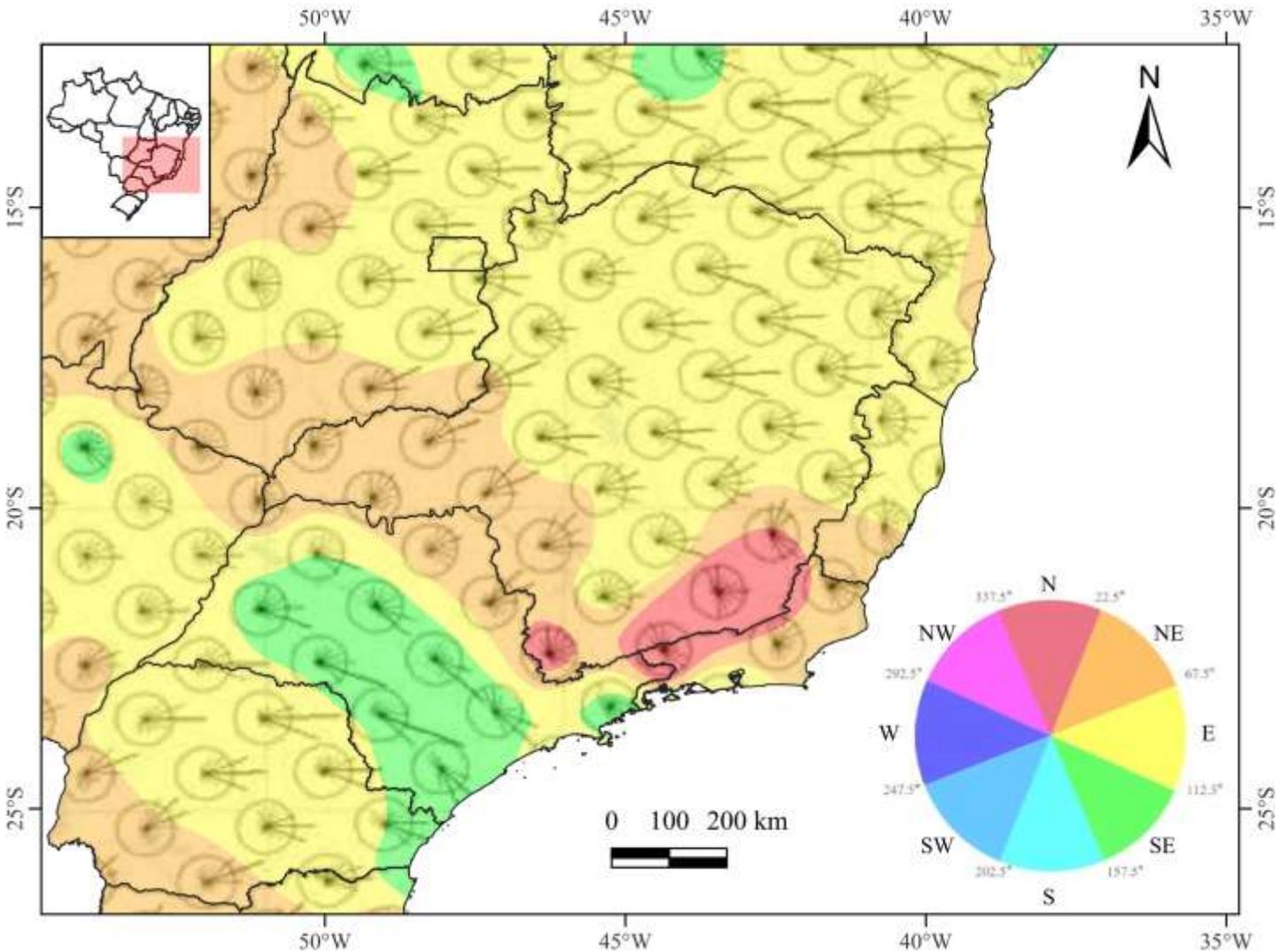**https://revistas.ufpr.br/raega**

Figure 1 – Representation of prevailing wind direction in raster format. The data are displayed using an octant color scheme, overlaid with the wind rose map obtained from Amarante et al. (2001). Source: The authors (2025).

Next, the spatial analysis process was carried out in the QGIS GIS software to examine wind direction in relation to urban areas (Figure 2). Initially, the wind direction raster data were converted into a vector point format, preserving the orientation values in degrees in the attribute table. In parallel, land use and land cover data from the MapBiomas Project, Collection 10, were used to extract and convert urban areas into vector polygon format.
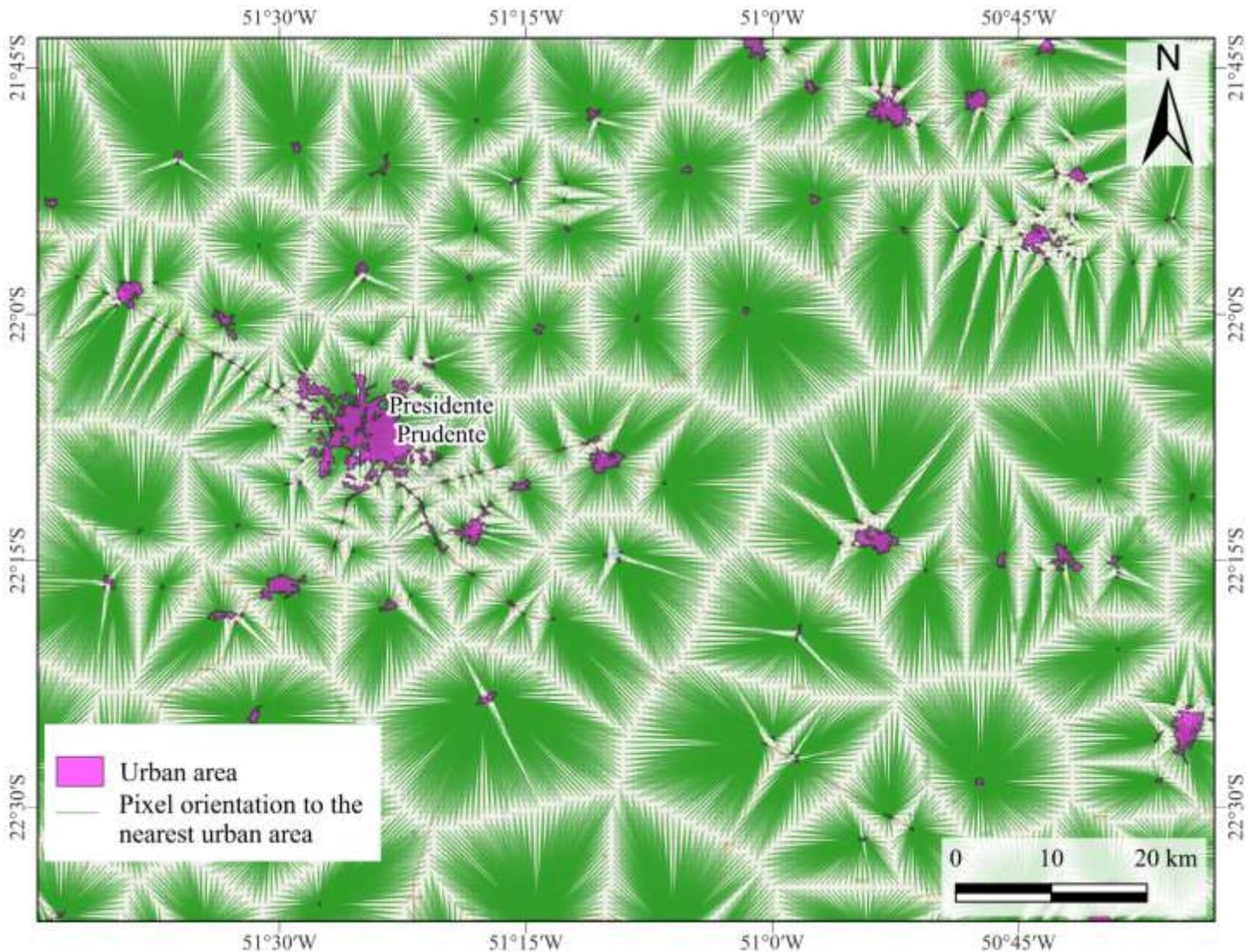
Figure 2 – Generation of lines connecting the points derived from pixels to the nearest urban area. Source: The authors (2025).

Using the "Distance to Nearest Hub" tool, lines were generated to connect each wind direction point to the nearest urban area (Fig. 2), while maintaining the same identifier (id) as the point layer. The directions of these lines, calculated from the points toward the nearest urban polygons, were integrated into the attribute table. This made it possible to merge the information and create columns that display both wind direction (Fig. 1) and pixel direction relative to the nearest urban area (Fig. 2), providing a detailed analysis of the interaction between wind patterns and urban areas.

The process of comparing wind directions with the pixel directions relative to the nearest urban areas also included the final step of rasterizing the vector data using the nearest neighbor method, preserving the original values without modifications or interpolations. In this case, the values range from 0° to 180°,

representing greater convergence and divergence between prevailing wind direction and the pixel direction relative to the nearest urban area (Figure 3).
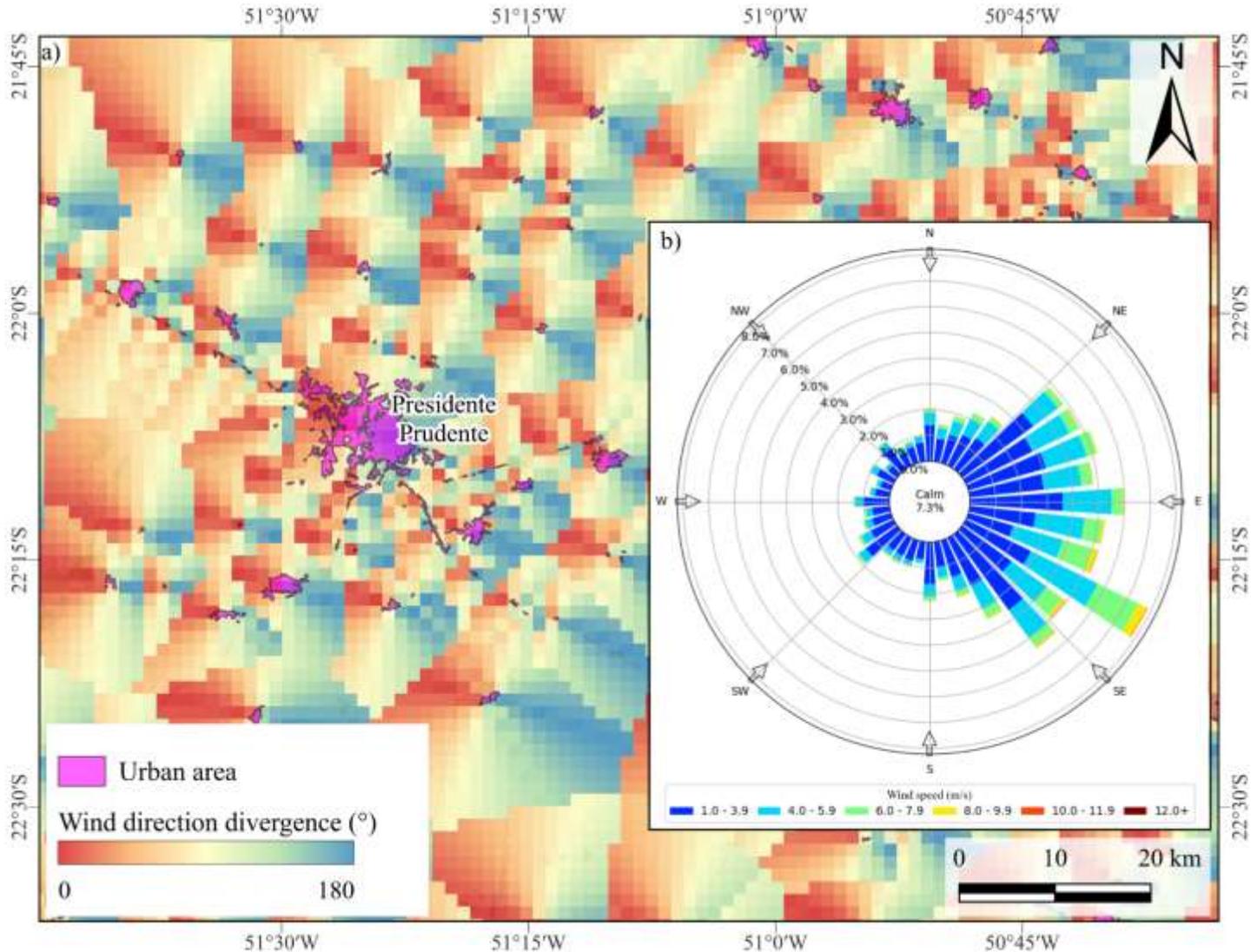

Figure 3 – Representation of wind direction divergence in relation to the urban area. a) Values range from 0 to 180°; the higher the value, the greater the divergence. Warm colors represent greater convergence of prevailing wind direction, while cool colors represent greater divergence. b) Wind rose of the city of Presidente Prudente, Southeastern Brazil, according to the Iowa Environmental Mesonet. Source: The authors (2025) and IEM (2025).

For the location of a WWTP, for example, this product would allow the avoidance of areas (pixels in the raster representation) with greater convergence between the prevailing wind direction and the orientation of the site relative to the nearest urban area. The color palette used in the figure facilitates the visual interpretation of the results. Warm colors (such as red and orange) represent areas with greater convergence between wind direction and the orientation of pixels relative to urban areas, while cool colors (such as blue and green) represent areas with greater divergence (Figure 3).

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IV. DISCUSSION

Contributions of Wind Divergence Modeling to Public Policies

The analysis of wind direction in odor dispersion is an important factor for understanding the dynamics of air pollution in communities. The location of odor sources and variations in wind direction influence public perception of odors (Eltarkawe; Miller, 2019). Spatial analysis of wind direction in relation to urban areas allows the location of odor-generating facilities, such as wastewater treatment plants, sanitary landfills, and factories that emit polluting gases (Yildirim et al., 2022). By considering the divergence between wind direction and the orientation of pixels relative to urban areas, it is possible to identify regions with lower probability of odor dispersion into residential and commercial areas, thereby minimizing environmental and social impacts.

The use of geographic data and GIS techniques, as employed in this study, represents an advance in the analysis and management of environmental impacts in urban areas. Integrating information on wind direction and the spatial distribution of urban areas makes it possible to identify odor dispersion patterns and plan the location of potentially polluting facilities (Shahmoradi; Isalou, 2013; Yildirim et al., 2022; Zhou et al., 2022; Moumane; Al Karkouri; Batchi, 2025). This approach provides a more comprehensive understanding of the interaction between wind patterns and urban areas, making it useful for urban and environmental planning.

The application of this methodology in other geographic areas and in different urban contexts may contribute to the development of more effective public policies to combat air pollution and promote quality of life in cities. This type of study has the potential to guide governmental decisions and urban planning practices aimed at mitigating environmental impacts and promoting more sustainable and healthier cities.

Understanding the dynamics of wind direction in relation to urban areas is relevant for achieving several Sustainable Development Goals (SDGs) established by the United Nations (UN, 2015). The analysis of wind patterns and their interaction with urban areas contributes to SDG 11: "Sustainable Cities and Communities." By identifying areas where wind direction converges more strongly with urban areas, this study provides information that supports sustainable urban planning, fostering healthier and more livable urban environments. The practical application of the results is also aligned with other SDGs, such as SDG 3: "Good Health and Well-Being." By avoiding the location of odor-generating facilities in areas with greater wind convergence, there is a potential reduction in public health risks associated with exposure to unpleasant odors.

Study limitations

By considering only the prevailing direction from the historical wind direction dataset, this study presents some limitations. The use of the prevailing direction may not fully capture seasonal variations in wind direction throughout the year, such as locations with bimodal wind orientation patterns (Fig. 4). In regions with distinct seasonal patterns, such as changes in atmospheric circulation, this metric may underestimate or overlook these fluctuations, resulting in a less accurate representation of wind patterns.
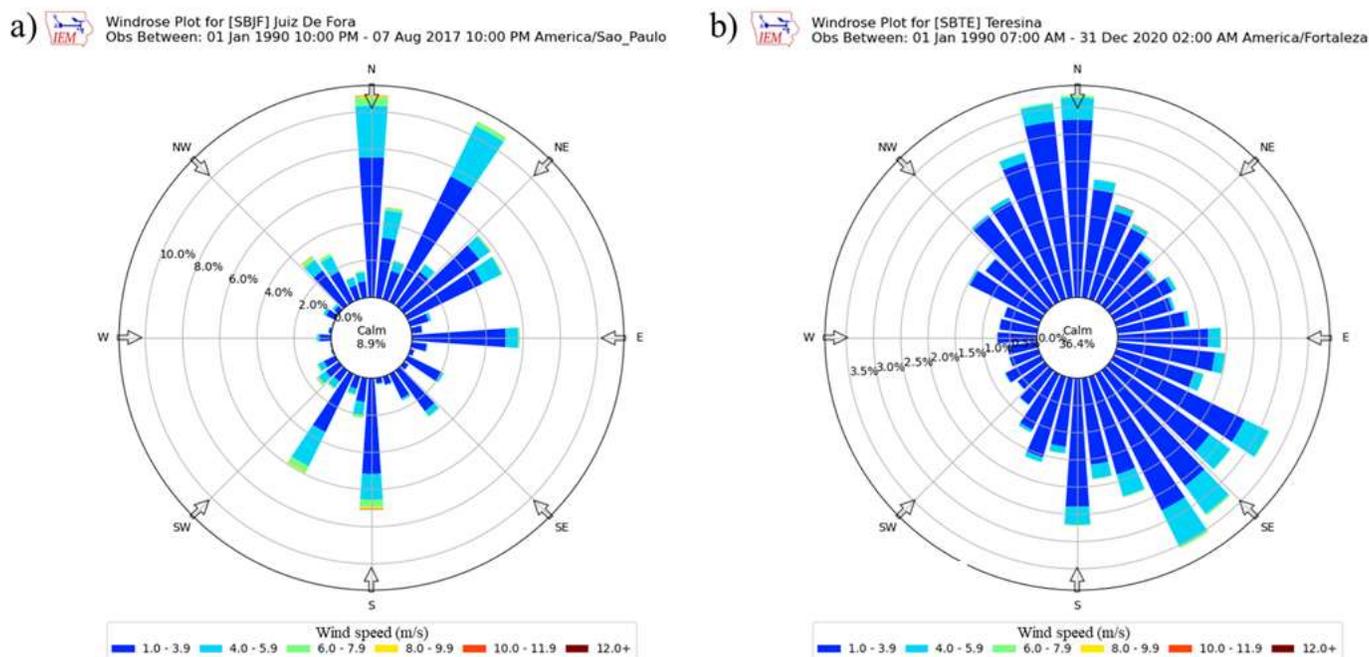

Figure 4 – Multimodal wind direction pattern. a) For the Juiz de Fora (MG) station, the prevailing northward (N) direction is accompanied by a southward (S) orientation; b) In Teresina (PI), the prevailing northward (N) orientation is followed by a southeastward (SE) orientation. Source: IEM (2025).

In addition, the prevailing direction does not account for short-term variations in wind direction that may occur due to transient meteorological phenomena, such as high- or low-pressure systems, cold fronts, or extreme events. These short-term variations can significantly affect odor dispersion and should be considered for a more comprehensive analysis of wind patterns. Another limitation is the lack of consideration of long-term trends in wind direction, such as those associated with climate change.

A complementary path to estimate prevailing wind direction is the use of global climatological datasets, such as the ERA5 collection from the Copernicus Climate Change Service (C3S, 2017). This dataset provides atmospheric reanalysis data with high temporal and spatial resolution, allowing wind direction to be calculated from the zonal (u) and meridional (v) components. The use of such data broadens analytical possibilities by enabling the assessment of wind patterns at different temporal scales and the identification of seasonal

variations or long-term trends, serving as a complementary alternative to the methodology presented in this study.

The choice of the input data scale has a direct impact on the ability of the analysis to represent the local environment. The input dataset used in this study (Amarante et al., 2001) falls within a broad-scale framework but is not suitable for representing microscale phenomena (Lewis et al., 2017). Local phenomena, such as winds channeled between buildings, turbulence induced by surface roughness, and short-duration gusts, cannot be captured by regional-scale data or by annual climatological averages.

Ultimately, the consequence of using large-scale data for a local application lies in the potential inadequacy of the analysis for decision-making. The calculated divergence may not reflect the airflow at a specific site, since prevailing regional wind conditions do not apply uniformly to a particular location. An area that the model identifies as having "greater divergence" based on low-resolution data may, in reality, be subject to microscale airflows that channel odors toward urban areas. This mismatch between the input data scale and the problem scale (the local location of an odor source), in addition to multimodal winds, constitutes a methodological limitation that should be acknowledged to ensure the safe and effective application of the tool, though it does not preclude its use if the analyst is aware of and accounts for these considerations.

V. Conclusions

The analysis of wind direction in relation to urban areas enables the strategic location of potentially polluting facilities, such as wastewater treatment plants and landfills. The approach presented in this study makes it possible to identify areas with lower potential for odor dispersion into residential and commercial zones, thereby mitigating negative environmental, social, and health impacts.

The use of geographic data and GIS techniques represents an advance in the analysis and management of environmental impacts in urban areas. By integrating information on wind direction and the spatial distribution of urban areas, it is possible to identify patterns and strategically plan the location of polluting facilities, contributing to more sustainable urban planning.

The method presented allows the development of a raster product representing the divergence of prevailing wind direction in relation to the nearest urban area. This is useful for data modeling within a GIS environment.

This methodology has the potential to contribute to the development of more effective public policies to combat air pollution and promote quality of life in urban areas. By providing inputs for sustainable urban

planning, this study can guide government decisions and urban planning practices aimed at mitigating environmental impacts and fostering healthier and more livable urban environments for residents.

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