



DATA ANALYTICS MODEL OF THE ACCESSIBILITY-VULNERABILITY RELATIONSHIP: RISK SCENARIOS IN URBAN AREAS

Modelo de analítica de datos de la relación accesibilidad-vulnerabilidad: Escenarios de riesgo en ciudades

Jose-David Sánchez-Grajales 
Universidad del Valle, Cali, Colombia. 
jose.d.sanchez@correounivalle.edu.co

Víctor Bucheli 
Universidad del Valle, Cali, Colombia. 
victor.bucheli@correounivalle.edu.co

Ciro Jaramillo 
Universidad del Valle, Cali, Colombia. 
ciro.jaramillo@correounivalle.edu.co

Received: 03-09-2025

Accepted: 10-09-2025

Available online: 30-09-2025



ABSTRACT

A clustering model that examines the relationship between accessibility and vulnerability was proposed. The aim was to observe spatial accessibility variables through urban public transportation and assess the vulnerability of the population in urban areas. This model was tested in the context of the COVID-19 pandemic in the city of Cali. A hierarchical agglomerative clustering analysis was conducted on 22 communes in Cali, Colombia, at three different points in time. The Shapiro-Wilk test was used to assess the normality of the data grouped into the obtained profiles. The model identifies homogeneous groups and defines the zones of concern within the city of Cali. These zones provide insight into the risk scenario regarding accessibility-vulnerability profiles, including access to essential services such as healthcare and food for various population groups (more vulnerable or less vulnerable). The results revealed a new zoning of the city of Cali within the context of the COVID-19 pandemic risk scenario. The accessibility-vulnerability profiles were automatically identified, supporting strategic decision-making processes related to public policies, risk management, and land use management. New zoning of the city enables targeted attention to each area based on its specific characteristics, thereby addressing the complexity of the problem.

Keywords: accessibility-vulnerability relationship; complex systems; population dynamics; risk management; space-temporal clustering

RESUMEN

Se propone la construcción de un modelo de agrupamiento automático de la relación accesibilidad-vulnerabilidad. Específicamente, se busca observar las variables de accesibilidad espacial a través del transporte público urbano y la vulnerabilidad de la población en una ciudad. El modelo se probó para el escenario de riesgo de la pandemia de COVID-19 en la ciudad de Cali. Por lo anterior, se llevó a cabo un análisis de clustering aglomerativo jerárquico en 22 comunas de la ciudad de Cali, Colombia, en tres momentos temporales. Se evaluó la distribución de los indicadores en cada grupo, utilizando la prueba

How to cite: J.D. Sánchez-Grajales, V. Bucheli, and C. Jaramillo, "Data Analytics Model of the Accessibility-Vulnerability Relationship: Risk Scenarios in Urban Areas". *Revista Facultad de Ingeniería*, vol. 34, no. 73, e18085, 2025. <https://doi.org/10.19053/01211129.v34.n73.2025.18085>

de Shapiro-Wilk, para contrastar la normalidad de los datos agrupados en los perfiles obtenidos. El modelo permite identificar grupos homogéneos y definir zonas de atención en la ciudad. Estas zonas ofrecen un entendimiento del escenario de riesgo en términos de perfiles de accesibilidad-vulnerabilidad: acceso en transporte público a equipamientos esenciales como el sistema de salud y alimentos para diferentes grupos de población (más vulnerables o menos vulnerables). Los resultados revelan una nueva zonificación de la ciudad de Cali en el escenario de riesgo de la pandemia de COVID-19 los cuales se muestran mediante representación cartográfica. Se identificaron automáticamente perfiles de accesibilidad-vulnerabilidad. Estos resultados apoyan los procesos de toma de decisiones estratégicas, particularmente los relacionados con políticas públicas, gestión de riesgos y gestión del uso del suelo a partir de variables relevantes. La nueva zonificación de la ciudad permite atender de forma específica cada zona de acuerdo a sus características intrínsecas, logrando así gestionar la complejidad del problema.

Palabras clave: agrupamiento espaciotemporal; dinámica poblacional; gestión de riesgos; relación accesibilidad-vulnerabilidad; sistemas complejos.

MODELO DE ANÁLISE DE DADOS DA RELAÇÃO ACESSIBILIDADE-VULNERABILIDADE: CENÁRIOS DE RISCO EM CIDADES

RESUMO

Propõe-se a construção de um modelo de agrupamento automático da relação acessibilidade-vulnerabilidade. Especificamente, busca-se observar as variáveis de acessibilidade espacial por meio do transporte público urbano e a vulnerabilidade da população em uma cidade. O modelo foi testado para o cenário de risco da pandemia de COVID-19 na cidade de Cali. Para isso, realizou-se uma análise de clustering aglomerativo hierárquico em 22 comunas da cidade de Cali, Colômbia, em três momentos temporais. Avaliou-se a distribuição dos indicadores em cada grupo utilizando o teste de Shapiro-Wilk, a fim de verificar a normalidade dos dados agrupados nos perfis obtidos. O modelo permite identificar grupos homogêneos e definir zonas de atenção na cidade. Essas zonas oferecem um entendimento do cenário de risco em termos de perfis de acessibilidade-vulnerabilidade: acesso por transporte público a equipamentos essenciais, como o sistema de saúde e alimentos, para diferentes grupos populacionais (mais vulneráveis ou menos vulneráveis). Os resultados revelam uma nova zonificação da cidade de Cali no cenário de risco da pandemia de COVID-19, apresentada por meio de representação cartográfica. Perfis de acessibilidade-vulnerabilidade foram identificados automaticamente. Esses resultados apoiam os processos de tomada de decisão estratégica, particularmente aqueles relacionados a políticas públicas, gestão de riscos e gestão do uso do solo com base em variáveis relevantes. A nova zonificação da cidade permite atender especificamente cada zona de acordo com suas características intrínsecas, possibilitando assim gerir a complexidade do problema.

Palavras-chave: agrupamento espaço-temporal; dinâmica populacional; gestão de riscos; relação acessibilidade-vulnerabilidade; sistemas complexos.

1. INTRODUCTION

Cities face multiple latent risk scenarios, including natural disasters such as earthquakes [1-4] and floods [5-8], among others. Likewise, they may be exposed to armed conflicts [9-11] or civil unrest [12-13]. Other risk scenarios are linked to pandemics, such as SARS (2002-2003) [14-15] or COVID-19 (2019-2020) [16-17]. In these contexts, risk management, land-use planning, and more broadly, public policy require robust tools to support strategic decision-making.

In this study, we examined the relationship between accessibility and urban vulnerability, as cities are the primary arenas in which stakeholders make decisions. This translates into managing access to essential facilities, such as healthcare systems and food supplies, for different population groups, whether they are more or less vulnerable.

Several studies have proposed multi-criteria decision-making methods to assess natural disaster risks in China, clustering, and classifying regions based on diverse indicators [18]. Research applying spatial clustering to analyze demographic changes in flood-prone areas across five cities in the southern

United States highlights the heightened vulnerability of minority populations, thereby supporting more equitable decision-making [19]. Other studies have introduced a seismic risk assessment method that leverages machine learning to achieve high prediction accuracy and determine the seismic vulnerability of buildings in earthquake-prone areas [20]. Finally, a multidimensional ecological risk assessment in Japan's coastal zones using spatial cluster analysis and spatial principal component analysis identified high-risk areas and key factors critical to sustainable development [21].

In the case of COVID-19 and the use of data analytics tools to support decision making, a review of the literature reveals a variety of approaches. Some studies analyzed contagion patterns using the k-means clustering algorithm and factor analysis [22], while others explored immunization strategies through the HJ-Biplot method [23] or investigated contagion dynamics using Ward's clustering method [24]. In the urban context, research has incorporated aspects such as mobility patterns [25] and spatial accessibility to healthcare services using Ward's clustering method [26], highlighting areas of vulnerability and emphasizing spatial disparities through hierarchical clustering [27-28]. Additional studies have focused on the geographic distribution of healthcare accessibility by applying multi-criteria decision analysis [29-32].

However, the literature reveals that this work is a pioneer investigation in automatic clustering that examines the accessibility–vulnerability relationship. Addressing this gap is essential for developing tools that account for both urban infrastructure and capacities as well as the needs of populations according to their vulnerability levels. This study contributes an innovative analytical framework for strategic urban planning by integrating spatial accessibility and socioeconomic vulnerability using a hierarchical clustering model applied during the COVID-19 pandemic. The results generate data-driven zoning that identifies priority areas for interventions in public transport and essential facilities, such as healthcare and food supply, thereby optimizing the allocation of public resources according to differentiated risk profiles. The resulting maps and profiles provide quantitative inputs for targeted public policies, such as sustainable mobility plans or risk-mitigation strategies, fostering the development of more inclusive and resilient cities. This paper presents the results of applying the proposed model to the city of Cali during the COVID-19 pandemic. The model outputs deliver a new cartography and zoning scheme that supports decision making in addressing population vulnerabilities while also revealing the city's response capacity in a risk scenario and highlighting how these capacities should be reinforced in the face of future risks.

The remainder of this paper is organized as follows: Section 2 presents the materials and methods employed for the clustering analysis. Section 3 reports the results and describes the groups. Finally, Section 4 discusses the findings, limitations, highlights the contributions, and concludes the paper.

2. MATERIALS AND METHODS

A descriptive analytical approach was used in this study. The proposed model was implemented in two stages: building the dataset and training the hierarchical clustering algorithm, as shown in [Figure 1](#).

Stage one consists of two phases. In the data source phase, information was collected, and in the data preparation phase, the data were cleaned, standardized, transformed, and integrated into a datamart.

In the second stage of automated modeling, the relevant variables were selected for inclusion in the model and their spatial distribution was represented through cartographic mapping. The optimal number of clusters was determined using the silhouette method, after which the clustering model was trained.

For the evaluation phase, the Shapiro–Wilk test was applied to each group and variable to confirm the homogeneity of the clusters resulting from the hierarchical clustering model. Finally, in the

communication phase, Product (A) was developed, consisting of the cartography, and Product (B), which corresponds to the indicators for the identified groups.

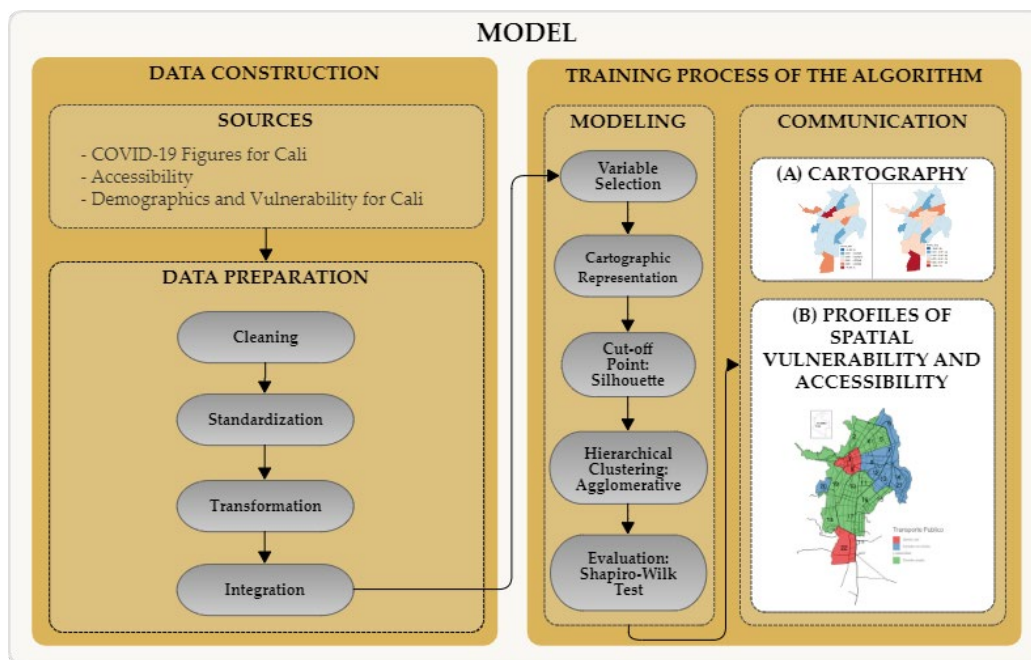


Figure 1. Process of constructing accessibility-vulnerability profile models through the SITM-MIO in SdC.

2.1 Data Construction

To characterize accessibility-vulnerability profiles, the variables of interest were organized along four dimensions: accessibility, COVID-19 indicators, demographics, and vulnerability. Each variable was constructed at the commune level, which corresponds to a grouping of neighborhoods. The study area is one of Colombia's main cities, referred to here as SdC. Administratively, the city is divided into 22 communes and 337 neighborhoods. The data construction considered the following time points in 2020: February, April, May, and September.

In terms of accessibility, the city currently offers several forms of public transportation, including the Integrated Mass Transit System (SITM) of the bus rapid transit (BRT) type, known as MIO (Masivo Integrado de Occidente), as well as taxis, among others. This study focuses on the SITM-MIO public transport system, with particular attention to its connection to priority facilities such as healthcare institutions, food markets, shopping centers, and intensive care units (ICUs). Spatial accessibility was assessed using gravitational measure [33] based on data from the SIGELO project database [34].

In addressing vulnerability, sociodemographic characterization data for each commune were drawn from the 2018 National Population and Housing Census conducted by the National Administrative Department of Statistics (DANE) [35]. Variables related to education, age distribution, employment status, socioeconomic stratification, and population density were obtained for this component. Finally, for the crisis scenario of COVID-19, a summary of COVID-19 cumulative cases includes data on confirmed cases reported by commune. The data were obtained from the official reports of the Municipal Mayor's Office of SdC [36]. The input variables used in this study are presented in [Table 1](#).

Table 1. Input variables used in the study.

Variable name	Temporality				Source
	Feb	Apr	May	Sep	
Accessibility to Food Supply through the SITM-MIO	x	x	x	x	SIGELO [34]
Accessibility to Shopping Centers via the SITM-MIO	x	x	x	x	
Accessibility to Healthcare Facilities through the SITM-MIO	x	x	x	x	
Accessibility to ICUs via the SITM-MIO	x	x	x	x	
COVID-19 Case Growth Rate		x	x	x	Town hall SdC [36]
Strata Delta: the difference between the highest and lowest socioeconomic strata	x				
Population Density (inhabitants/km ²)	x				
Proportion of residents employed in the informal sector	x				DANE [35]
Proportion of residents whose highest level of education is secondary school	x				
Proportion of adults aged 60 and over	x				

2.2 Training process of the algorithm

In this stage, thematic maps were generated for all variables included in the study using standard deviation mapping. The data were transformed into their corresponding z-scores, enabling direct comparison of the variable distributions [37]. This procedure was carried out using GeoDa 1.22 software [38].

For the automatic clustering model, we implemented an agglomerative hierarchical clustering approach using Euclidean distance as the similarity metric and average linkage as the optimization method [39]. Subsequently, a dendrogram was generated [40] and proceeded to a cutting process to define the clusters. The silhouette method was applied to determine the optimal number of clusters [40-41]. The highest silhouette coefficient obtained was 0.27, which led to the identification of three clusters. These three clusters correspond to the three accessibility–vulnerability profiles.

Information related to the identified profiles was described using summary statistics for each group or profile. In addition, the distribution of the indicators corresponding to each study variable within each group was analyzed using the Shapiro–Wilk test [42] to assess data normality. For 88% of the variables, the null hypothesis of normality was not rejected at the significance level of 0.05.

To conduct the analyses described, we used R 3.5.1 [43] and Python 3 [44], along with the scikit-learn [45] and SciPy Stats [46] libraries. Ethical principles were observed throughout the study. Moreover, the data employed were publicly available, and all information was anonymized.

3. RESULTS

This study presents an approach for applying automated data analytics tools to risk scenarios and highlights the potential of following the process outlined here when addressing such contexts. The proposed model enabled the identification of homogeneous groups and delineation of priority areas within the city. These areas provide insights into risk scenarios in terms of accessibility–vulnerability profiles. The findings reveal new ways of observing and managing the city of Cali in the context of the COVID-19 pandemic.

Regarding spatial accessibility by urban public transportation within the study period, the median of the gravitational measure showed the following patterns. For food supply, persistently high levels were observed in the central and southern sectors, with lower values surrounding the city center. For shopping centers, high values appeared near the center extending east and west, whereas low levels

were concentrated in the eastern part of the study area. For healthcare facilities, high accessibility values were located close to the center on both the eastern and western sides, with lower levels toward the western and eastern edges of the urban area. And for ICUs, high values persisted in the central and southern sectors, with low levels in the eastern and western parts of the city (see [Figures 2 and 3](#)).

For the crisis analyzed here, the spatiotemporal variation of positive COVID-19 cases in SdC exhibited marked heterogeneity. Initially, high values were concentrated in the southern, eastern, and northern regions. Subsequently, the highest levels were concentrated in the east, and later, the distribution became more dispersed, with elevated values reappearing from the south toward the west and north of the city. Regarding socioeconomic stratification, the greatest disparities were observed in the central-eastern area, whereas the most homogeneous conditions appeared in the southern portion of the study area. The population density reached its highest values in the eastern sector and parts of the north, in contrast to the longitudinal north-south axis, which showed the lowest levels within the area of interest. Informal labor and residents with secondary education as their highest level were predominantly located in a circular sector with its vertex in the city center, expanding significantly eastward with some clusters in the west, whereas the central north-south strip recorded the lowest values. Finally, the population aged 60 years and over was concentrated at higher levels in the central-northern band, with lower values in the eastern sector of the city ([Figure 4](#)).

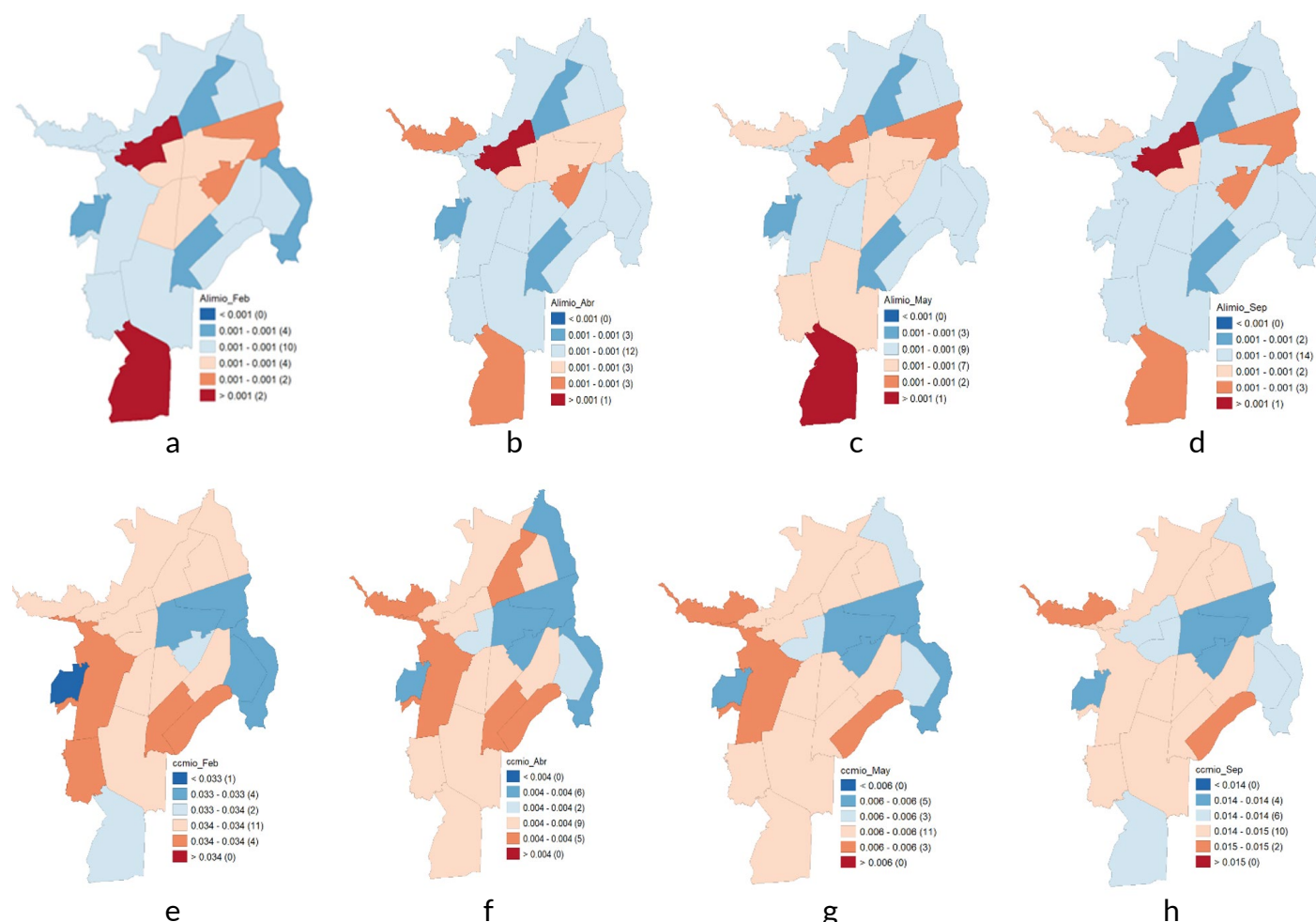


Figure 2. Cartographic representation by district of spatial accessibility in public transportation for 2020. Food supply: (a) February, (b) April, (c) May, and (d) September. Shopping centers: (e) February, (f) April, (g) May, and (h) September.

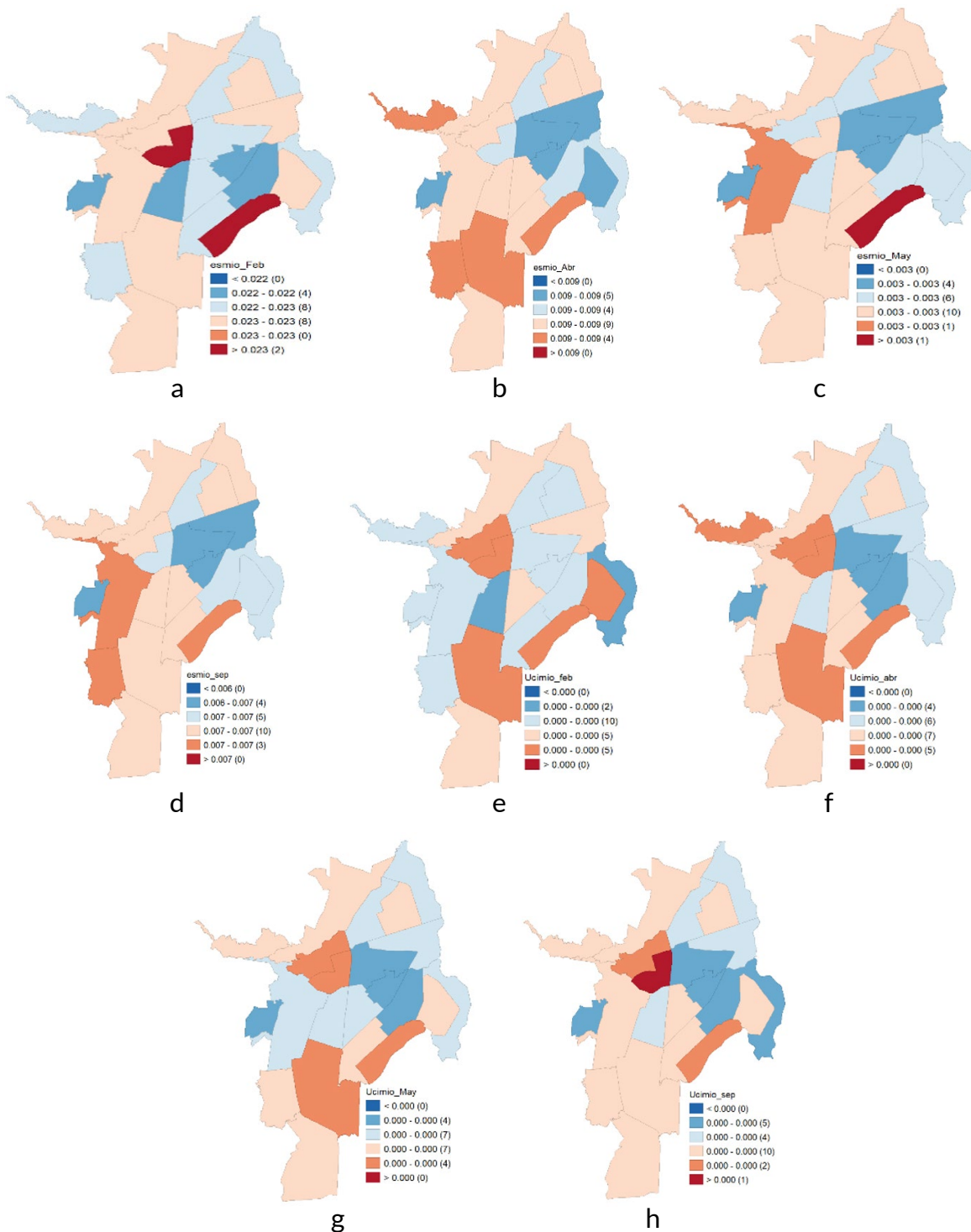


Figure 3. Cartographic representation by district of spatial accessibility in 2020 using public transportation. Health facilities: (a) February, (b) April, (c) May, and (d) September. ICUs: (e) February, (f) April, (g) May, and (h) September.

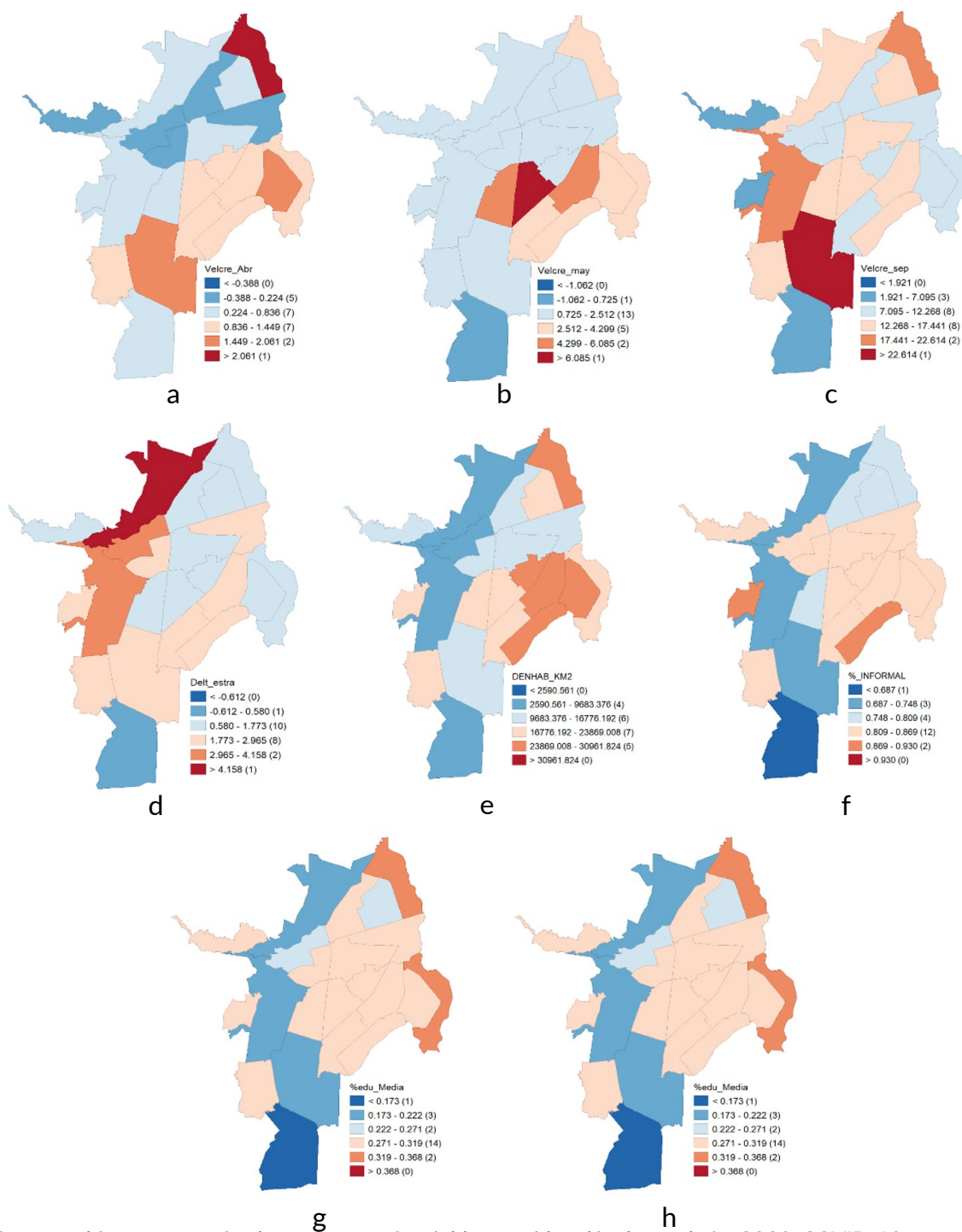


Figure 4. Cartographic representation by commune of variables considered in the study for 2020. COVID-19 case growth rates in: (a) April, (b) May, and (c) September. Change in socioeconomic strata (d), population density (e), proportion of residents working in the informal sector (f), proportion of residents with secondary education as the highest educational level attained (g), and proportion of adults over 60 years of age (h).

Cartographic representations reveal the complexity of the problem when incorporating both accessibility and vulnerability dimensions. Combined with information from the COVID-19 crisis, they highlight the challenges of making geolocated decisions in contexts where strategic planning requires the consideration of multiple dimensions. Furthermore, we recognize that the variables involved are geolocated and evolve over time. In this regard, this study seeks to provide insights into the development of tools that can support decision-making in crisis scenarios.

In this study, an agglomerative hierarchical clustering model was trained to identify the intrinsic patterns underlying the behaviors of accessibility, vulnerability, and crisis-related variables, as well as their georeferencing and temporality. A Shapiro-Wilk test was applied to statistically validate the resulting groups, thereby confirming the homogeneity of the clusters. For the three groups, the null hypothesis of normality was accepted for the majority of the variables considered. Specifically, the Shapiro-Wilk tests showed that in the first cluster, all variables followed a normal intracluster distribution, while in the remaining two clusters, 90% and 76% of the variables exhibited a normal intracluster distribution.

The agglomerative hierarchical clustering model generated three groups, each corresponding to a distinct geographic zone. This represents the initial result of the analysis, because the column positions were not included as inputs to the model. Nevertheless, the resulting clusters were composed of neighboring communes. Accordingly, the first cluster (shown in green in [Figure 5](#)), referred to as the “broad corridor,” delineates a longitudinal strip spanning the northwest and south-central areas. This group contained the largest number of communes, representing 50% of the total population of the city of Cali. It is composed of Communes 1, 2, 4, 5, 10, 11, 15, 16, 17, 18, and 19, forming a contiguous area that connects the southern and northern parts of the city through its west-central sector. Group two (blue group in [Figure 5](#)) was labeled as the “Northeastern Corridor and Siloé Hillside.” This cluster consisted of seven contiguous communes located in the northeastern sector of the study area, communes 6, 7, 8, 12, 13, 14, and 21, along with commune 20, situated separately in the western part of the city. This group has a total of eight communes. The third group (shown in red in [Figure 5](#)), referred to as “Center and South,” included Communes 3 and 9, which are contiguous in the city center, along with Commune 22, located separately at the southernmost end of the city.

The automatically derived groups formed zones with centripetal spatial characteristics around the city’s economic activity center. In most cases, these zones were continuous and encompassed the entire urban area, enabling the identification of homogeneous regions within the SdC. The territorial configuration revealed a pronounced center of gravity, closely associated with the city’s traditional business and commercial core.

The groups obtained—defined as accessibility–vulnerability profiles—display distinct characteristics, which are described below. The broad corridor profile includes the highest proportion of neighborhoods, inhabitants, and COVID-19 cases. It also records the second-highest average share of residents engaged in informal employment as well as the second-highest average proportion of residents whose highest educational level is secondary education. In addition, it ranks second in the average proportion of adults aged 60 and over.

The Northeast Corridor and Siloé Hillside profiles presented the second-highest proportion of neighborhoods, inhabitants, and COVID-19 cases. This group shows relatively high values, although not the highest, in the average share of informal workers and in the average proportion of residents with secondary education as their maximum educational level. However, it had the lowest average proportion of adults aged over 60 years.

Finally, the Central and Southern profiles had the smallest proportion of neighborhoods and inhabitants, which explains the lower rate of COVID-19 cases. At the same time, it shows the second-highest average proportion of residents working informally, the lowest average proportion of residents with secondary education as their highest level of education, and the highest average proportion of adults over 60 years of age.

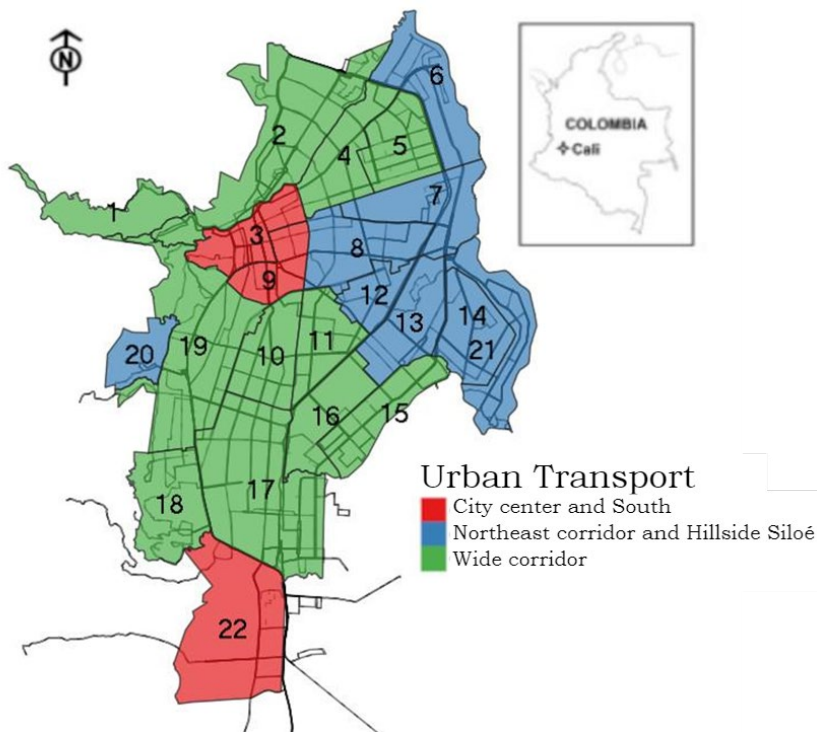


Figure 5. Cartographic representation of the groups obtained through the agglomerative hierarchical clustering method in SdC.

Overall, the profiles reveal that the Central and Southern groups differ from the other two, whereas the Broad Corridor and Northeast Corridor and Siloé Hillside profiles share similar characteristics, with values differing by only a few percentage points. This indicates that the profiles are shaped by both spatial accessibility to public transport (SITM-MIO) and the intrinsic vulnerabilities of the communities, which serve as descriptors of each group. The results confirmed that the profiles obtained corresponded to the distinctive patterns within each group (Table 2).

Table 2. Descriptive statistics of vulnerability profiles and spatial accessibility using SITM-MIO in SdC.

Cluster Profile: Accessibility- Vulnerability	No. of Neighborhoods	Neighborhoods (%)	Population (Inhab.)	Reported COVID-19 Cases	Reported COVID-19 Cases (%)	Pop. (%)	Average employed in the informal sector	Average Secondary	Average Age ≥60 (%)
The Central and Southern group	31	9	87,161	341	5	5	79	22	22
The Northeast Corridor and Siloé Hillside	114	34	717,171	2,942	46	40	84	30	15
The Broad Corridor profile	192	57	965,922	3,170	49	55	79	26	18

4. DISCUSSION

The results presented in [Figures 2–4](#) illustrate the complexity of making georeferenced decisions in a pandemic scenario, as reflected by the distinctive organization of each map. Decision making in a crisis context is inherently complex, with different patterns emerging across dimensions such as accessibility, vulnerability, and the crisis itself. The proposed tool enables the automatic recognition of intrinsic relationships within the data and the construction of clusters or profiles that support data-driven decision making in response to a crisis. The resulting clusters indicated that the city could be addressed in three zones with shared vulnerabilities and levels of accessibility. Intracluster similarity reveals that variables related to accessibility, vulnerability, and crises exhibit common patterns. These three zones effectively segmented the city, allowing interventions tailored to the specific characteristics of each population group and the implementation of measures adapted to each profile.

Thus, it is observed that the values of the variables of interest within each group are similar (intracluster similarity), whereas this pattern contrasts across the three groups identified in this study (intercluster similarity). This finding aligns with what has been reported in the literature for the case of SdC, likely due to its association with population vulnerability conditions [27], [47]. This pattern may be linked to the unmet basic needs of individuals in vulnerable situations, who were compelled to leave their residences for work despite the government having imposed full lockdown. Consequently, this also contributed to a reduction in spatial accessibility to various critical facilities.

In terms of spatial accessibility, using measures based on infrastructure and public transport provision [48], [49], as well as travel times to healthcare facilities [30], [31], the patterns and profiles identified in this study are consistent with previous research conducted in Colombia and specifically in SdC. In summary, the spatial behavior of the identified groups follows a concentric pattern, aligned with findings reported in the literature on spatial accessibility studies.

In the case of accessibility to healthcare facilities, the results obtained were consistent with other studies based on gravity models of ICU demand in the United States [26] and China [50]. This pattern may be associated with the city's expansion toward the periphery, which has intensified spatial separation on the western slopes and in areas near the Cauca River to the east. This aligns with the distribution of ethnic groups and populations living in situations of poverty, in contrast to other socioeconomic groups that are concentrated in the northern and southern areas of the city.

The spatial distribution of the groups identified in this study, which shows clusters of contiguous neighborhoods and districts, may be related to the synergy of several factors: the spatial arrangement of healthcare facilities providing diverse services, often concentrated in the centers of urban areas [51]; the location of the most vulnerable populations [52], frequently on the peripheries of cities [25] [53]; accessibility measures based on infrastructure and spatial separation [54]; and the stronger provision of public transportation systems in central urban areas, which coincides with the concentration of employment opportunities and generates “mandatory” trips for public transport users [29].

The limitations of this study include the fact that the model is highly data-dependent and that the results may vary depending on the variables considered. For future work, it is proposed to increase data granularity by considering spatial units at the neighborhood level to achieve a more detailed understanding of the findings and to incorporate the effects of demand competition on services. Additionally, other variables could be included to enrich the accessibility-vulnerability relationship, or information could be integrated from other types of crises such as health emergencies, climate-related events, or terrorist attacks.

Citizens' equity in access to opportunities is fundamental to social justice. However, urban planning has rarely incorporated research that evaluates and enhances equity in geographic accessibility [29]. This study provides a key tool for decision-making in urban management and public policy, offering scientific evidence to support concrete actions. The proposed zoning framework facilitates the integration of spatial equity criteria into territorial planning instruments, thereby enabling a more efficient distribution of critical infrastructure. Furthermore, the identified profiles support the design of differentiated protocols for emergencies, such as resource allocation during health crises, and prioritize investments in areas with high vulnerability and low accessibility. These contributions underscore the importance of data-driven approaches in building more just and resilient cities. This study provides structured information to inform public policy decisions by authorities responsible for population management, land use, crisis scenarios, and risk mitigation. Using this methodology, it is possible to make informed decisions more quickly, such as prioritizing actions for efficient resource allocation, achieving equitable impacts on vulnerable populations, and optimizing the interaction between these populations and urban land use.

AUTHORS' CONTRIBUTION

Jose-David Sánchez-Grajales: Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, writing-original draft.

Victor Buchelli: Conceptualization, data curation, investigation, methodology, project administration, supervision, validation, writing-review and editing.

Ciro Jaramillo: Conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, validation, writing-review and editing.

FUNDING

Universidad del Valle, Escuela de Ingeniería de Sistemas y Computación, Escuela de Ingeniería Civil y Geomática, and Ministry of Science, Technology and Innovation of Colombia (MINCIENCIAS) through the project “Sistema de gestión logística local en escenarios de riesgo de pandemia COVID-19 - SIGELO” with code 1106101577569.

REFERENCES

- [1] News Mundo BBC, *Terremoto en Japón: un fuerte sismo de magnitud 7,6 deja al menos 48 muertos y graves daños en el país asiático*, 2024. <https://www.bbc.com/mundo/articles/c19y0zn4p2no>
- [2] News Mundo BBC, *El terremoto de Haití deja ya más de 2.100 muertos y casi 10.000 heridos*, 2024. <https://www.bbc.com/mundo/noticias-internacional-58214474>
- [3] M. Contreras, J. Abarza, S. Dupont, C. Danniau, C. Castelli, P. Garrido, “Consultas de urgencia posteriores al terremoto del 27 de febrero 2010, en el hospital de Cauquenes,” *Revista Chilena de Salud Pública*, vol. 14, no. 1, pp. 26-33, Nov. 2010.
- [4] C. Nieves, J. Bommer, H. Crowley, J. Van Elk, “Global occurrence and impact of small-to-medium magnitude earthquakes: a statistical analysis,” *Bulletin of Earthquake Engineering*, vol. 18, no. 1, pp. 1-35, Jan. 2020. <https://doi.org/10.1007/s10518-019-00718-w>
- [5] M. Bertola, A. Viglione, D. Lun, J. Hall, G. Blöschl, “Flood trends in Europe: are changes in small and big floods different,” *Hydrology and Earth System Sciences*, vol. 24, no. 4, pp. 1805-1822, Apr. 2020. <https://doi.org/10.5194/hess-24-1805-2020>
- [6] S. Bossa, “Gestión del Riesgo en Cartagena atendió seis emergencias tras el paso de onda tropical 24,” *Caracol Radio*, 2024. <https://caracol.com.co/2024/07/28/gestion-del-riesgo-en-cartagena-atendio-seis-emergencias-tras-el-paso-de-onda-tropical-24/>
- [7] CN News, *China launches emergency response to floods in Guizhou, Yunnan provinces*, 2024. <https://english.news.cn/20240729/3ffd4e0f2f864c859fc61afb4a8a417d/c.html>
- [8] ReliefWeb, *Media Advisory: UN and partners support 100s of families affected by heavy rainfall and floods in Sa'dah Governorate*, 2024. <https://reliefweb.int/report/yemen/media-advisory-un-and-partners-support-100s-families-affected-heavy-rainfall-and-floods-sadah-governorate-enar>
- [9] G. Del-Lo, I. Marcelin, T. Bassène, B. Sène, “The Russo-Ukrainian war and financial markets: the role of dependence on Russian commodities,” *Finance Research Letters*, vol. 50, e103194, Dec. 2022. <https://doi.org/10.1016/j.frl.2022.103194>
- [10] M. I. Portillo, V. C. Vázquez, “En la guerra no solo matan las armas: impacto de los conflictos bélicos en las enfermedades crónicas,” *The Conversation*, 2024. <http://theconversation.com/en-la-guerra-no-solo-matan-las-armas-impacto-de-los-conflictos-belicos-en-las-enfermedades-cronicas-224519>
- [11] R. Torres, “El impacto paradójico de los conflictos bélicos en la economía española,” *El País*, 2024. <https://elpais.com/economia/negocios/2024-04-21/el-impacto-paradojico-de-los-conflictos-belicos-en-la-economia-espanola.html>
- [12] R Aríza, E. S. Velásquez, “La violencia estatal frente a la protesta social: el escuadrón móvil anti-disturbios (ESMAD) en Colombia,” *Revista Jurídica Derecho*, vol. 9, no. 13, pp. 19-38, 2020.
- [13] C. C. Basconzuelo, “Las protestas sociales situadas y conectadas. Una lente para abordar las desigualdades en la Argentina contemporánea,” *CRONÍA*, vol. 18, no. 1, e1, Oct. 2022.
- [14] K. Boutis, “The impact of SARS on a tertiary care pediatric emergency department,” *Canadian Medical Association Journal*, vol. 171, no. 11, pp. 1353-1358, Nov. 2004. <https://doi.org/10.1503/cmaj.1031257>

- [15] S. W. Chau, O. W. Wong, R. Ramakrishnan, S. S. Chan, E. K. Wong, P. Y. Li, *et al.*, “Long-term mental health impact of the 2002–2003 Severe Acute Respiratory Syndrome (SARS) outbreak,” *BMC Public Health*, vol. 21, no. 1, e670, Apr. 2021. <https://doi.org/10.1186/s12889-021-10701-3>
- [16] F. Angulo, L. Finelli, D. Swerdlow, “Estimation of US SARS-CoV-2 Infections, Symptomatic Infections, Hospitalizations, and Deaths Using Seroprevalence Surveys,” *JAMA Network Open*, vol. 4, no. 1, e2033706, Jan. 2021. <https://doi.org/10.1001/jamanetworkopen.2020.33706>
- [17] R. M. Barber, R. J. Sorensen, D. M. Pigott, C. Bisignano, A. Carter, J. O. Amlag, *et al.*, “Estimating global, regional, and national daily and cumulative infections with SARS-CoV-2 through Nov 14, 2021: a statistical analysis,” *The Lancet*, vol. 399, no. 10344, pp. 2351-2380, Jun. 2022. [https://doi.org/10.1016/S0140-6736\(22\)00484-6](https://doi.org/10.1016/S0140-6736(22)00484-6)
- [18] N. Chen, L. Chen, Y. Ma, A. Chen, “Regional disaster risk assessment of China based on self-organizing map: Clustering, visualization and ranking,” *International Journal of Disaster Risk Reduction*, vol. 33, pp. 196-206, Feb. 2019. <https://doi.org/10.1016/j.ijdr.2018.10.005>
- [19] M T. Islam, Q Meng, “Spatial dynamic analysis and thematic mapping of vulnerable communities to urban floods,” *Cities*, vol. 145, e104735, Feb. 2024. <https://doi.org/10.1016/j.cities.2023.104735>
- [20] O. Coskun, A. Aldemir, “Machine learning network suitable for accurate rapid seismic risk estimation of masonry building stocks,” *Natural Hazards*, vol. 115, no. 1, pp. 261-287, Jan. 2023. <https://doi.org/10.1007/s11069-022-05553-y>
- [21] M. Xu, H. Matsushima, “Multi-dimensional landscape ecological risk assessment and its drivers in coastal areas,” *The Science of The Total Environment*, vol. 908, e168183, Jan. 2024. <https://doi.org/10.1016/j.scitotenv.2023.168183>
- [22] K. Gohari, A. Kazemnejad, A. Sheidaei, S. Hajari, “Clustering of countries according to the COVID-19 incidence and mortality rates,” *BMC Public Health*, vol. 22, no. 1, e632, Apr. 2022. <https://doi.org/10.1186/s12889-022-13086-z>
- [23] E. J. Medina, J. L. Muñiz, E. Barco, “Análisis multidimensional de la evolución de la pandemia de la COVID-19 en países de las Américas,” *Revista Panamericana de Salud Pública*, vol. 46, e1, Jun. 2022. <https://doi.org/10.26633/RPSP.2022.49>
- [24] M. Roman, M. Roman, E. Grzegorzewska, P. Pietrzak, K. Roman, “Influence of the COVID-19 Pandemic on Tourism in European Countries: Cluster Analysis Findings,” *Sustainability*, vol. 14, no. 3, e3, Jan. 2022. <https://doi.org/10.3390/su14031602>
- [25] P. Vega Centeno, J. Robert, F. Demoraes, C. Moreno, V. Gouëset, “Estructura urbana y movilidad como factores de vulnerabilidad. Lima y Bogotá en tiempos de cuarentena,” *Bitácora Urbano Territorial*, vol. 32, no. 2, pp. 47-62, Apr. 2022. <https://doi.org/10.15446/bitacora.v32n2.99425>
- [26] J. Park, D. Goldberg, “An Examination of the Stochastic Distribution of Spatial Accessibility to Intensive Care Unit Beds during the COVID-19 Pandemic: A Case Study of the Greater Houston Area of Texas,” *Geographical Analysis*, vol. 55, no. 3, pp. 384-398, 2022. <https://doi.org/10.1111/gean.12340>
- [27] J. D. Sánchez, V. A. Bucheli, D. E. Cuartas, “Análisis de clustering para entender la vulnerabilidad poblacional relacionada con el COVID-19,” *Investigación e Innovación en Ingeniería*, vol. 10, no. 2, e2, Jul. 2022. <https://doi.org/10.17081/invinno.10.2.5973>

- [28] J. P. dos Santos, A. San Pedro Siqueira, H. L. Ferreira, H. Gomes, "Vulnerabilidade a formas graves de COVID-19: uma análise intramunicipal na cidade do Rio de Janeiro, Brasil," *Cadernos de Saúde Pública*, vol. 36, e00075720, May 2020. <https://doi.org/10.1590/0102-311X00075720>
- [29] L. G. Cuervo, E. Martínez-Herrera, D. Cuervo, C. Jaramillo, "Improving equity using dynamic geographic accessibility data for urban health services planning," *Gaceta Sanitaria*, vol. 36, pp. 497-499, May 2023. <https://doi.org/10.1016/j.gaceta.2022.05.001>
- [30] L. G. Cuervo, C. J. Villamizar, L. Osorio, M. B. Ospina, D. E. Cuervo, D. Cuervo, et al., "Cross-Sectional Equity Analysis of Accessibility by Automobile to Haemodialysis Services in Cali, Colombia, in 2020," *SSRN*, Jan. 2022. <https://doi.org/10.2139/ssrn.4299562>
- [31] L. G. Cuervo, E. Martinez-Herrera, L. Osorio, J. Hatcher-Roberts, D. Cuervo, M. O. Bula, et al., "Dynamic accessibility by car to tertiary care emergency services in Cali, Colombia, in 2020: cross-sectional equity analyses using travel time big data from a Google API," *BMJ Open*, vol. 12, no. 9, e062178, Sep. 2022. <https://doi.org/10.1136/bmjopen-2022-062178>
- [32] A., Avipsa, B. Kar, "A multicriteria decision analysis framework to measure equitable healthcare access during COVID-19," *Journal of Transport and Health*, vol. 24, e101331, mar. 2022. <https://doi.org/10.1016/j.jth.2022.101331>
- [33] W. Hansen, "How Accessibility Shapes Land Use," *Journal of Geographic Information System*, vol. 25, no. 2, pp. 73-76, May 1959. <https://doi.org/10.1080/01944365908978307>
- [34] MinCiencias, *Proyectos Mincienciaton*, 2023. <https://minciencias.gov.co/mincienciaton/proyectos>
- [35] DANE, *Procesamiento y Difusión de Microdatos*, 2020. <http://systema59.dane.gov.co/bincol/RpWebEngine.exe/Portal?BASE=CNPVBASE4V2&lang=esp>
- [36] Alcaldía de Santiago de Cali, *Boletines Epidemiológicos*, 2020. <https://www.cali.gov.co/publicaciones/152840/boletines-epidemiologicos/>
- [37] G. Buzai, C Baxendale, *Análisis socioespacial con sistemas de información geográfica*, Buenos Aires, Argentina: GEPAMA, 2006.
- [38] L. Anselin, I. Syabri, Y. Kho, "GeoDa: An introduction to spatial data analysis," *Geographical Analysis*, vol. 38, no. 1, pp. 5-22, Jan. 2006. <https://doi.org/10.1111/j.0016-7363.2005.00671.x>
- [39] S. Wierzchoń, M. Kłopotek, "Modern Algorithms of Cluster Analysis," In *Studies in Big Data*, Springer International Publishing, 2018. <https://doi.org/10.1007/978-3-319-69308-8>
- [40] C. Pineda Pertuz, *Aprendizaje automático y profundo en Python*, Ra-Ma S.A. Editorial y Publicaciones, 2022. <https://books.google.com.co/books?id=NEi9EAAAQBAJ>
- [41] V. Mirjalili, S. Raschka, *Python Machine Learning*, Marcombo, 2020. <https://books.google.com.co/books?id=5EtOEAAAQBAJ>
- [42] Stanford University, *Asymptotic Distribution of the Shapiro-Wilk W for Testing for Normality*, 1988. <https://doi.org/10.1214/aos/1176350172>
- [43] R Core Team, *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, 2020. <https://www.R-project.org/>
- [44] G. Van Rossum, F. Drake Jr, *Python reference manual*, Centrum voor Wiskunde en Informatica Amsterdam, 1995.

- [45] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, *et al.*, “Scikit-learn: Machine Learning in Python,” *Journal of Machine Learning Research*, vol. 12, pp. 2825-2830, 2011.
- [46] P. Virtanen, R. Gommers, T. E. Oliphant, M. Haberland, T. Reddy, D. Cournapeau, *et al.* “SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python,” *Nature Methods*, vol. 17, pp. 261-272, 2020. <https://doi.org/10.1038/s41592-019-0686-2>
- [47] D. Arango-Londoño, D. Ortega-Lenis, P. Moraga, M. Torres, F. Rodríguez-Cortés, “Spatial modeling and socioeconomic inequities of COVID-19 in the urban area of the city of Cali, Colombia,” *Spatial and Spatio-temporal Epidemiology*, vol. 44, e100561, Feb. 2023. <https://doi.org/10.1016/j.sste.2022.100561>
- [48] A. Grindlay, C. Jaramillo, C. Lizárraga, “Spatial Relationships between Mobility Opportunities and Constraints of Transport Disadvantages: The Case of Santiago de Cali, Colombia,” in *Urban Transport*, Sep. 2017, pp. 119-129. <https://doi.org/10.2495/UT170111>
- [49] C. Jaramillo, C. Lizárraga, A. L. Grindlay, “Spatial disparity in transport social needs and public transport provision in Santiago de Cali (Colombia),” *Journal of Transport Geography*, vol. 24, pp. 340-357, Sep. 2012. <https://doi.org/10.1016/j.jtrangeo.2012.04.014>
- [50] D. Xu, Q. Wu, Y. Feng, Yingkun, S. Wu, “COVID-19: Evaluation of Fever Clinic and Fever Sentinel Configuration—A Case Study of Harbin, China,” *Sustainability*, vol. 14, no. 15, e15, Jan. 2022. <https://doi.org/10.3390/su14159117>
- [51] M. M. Khan, A. Odoi, E. W. Odoi, “Geographic disparities in COVID-19 testing and outcomes in Florida,” *BMC Public Health*, vol. 23, e79, Jan. 2023. <https://doi.org/10.1186/s12889-022-14450-9>
- [52] J. Whitehead, P. A. Carr, N. Scott, R. Lawrenson, “Structural disadvantage for priority populations: the spatial inequity of COVID-19 vaccination services in Aotearoa,” *The New Zealand Medical Journal*, vol. 135, no. 1551, pp. 54-67, 2022. <https://pubmed.ncbi.nlm.nih.gov/35728170/>
- [53] H. Vivas-Pacheco, J. Ipiá-Astudillo, D. Rodríguez-Mariaca, “Precios del suelo y accesibilidad a las centralidades de empleo en Cali: análisis exploratorio con información 2015-2017,” *Estudios Gerenciales*, vol. 36, no. 155, pp. 141-155, May 2020. <https://doi.org/10.18046/j.estger.2020.155.3336>
- [54] C. A. Wilches Astudillo, C. Jaramillo, J. Murillo-Hoyos, “Accesibilidad y equidad espacial al transporte público para pacientes con enfermedad neurodegenerativa en Santiago de Cali, Colombia,” *Investigaciones Geográficas*, no. 76, e17589, Jul 2021. <https://doi.org/10.14198/INGEO.17589>