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GEOSTATISTICAL MICRO-VARIANCES ON THE ACCESSIBILITY OF URBAN PUBLIC SPACE: THE CASE OF COMALA, COLIMA, MEXICO [1]

MICRO-VARIANZAS GEOESTADÍSTICAS SOBRE LA ACCESIBILIDAD DEL ESPACIO PÚBLICO URBANO: EL CASO DE COMALA, COLIMA, MÉXICO

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Al entender la accesibilidad como el potencial localizado para la interacción humana y la integración urbano-territorial, la presente investigación tiene como objetivo analizar el patrón distributivo de la accesibilidad del espacio público urbano. Para ello, se propone un método para la integración geoestadística de indicadores socio-ambientales, de la calidad ambiental y de la eficiencia espacial-morfológica del tejido urbano; además, se incluyen datos perceptuales/subjetivos recopilados en sitio sobre a la accesibilidad y seguridad peatonal, calidad perceptual/sensorial y vitalidad urbana. Los resultados destacan una tendencia centralizadora sobre la accesibilidad urbana, asociada a la proximidad espacial al Centro Histórico de Comala, como factor protector del territorio. Asimismo, se registra que el 20.53% de la población se encuentra en núcleos consolidados con altos índices de accesibilidad, mientras que el 19.44% está vulnerado por su aislamiento funcional. A partir del análisis, se identificaron diez tipologías territorial-urbanas, basadas en su similitud geoestadística respecto a los indicadores de accesibilidad incorporados.

Palabras clave: accesibilidad, espacio público, ciudades pequeñas, análisis geoestadístico, morfología urbana

Understanding accessibility as the localized potential for human interaction and urban-territorial integration, this research aims to analyze the distributional patterns of accessibility in urban public spaces. To this end, a method is proposed for the geostatistical integration of socio-environmental, environmental quality, and the spatial-morphological efficiency indicators of the urban fabric. In addition, perceptual/subjective data collected on-site on pedestrian accessibility and safety, perceptual/sensory quality, and urban vitality are included. The results highlight a centralizing tendency in urban accessibility, associated with spatial proximity to the Historic Center of Comala, which serves as a protective factor for the territory. Furthermore, it is seen that 20.53% of the population is located in consolidated centers with high accessibility, while 19.44% is vulnerable due to their functional isolation. From the analysis, 10 territorial-urban typologies are identified, based on their geostatistical similarity, taking into account the accessibility indicators incorporated.

Keywords: accessibility, public space, small cities, geostatistical analysis, urban morphology

I. INTRODUCTION

Public space is a fundamental component for the articulation of urban systems of any scale and location (UN-Habitat, 2020), whose availability and quality have demonstrated benefits for the psychophysical and environmental and social health of the environment (Clarke et al., 2023; Houlden et al., 2019; Wang et al., 2023), as well as for the vitality and use of the urban environment (Gehl, 2004; Jin & Kim, 2024; Sevtsuk, 2020). However, the lack of planning, coupled with the accelerated, fragmented growth of contemporary urban systems, poses profound challenges for the effective articulation of Urban Public Space (UPS) in cities. In Mexico, there are inequalities in access to UPS, as only 24% of the population has UPS within 500 meters of their home (Secretariat of Agrarian, Territorial and Urban Development [SEDATU], 2019). This affects peripheral/marginalized areas to a greater extent (Vazquez et al., 2024) or small localities with <15,000 inhabitants, where 30.65% of the national population resides (SEDATU and National Population Council [CONAPO], 2024).

Based on the recognition of cities as spatial systems of potential interaction (Hansen, 1959; Hillier & Hanson, 2009), the analysis of accessibility addresses the degree of functional articulation provided by the urban environment, based on the effective link between population centers and points of interest (Sdoukopoulos et al., 2024; Wang et al., 2024). Such a connection can be facilitated or restricted by environmental factors that influence human displacement and interaction (Fonseca et al., 2021; Mitropoulos et al., 2023; Yu et al., 2024), which define the structures and hierarchies for the use of elements, zones, and sectors of the urban territory.

This research aims to analyze the spatial distribution of UPS accessibility to detect and explain geostatistical micro-variances at the urban lot as a Basic Geostatistical Unit [GU], and to identify patterns and trends in the urban territory. A methodology is proposed that includes indicators of 1) the socio-environmental articulation, 2) the environmental quality, and 3) the spatial-morphological efficiency of the urban fabric. In addition, the results of the physical evaluation on qualities of A) pedestrian accessibility and safety; B) the perceptual-sensory quality of the environment, and C) urban vitality are included, to calculate the Urban Public Space Accessibility Index [IAEP, in Spanish] and an adjustment factor [IAAEP] that weighs the qualitative evaluation and the proximity to the UPS.

The analysis was conducted in the urban area of Comala, a town in the state of Colima, northern Mexico, under the hypothesis of potential spatial heterogeneity in UPS accessibility. The results highlight the main factors that influence accessibility and the IAAEP, as well as the role of Public Space (gardens, parks, squares) in generating articulated nuclei of urban interaction and integration. As the first geostatistical study on Comala, the work provides substantial advances in efforts to ensure the equitable distribution of UPS quality and accessibility, and develops widely replicable methodological principles.

II. THEORETICAL FRAMEWORK

The principles of accessibility defined by Hansen (1957) are presented as the localized conjunction of two fundamental dimensions for human displacement and interaction:

I. The motivations [points of interest, facilities, habitational or work centers]
II. The facilities [psychophysical comfort, environmental conditioning factors for the efficiency of movements]

In this sense, contemporary studies on accessibility address the integration between elements of the urban environment, based on parameters related to: 1) the spatial proximity between points, zones, and sectors, and 2) the physical-spatial, functional, and perceptual activation of the setting to promote its use.

As for spatial articulation based on proximity, studies of "15-minute cities" refer to the comprehensive satisfaction of needs within the maximum distances of influence, prioritizing pedestrian modes of displacement. This provides a "human scale" to cities of any dimension and location, to detect consolidated nuclei with high indices of vitality, connectivity, and integration (Sdoukopoulos et al., 2024; Wang et al., 2024), or, in its lowest indices, of the possible presence of disconnected, marginalized, and vulnerable sectors within the territories.

The definition of parameters that encourage human displacement and interaction, as indicators of accessibility, has been approached by examining micro-variations in urban elements (road sections, areas, and/or sectors) that determine the preferences, frequencies, and intensities of UPS use (Fonseca et al., 2021). In this, aspects related to the sensory or perceptual comfort of the environment stand out (Jin & Kim, 2024), the symbolic and historical value of the surroundings (Bernabeu-Bautista et al., 2023; Clarke et al., 2023), as well as indices that define the connectivity and efficiency of the road network (Van Nes, 2021; Schön et al., 2025; Yu et al, 2024), to identify correlations between factors that influence socio-environmental interaction, thus defining hierarchies and typologies in the urban territory.

Urban public space refers to the physical space where the activities and dynamics that define life in cities,

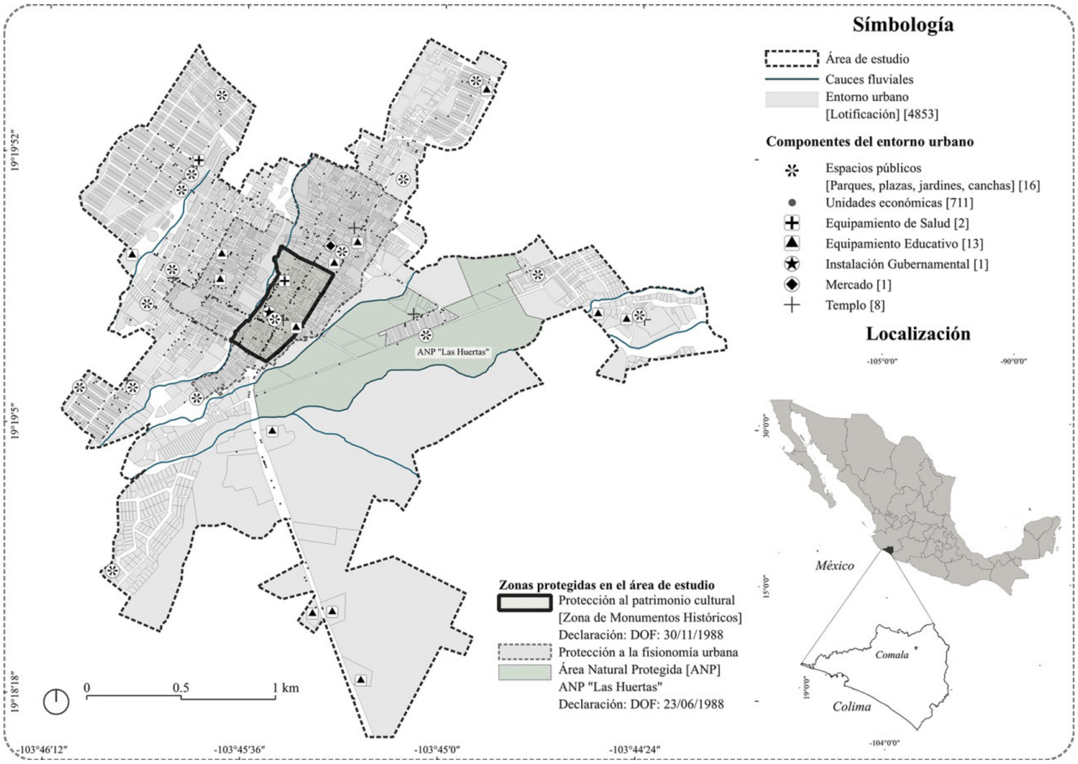

Figure 1. Study area: Comala, Colima, Mexico. Source: Prepared by the authors.

shape the identity of their populations, and determine the appropriation of their territories occur (Vazquez et al., 2024). The sound management of public space, as an articulated and functional urban subsystem, improves socio-environmental cohesion and the psychophysical health of inhabitants/users, being fundamental to increasing the cities' habitability, vitality, and resilience (Clarke et al., 2023; Gehl, 2004; SEDATU, 2019). Consequently, distributive efficiency, accessibility, and UPS quality are crucial indicators for the functionality and integrity of urban systems.

To approach UPS as an articulated spatial system, it is necessary to establish two main groups: 1) urban equipment and formal facilities for public use (parks, squares, gardens, sports facilities) and 2) the road network that interconnects the urban territory. Both are necessarily interdependent in generating flows and dynamics in social everyday life (Fonseca et al., 2021; Gehl, 2004; Sevtsuk, 2020). Their effective conjunction allows identifying patterns of urban interaction and integration, recognizing it as a continuous spatial phenomenon whose analysis considers factors that promote or inhibit the use and exploitation of UPS.

The research proposes a method to integrate both components of UPS and analyze their influence on the accessibility of the urban territory, incorporating indicators that define the degree of functional articulation, as well as adjustment factors related to UPS proximity and quality.

III. CASE STUDY

The study area was the municipal seat of Comala, Colima, with a total of 9,169 inhabitants (National Institute of Statistics and Geography [INEGI], 2020), covering 527.01 hectares (INEGI, 2023), located 3.26 km northeast of the Colima-Villa de Álvarez conurbation, with 265,770 inhabitants. Figure 1 shows the components of the urban environment, including subdivisions and the spatial arrangement of points of interest that define various uses and activities. In the study area, there are protection perimeters for Cultural Heritage in the Area of Historical Monuments[6], as well as for the "Las Huertas" Protected Natural Area [PNA][7].

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[6] DOF Decree (1988a): https://sic.cultura.gob.mx/documentos/1844.pdf
[7] DOF Decree (1988b): https://www.conanp.gob.mx/sig/decretos/aprn/Huertas.pdf

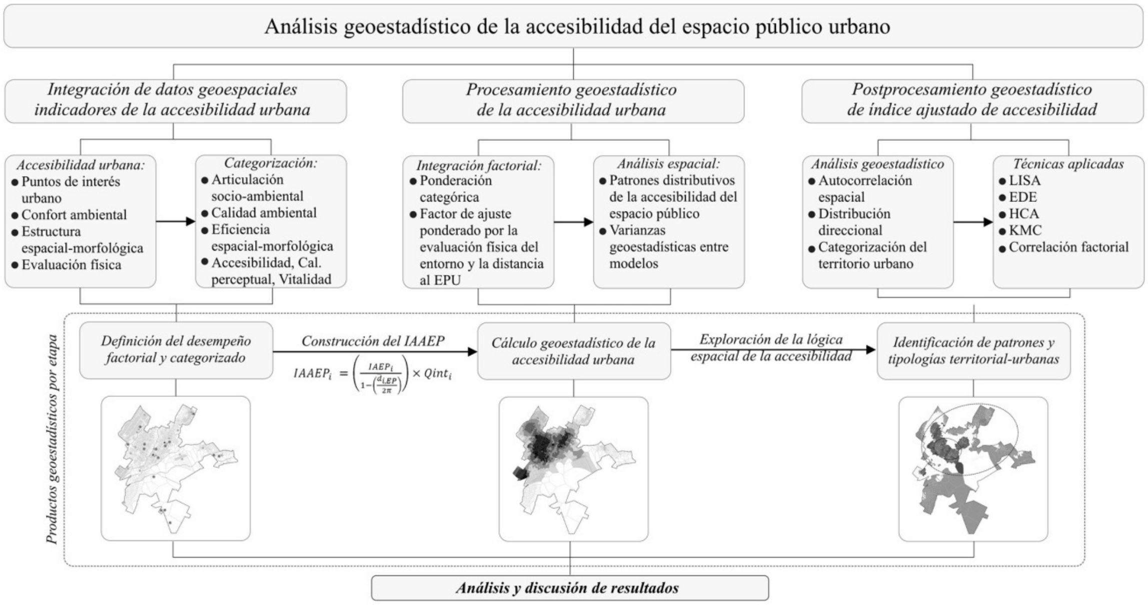


Figure 2. Methodological outline. Source: Prepared by the authors.

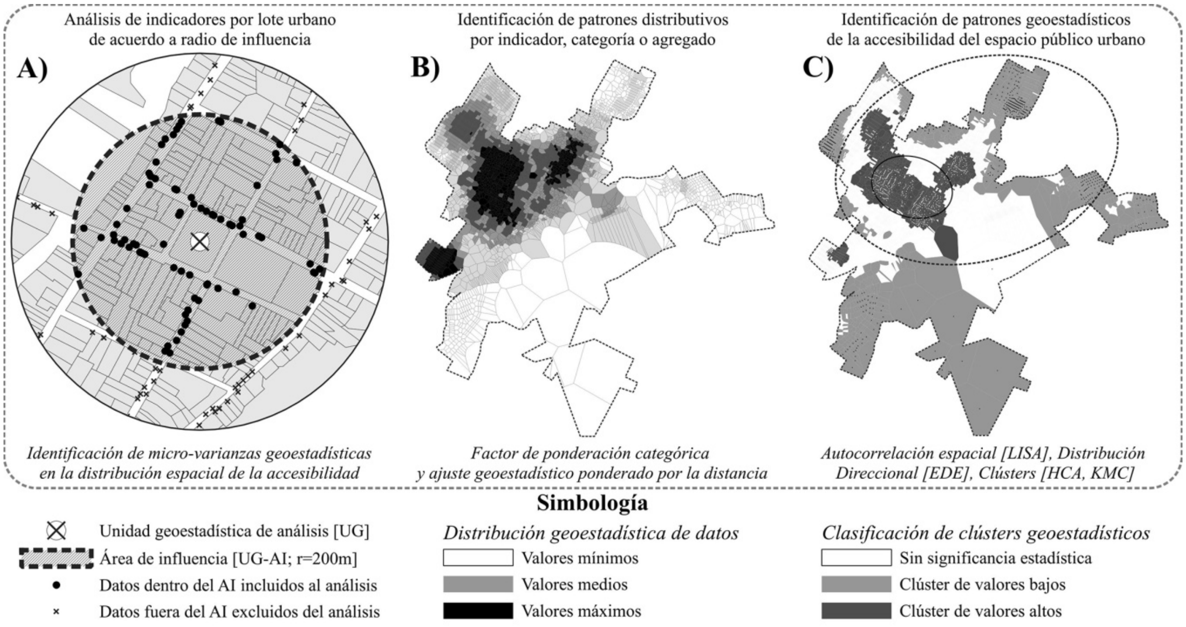


Figure 3. Principles for the geostatistical analysis of accessibility. Source: Prepared by the authors.

IV. METHODOLOGY

The research is divided into three sequential stages: 1) integration and weighting of urban accessibility indicators; 2) geostatistical processing of the Urban Public Space Accessibility Index (IAEP) and its adjusted version (IAAEP); and 3) analysis of typologies, trends, and urban spatial patterns using geostatistical techniques. Figure 2 shows a graphical synthesis of the proposed methodology.

CONSTRUCTION OF THE IAEP

The general principles for calculating the IAEP are based on geostatistical processing of localized indicators that define UPS accessibility to identify microvariations in the performance of the urban territory. Figure 3 shows the analysis approach, where:

a. The urban lot is considered a basic geostatistical unit [GU] of micro-scale analysis, to represent the real structure of Comala in its minimum unit. Each GU was given a radius of influence (200m), with which the differentiated performance of the indicators is weighted.
b. Distributive patterns in accessibility are identified at a micro-scale, on the urban system (micro-macro integration).
c. Spatial trends and territorial-urban typologies are identified at the systemic (macro) level based on the localized performance of the IAEP-IAAEP.

The proposed IAEP comprises nine indicators in three categories: 1) Socio-environmental articulation; 2) Environmental quality; and 3) Spatial-morphological efficiency. Table 1 shows their categorization, data sources, and the weighting assigned to each category, based on their frequency and importance in urban accessibility studies (Fonseca et al., 2021; Sdoukopoulos et al., 2024). These variables, found in human settlements of any scale, location, and degree of urban integration (conurbations, etc.), constitute the localized potential for interaction analyzed in this research.

Category		Variable	Data source
Name	Weighting (f)		
Socio-Environmental (S)	1.00	S1. Population density	Population and Housing Census 2020 [CPV] (INEGI, 2020)
		S2. Commercial connectivity	National Statistical Directory of Economic Units [DENUE] (INEGI, 2024)
		S3. Institutional connectivity	National Geostatistical Framework [MGN] (INEGI 2023)
Environmental quality (A)	0.75	A1. Thermal quality	LANDSAT-8 (USGS, 2024) [Bands 4 and 5]
		A2. Tree density	LANDSAT-8 (USGS, 2024) [Band 10]
		A3. Slope	INEGI Digital Elevation Model (DEM) (2019)
Spatial-morphological efficiency (E)	0.50	E1. Centrality	Calculated with sDNA (Cooper & Chiaradia, 2020), based on MGN road fabric vector data (INEGI, 2023)
		E2. Intermediation	
		E3. Links	

Table 1. Categories, indicators, and information sources for the accessibility of urban public space. Source: Prepared by the authors.

SOCIO-ENVIRONMENTAL ARTICULATION INDICATORS

Correlated with urban vitality, the indicators of population density, commercial connectivity, and institutional connectivity represent the spatial connection between population, work, recreation, and commercial centers in human settlements. Their data for the Mexican context are taken from the MGN (INEGI, 2023), the DENUE (INEGI, 2024), and the Population and Housing Census (INEGI, 2020).

ENVIRONMENTAL QUALITY INDICATORS

The indicators of thermal quality, tree density (NDVI), and slope, which reflect the ease and comfort of human movement, define the degree of physical-spatial habilitation of the urban environment for human interaction and movement. They are acquired from raster data recovered from Landsat-8-9- L2 (USGS, 2024) and INEGI's digital elevation models (DEM) (2019), whose calculations are defined in Equations 1 and Equations 2:

$$NDVI = \left(\frac{B5 - B4}{B5 + B4}\right)$$

(Equation 1)

$$Temperatura_{°C} = \left(\left(B10(0.003418)\right) + 149\right) - 273.15$$

(Equation 2)

Where:
B4: Band 4 Landsat-8-9- L2 (Red)
B5: Band 5 Landsat-8-9- L2 (Near infrared)
B10: Band 10 Landsat-8-9- L2 (Thermal infrared)

SPATIAL-MORPHOLOGICAL EFFICIENCY INDICATORS

Taken from graph theory, the indicators of centrality, intermediation (frequency where a vector is the shortest path), and the density of links are micro-scale indicators that define the scope, hierarchy, and potential interactions of each component within a spatial network. For their calculation, the Street Design Network Analysis (sDNA) (Cooper, 2021; Cooper & Chiaradia, 2020) was used, with 524 road sections of the study area and a radial entry distance of 400 meters. Their calculations are defined in Equations 3, Equations 4, and Equations 5:

$$Centralidad = \frac{\sum_{y \in R_z} d_M(x,y)W(y)P(y)}{\sum_{y \in R_z} W(y)P(y)}$$

(Equation 3)

$$Intermediation = \sum_{y \in N} \sum_{z \in R} W(y)W(z)P(z)OD(y,z,x)$$

(Equation 4)

$$Links = \sum_{y \in R_x} P(y)$$

(Equation 5)

Where:
$d_M(x, y)$: Metric distance between two vectors x, y.
P: Effective nodes.
N. Total number of vectors.
R: Calculation radius.
V: Total number of nodes.
W: Vector weighting.

GEOSTATISTICAL WEIGHTING: CALCULATION OF THE IAEP-IAAEP

To calculate the performance with the IAEP indicators, data processing for each geostatistical unit was performed from the centroid of each urban lot, with an area of influence of 200 meters. Equation 6 defines the calculation.

$$DI_i = \sum_{U \in A(c;r)_i} V_{U,I}$$

(Equation 6)

Where:
DI_i : Performance of indicator I on GU i
$U \in A(c; r)_i$:: Units (points/polygons/pixels) within area A with a center c and radius r.
$V_{U,I}$ Value of the units U on indicator I.

The integration of the IAEP was based on the average of the indicators, adjusted by the factor described in Table 1, using standardized values [0-1] derived from the maximum and minimum values observed for each variable. Equation 7 defines the calculation.

$$IAEP_i = \frac{f\bar{S}_i + f\bar{A}_i + f\bar{E}_i}{3}$$

(Equation 7)

Where:
f: Adjustment factor.
S_i, A_i E_i: Average value per category.

PERCEPTUAL/SUBJECTIVE EVALUATION OF THE URBAN FABRIC

As a weighted factor for road accessibility, an exploratory tour was conducted along the 524 road sections of the study area, which was evaluated on a scale of 1 (minimum) to 5 (maximum): 1) Pedestrian accessibility and safety; 2) Perceptual and sensory quality, and 3) Urban vitality. The tours were conducted in October and November 2024 at approved times between 10:00 and 14:00 hours. The collected data were coupled with the road vector base for their geostatistical processing (Table 2).

Variable	Description
Q1. Pedestrian accessibility and safety	Physical activation for pedestrian movement, environmental safety, and active surveillance of the transformed environment.
Q2. Perceptual/ sensory quality	Landscape and urban image quality; clarity and intuition of the transformed environment; hygrothermal comfort.
Q3. Urban vitality	Diversity of activities on the site; intensity and continuity of pedestrian flows.

Table 2. Description of indicators for the urban fabric's perceptual/ subjective evaluation. Source: Prepared by the authors.

INTEGRATION AND CALCULATION OF THE IAAEP

Finally, the IAAEP's calculation was conducted by weighting the standardized distance to the formal public space and integrating qualitative indicators [Q1:Q3] as geostatistical adjustment factors to the IAEP. Equations 8 and Equations 9 define its calculation.

$$Qint_i = \frac{Q1+Q2+Q3}{3}$$

(Equation 8)

$$IAAEP_i = \left(\frac{IAEP_i}{1-\left(\frac{\bar{d}_{i,EP}}{2\pi}\right)}\right) \times Qint_i$$

(Equation 9)

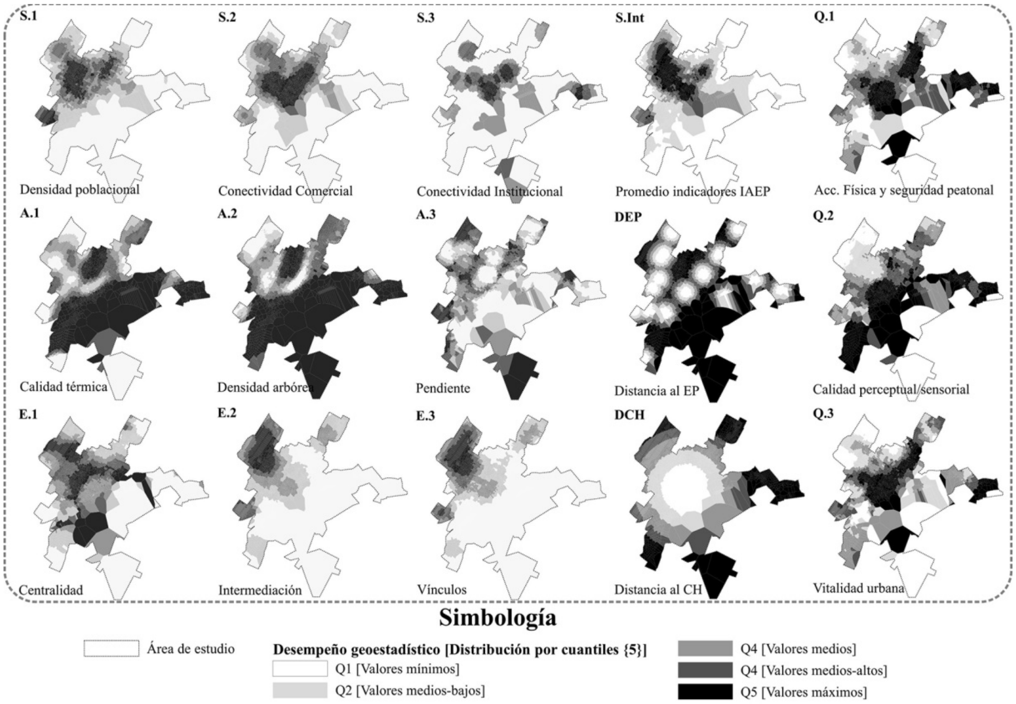


Figure 4. Geostatistical distribution: IAEP-IAEP indicators. Source: Prepared by the authors.

Where:
$Qint_i$: Average of the perceptual/subjective indicators.
Di_{EP}: Average (standardized) distance to the nearest public space.

GEOSPATIAL AND GEOSTATISTICAL ANALYSIS OF RESULTS

To identify spatial agglomeration patterns in the maximum and minimum values, LISA analysis (Anselin, 1995) was used in GeoDa v. 1.22.0.4 (Anselin et al., 2005); spatial clusters were detected using Moran's Local I following the trend of the observed values: High-High [A-A], Low-High/High-Low [B-A; A-B], Low-Low [B-B], and Without Significance [SS], defined in Equation 10.

$$I_i = \frac{\sum_i \sum_j w_{ij} z_i z_j}{\sum_i z_i^2} = z_i \sum_{j=1}^{n} w_{ij} z_j \qquad \text{(Equation 10)}$$

Where:
I_i: Moran's Local I in GU i.
W_{ij}: Spatial relationship matrix between the GUs i, j.
Z_{ij}: Numerical values observed in GUs i, j.

The Standard Deviation Ellipse (SDE) was used (Tveite, 2016; Yuill, 1971) to define the spatial extension and to address the geostatistical extremes [the highest and lowest 10% of the observed records], as defined in Equations 11, Equations 12, Equations 13, and Equations 14.

$$EDE(centro)\ _{i(x,y)} = \frac{\sum_{i=1}^{n} x_i}{n}, \frac{\sum_{i=1}^{n} y_i}{n} \qquad \text{(Equation 11)}$$

$$EDE(Rotación\ angular)_i(tan\theta) = \frac{\left(\sum_{i=1}^{n} x_i^2 w_i - \sum_{i=1}^{n} y_i^2 w_i\right) + \left(\sqrt{\left(\sum_{i=1}^{n} x_i^2 w_i - \sum_{i=1}^{n} y_i^2 w_i\right)^2 + 4\left(\sum_{i=1}^{n} x_i y_i w_i\right)}\right)}{2\sum_{i=1}^{n} x_i y_i w_i}$$

(Equation 12)

$$EDE(Desv.estándar)_{i(\delta x,y)} = \sqrt{\frac{\sum_{i=1}^{n}(x_i cos\theta - y_i sin\theta)^2 w_i}{n \times w_i}}, \sqrt{\frac{\sum_{i=1}^{n}(y cos\theta - x_i sin\theta)^2 w_i}{n \times w_i}}$$

(Equation 13)

$$EDE(Excentricidad)_i = \frac{c_i}{a_i}$$

(Equation 14)

Where:
EDE_i= Standard Deviation Ellipse i defined by the set n of points (x, y).
x_i,y_i= Coordinates of the centroid of GU i.
W_i= Weighting (variable) of GU i.
C_i= Focal length.
a_i= Longest axis distance.

Finally, territorial-urban typologies were identified, representing functionally differentiated zones/sectors within

Variable	Min	Max	Average	Median	1Q	3Q
Population density (inhab.)	0.00	1764.00	687.45	725.00	363.00	973.00
Commercial connectivity (#UE)	0.00	129.00	30.42	24.00	8.00	43.00
Institutional connectivity (#Inst.)	0.00	5.00	0.83	0.00	0.00	1.00
Average temperature (°C)	33.53	42.18	39.17	39.44	38.88	39.85
Tree density (NDVI)	0.12	0.30	0.16	0.16	0.15	0.17
Altitude variance (m)	12.38	49.52	30.12	30.47	25.58	34.79
Centrality A(c;r400m)	0.00	310.25	245.95	252.42	235.76	262.36
Intermediation A(c;r400m)	0.00	278.33	122.67	119.15	74.22	166.83
Links A(c;r400m)	0.00	3602.00	1255.07	1091.00	622.00	1842.00
Distance to the Public Space [DEP] (m)	12.09	1536.01	209.45	199.94	127.80	274.68
Distance to the Historical Center [DCH] (m)	10.59	2278.23	886.68	922.79	551.16	1162.64
Pedestrian accessibility and safety	1.53	4.16	2.88	2.84	2.64	3.14
Perceptual and sensory quality	2.16	4.25	2.83	2.84	2.54	3.00
Urban vitality	1.60	4.25	2.67	2.66	2.41	2.90
Average accessibility variables [	0.12	0.61	0.39	0.39	0.32	0.45
Accessibility Index [IAEP]	0.00	0.45	0.27	0.27	0.21	0.32
Adjusted Accessibility Index [IAAEP]	0.00	0.45	0.25	0.24	0.19	0.30

Table 3. Statistical synthesis: indicators of urban public space accessibility. Source: Prepared by the authors.

the study area, defined by geostatistical similarity among spatial units (GU) based on their performance on the IAEP-IAAEP indicators. For this, hierarchical cluster analysis (HCA) and K-means cluster analysis (KMC) were used (Arthur & Vassilvitskii, 2007), implemented in GeoDa.

V. RESULTS

GEOSPATIAL ASSESSMENT: ACCESSIBILITY INDICATORS

Figure 4 shows the geostatistical distribution of the indicators that the IAEP-IAAEP comprise by quantiles (5), which shows: 1) the centralization of the maximum values of socio-environmental articulation [S1-S3]; 2) the presence of areas with high environmental value [A1-A3] in areas with low built density and 3) the highest morphological efficiency [E1-E3] in the northeast of the urban area.

In contrast, there is a greater variance in the spatial distribution of nuclei with high accessibility and safety for pedestrian circulation, perceptual/sensory quality, and urban vitality [Q1-Q3] (derived from the 1566 individual evaluations) on public road space, in which localized deficits on peripheral, isolated, and/or transitional areas stand out. Table 3 shows the statistical synthesis of the collected data.

Figure 5 shows the statistical distribution of the standardized indicators. It highlights a marked asymmetry and the orientation of outliers. The socio-environmental [S2-S3] and environmental [A1-A2] variables exhibit prevalent low performance, with positive outliers; conversely, the centrality [E1] and perceptual quality [Q1-Q3] variables exhibit high performance, with negative outliers. The IAEP-IAEP calculation yielded a core of typically high outliers around the Historic Center.

GEOSTATISTICAL PATTERNS ON THE URBAN TERRITORY

Figure 6 shows the comparison of the geostatistical distribution of the aggregate indicators [S_{int}-IAEP-IAAEP] and the LISA cluster definition of spatial autocorrelation. A geospatial prevalence toward the centralization of maximum values is observed; however, by incorporating perceptual/subjective variables into the IAAEP calculation, a break in the continuity and extension of the High-High cluster [A-A] is observed. This highlights the presence of discontinuities and fractures in the urban-territorial integrity, as well as disconnected and marginalized areas of the Low-Low cluster [B-B].

Table 4 shows the statistical synthesis of the LISA clusters, in

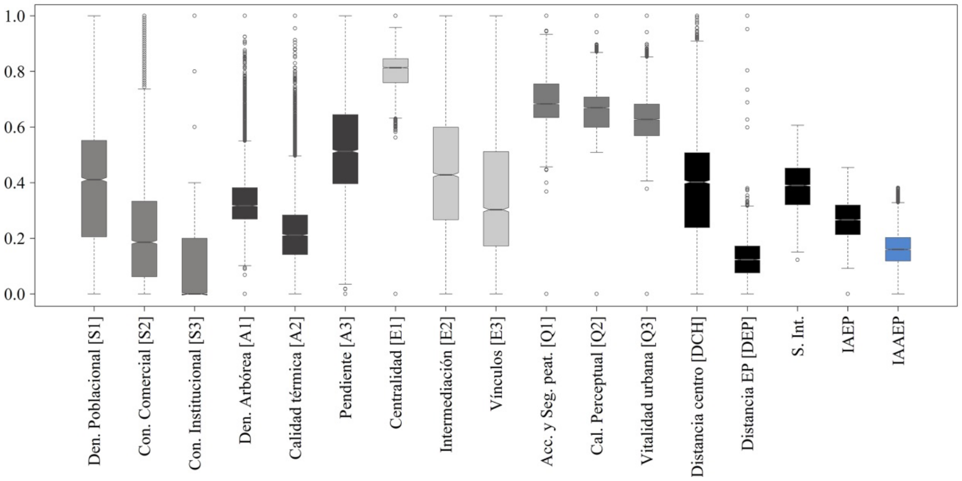


Figure 5. Statistical distribution: accessibility indicators. Standardized values. Source: Prepared by the authors.

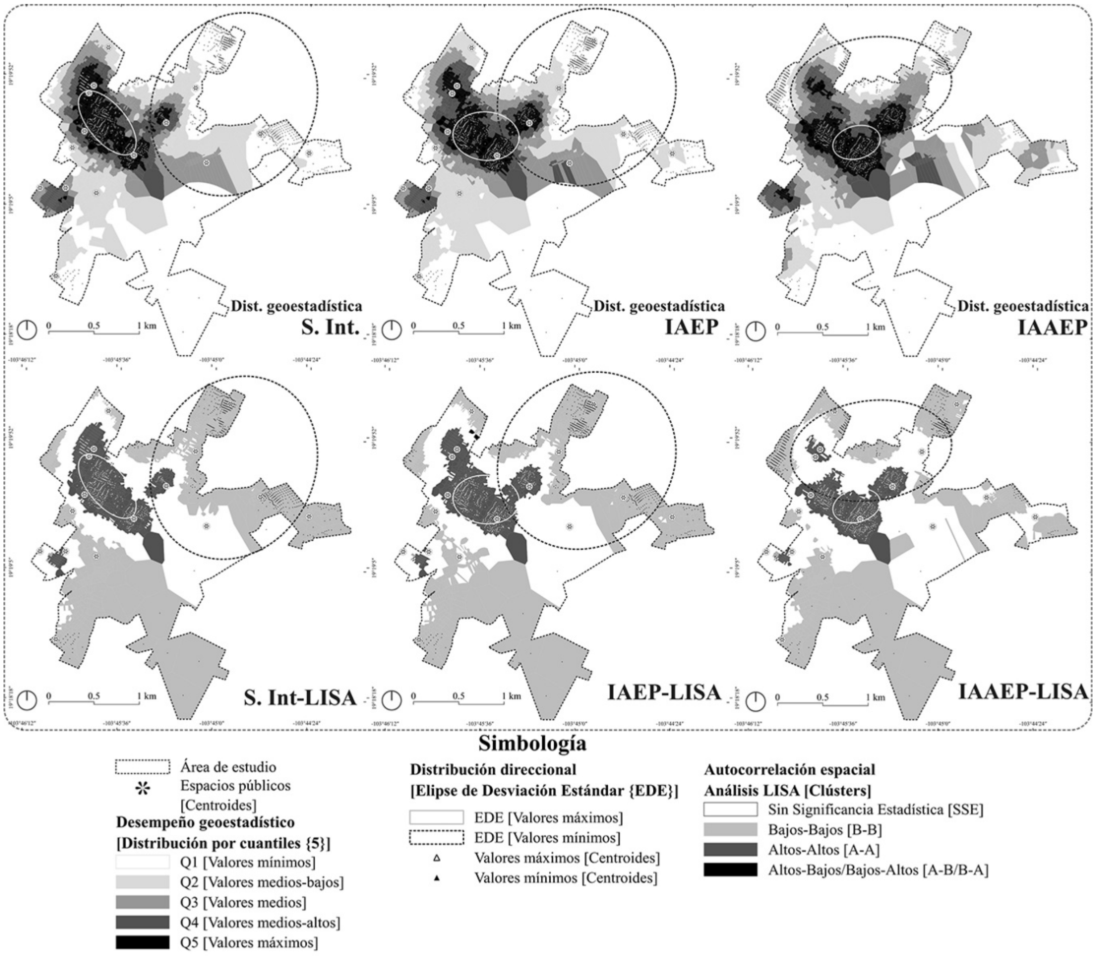


Figure 6. Geostatistical distribution; IAEP-IAAEP. LISA analysis and directional distribution [EDE]. Source: Prepared by the authors.

Category	Geometric tessellations [Voronoi polygons]					Population covered	
	Cluster typology	(#)	(% AE)	Area (ha)	(% AE)	(inhab. #)	(% inhab. AE)
	High-High	1388	28.60%	73.37	13.92%	2863	31.22%
	Low-Low	1404	28.93%	286.95	54.46%	1915	20.89%
	High-Low/Low-High	0	0.00%	0.00	0.00%	0	0.00%
	Not significant	2061	42.47%	166.62	31.62%	4391	47.89%
IAEP	High-High	1295	26.68%	71.84	13.63%	3056	33.33%
	Low-Low	1472	30.33%	275.03	52.19%	1679	18.31%
	High-Low/Low-High	2	0.04%	0.41	0.08%	0	0.00%
	Not significant	2084	42.94%	179.67	34.10%	4434	48.36%
IAAEP	High-High	1035	21.33%	60.98	11.57%	2295	25.03%
	Low-Low	1561	32.17%	257.43	48.85%	1782	19.44%
	High-Low/Low-High	0	0.00%	0.00	0.00%	0	0.00%
	Not significant	2257	46.51%	208.53	39.57%	5092	55.53%

Table 4. Comparative statistics; Spatial autocorrelation clusters [LISA]. Source: Prepared by the authors.

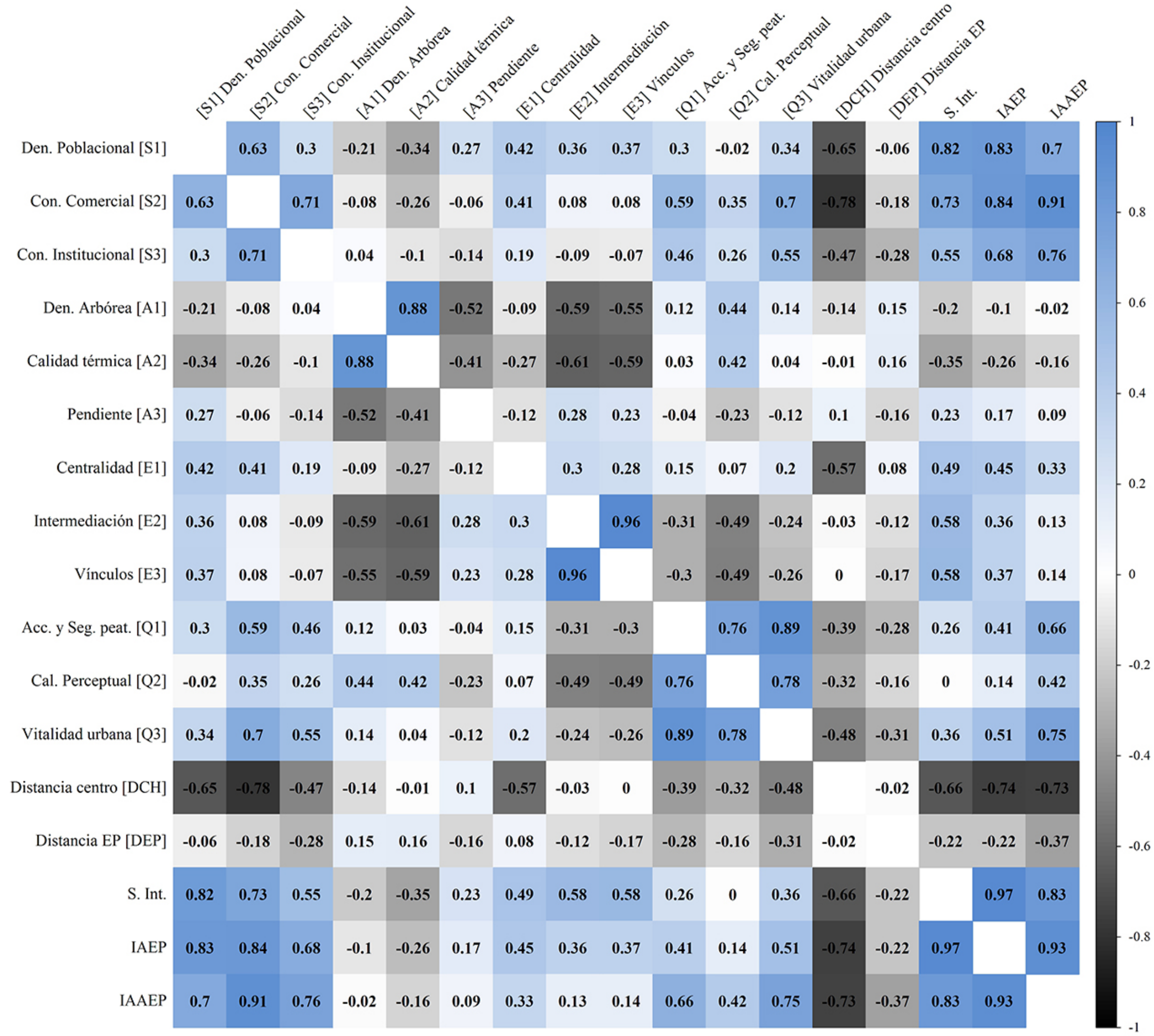
Category	Values	Center	Area		Eccentricity	Rotation	Standard Deviation	
		(°lat, °long)	(ha)	(% AE)	(#)	(°; N→E)	(σmax)	(σmin)
S. Int.	Max	19.3262,-103.7610	27.89	5.29%	0.88	139.89	428.39	207.24
	Min	19.3283,-103.7477	290.15	55.06%	0.53	28.25	1042.91	885.63
IAEP	Max	19.3249,-103.7597	30.68	5.82%	0.68	94.80	365.55	267.19
	Min	19.3288,-103.7491	301.32	57.18%	0.43	47.12	1031.93	929.51
IAAEP	Max	19.3242,-103.7586	15.14	2.87%	0.68	106.72	404.38	296.05
	Min	19.3299,-103.7575	154.72	29.36%	0.79	82.70	893.28	551.35

Table 5. Statistical comparison; outline of the Standard Deviation Ellipse (SDE). Source: Prepared by the authors.

which the presence of 48.85% of the territory and 19.44% of the population in a vulnerable condition due to their functional disconnection is registered [IAAEP; B-B], as well as 25.03% of the population and 11.57% of the territory in highly integrated nuclei [IAAEP; A-A]. The variances between S_{int}-IAAEP are used to assess the index's effectiveness in identifying patterns of territorial-urban integration, as well as their effective limits.

The directional distribution defined by the Standard Deviation Ellipses [SDE] illustrated in Figure 6 is described in Table 5. A significant geometric variance is observed between S_{int}-IAAEP, where there is a focus around the Historical Center of Comala, covering only 2.87% of the urban territory, and whose center is located 151.61 meters from the Municipal Garden.

Figure 7 shows a correlation matrix (Pearson) between the IAAEP indicators. It highlights the positive (→1), negative (→-1), or null (0) relationships between pairs of variables, according to their Correlation Coefficient [CC]. The most significant geostatistical predictors of the IAAEP are commercial connectivity [S2], institutional connectivity [S3],



	[S1] Den. Poblacional	[S2] Con. Comercial	[S3] Con. Institucional	[A1] Den. Arbórea	[A2] Calidad térmica	[A3] Pendiente	[E1] Centralidad	[E2] Intermediación	[E3] Vínculos	[Q1] Acc. y Seg. peat.	[Q2] Cal. Perceptual	[Q3] Vitalidad urbana	[DCH] Distancia centro	[DEP] Distancia EP	S. Int.	IAEP	IAAEP
Den. Poblacional [S1]		0.63	0.3	-0.21	-0.34	0.27	0.42	0.36	0.37	0.3	-0.02	0.34	-0.65	-0.06	0.82	0.83	0.7
Con. Comercial [S2]	0.63		0.71	-0.08	-0.26	-0.06	0.41	0.08	0.08	0.59	0.35	0.7	-0.78	-0.18	0.73	0.84	0.91
Con. Institucional [S3]	0.3	0.71		0.04	-0.1	-0.14	0.19	-0.09	-0.07	0.46	0.26	0.55	-0.47	-0.28	0.55	0.68	0.76
Den. Arbórea [A1]	-0.21	-0.08	0.04		0.88	-0.52	-0.09	-0.59	-0.55	0.12	0.44	0.14	-0.14	0.15	-0.2	-0.1	-0.02
Calidad térmica [A2]	-0.34	-0.26	-0.1	0.88		-0.41	-0.27	-0.61	-0.59	0.03	0.42	0.04	-0.01	0.16	-0.35	-0.26	-0.16
Pendiente [A3]	0.27	-0.06	-0.14	-0.52	-0.41		-0.12	0.28	0.23	-0.04	-0.23	-0.12	0.1	-0.16	0.23	0.17	0.09
Centralidad [E1]	0.42	0.41	0.19	-0.09	-0.27	-0.12		0.3	0.28	0.15	0.07	0.2	-0.57	0.08	0.49	0.45	0.33
Intermediación [E2]	0.36	0.08	-0.09	-0.59	-0.61	0.28	0.3		0.96	-0.31	-0.49	-0.24	-0.03	-0.12	0.58	0.36	0.13
Vínculos [E3]	0.37	0.08	-0.07	-0.55	-0.59	0.23	0.28	0.96		-0.3	-0.49	-0.26	0	-0.17	0.58	0.37	0.14
Acc. y Seg. peat. [Q1]	0.3	0.59	0.46	0.12	0.03	-0.04	0.15	-0.31	-0.3		0.76	0.89	-0.39	-0.28	0.26	0.41	0.66
Cal. Perceptual [Q2]	-0.02	0.35	0.26	0.44	0.42	-0.23	0.07	-0.49	-0.49	0.76		0.78	-0.32	-0.16	0	0.14	0.42
Vitalidad urbana [Q3]	0.34	0.7	0.55	0.14	0.04	-0.12	0.2	-0.24	-0.26	0.89	0.78		-0.48	-0.31	0.36	0.51	0.75
Distancia centro [DCH]	-0.65	-0.78	-0.47	-0.14	-0.01	0.1	-0.57	-0.03	0	-0.39	-0.32	-0.48		-0.02	-0.66	-0.74	-0.73
Distancia EP [DEP]	-0.06	-0.18	-0.28	0.15	0.16	-0.16	0.08	-0.12	-0.17	-0.28	-0.16	-0.31	-0.02		-0.22	-0.22	-0.37
S. Int.	0.82	0.73	0.55	-0.2	-0.35	0.23	0.49	0.58	0.58	0.26	0	0.36	-0.66	-0.22		0.97	0.83
IAEP	0.83	0.84	0.68	-0.1	-0.26	0.17	0.45	0.36	0.37	0.41	0.14	0.51	-0.74	-0.22	0.97		0.93
IAAEP	0.7	0.91	0.76	-0.02	-0.16	0.09	0.33	0.13	0.14	0.66	0.42	0.75	-0.73	-0.37	0.83	0.93	

Figure 7. Statistical correlation [Pearson]; indicators of urban accessibility. Source: Prepared by the authors.

urban vitality [Q2], and proximity to the Historical Center [DEP] (CC: 0.91, 0.76, 0.75, and -0.73). The centrality [E1] is the most relevant spatial-morphological factor compared to the IAAEP [CC: 0.33]. However, the intermediation and density of links [E2-E3] are significant inverse (negative) predictors relative to the perceptual quality [Q1-Q3], given their focus on peripheral areas.

Figure 8 shows a comparison of the performance of the aggregate indicators [Sint-IAEP-IAEP] based on the distance of each GU to formal public spaces (parks, gardens, etc.). It demonstrates its positive influence on generating integrated accessibility cores, where values with geostatistical performance above the third quartile [3Q] are concentrated within ≤200 meters, as indicated by CCs of 0.32 [DEP-IAAEP] and -0.73 [DCH-IAAEP], respectively.

To identify territorial-urban typologies based on the geostatistical similarity of IAEP-IAAEP indicators, the K-means [KMC] and hierarchical [HCA] clusters were used, optimized into 10 classes representing functionally differentiated sectors of the study area. Table 6 and Figure 9 show their geospatial distribution and their integrated average performance [IAAEP].

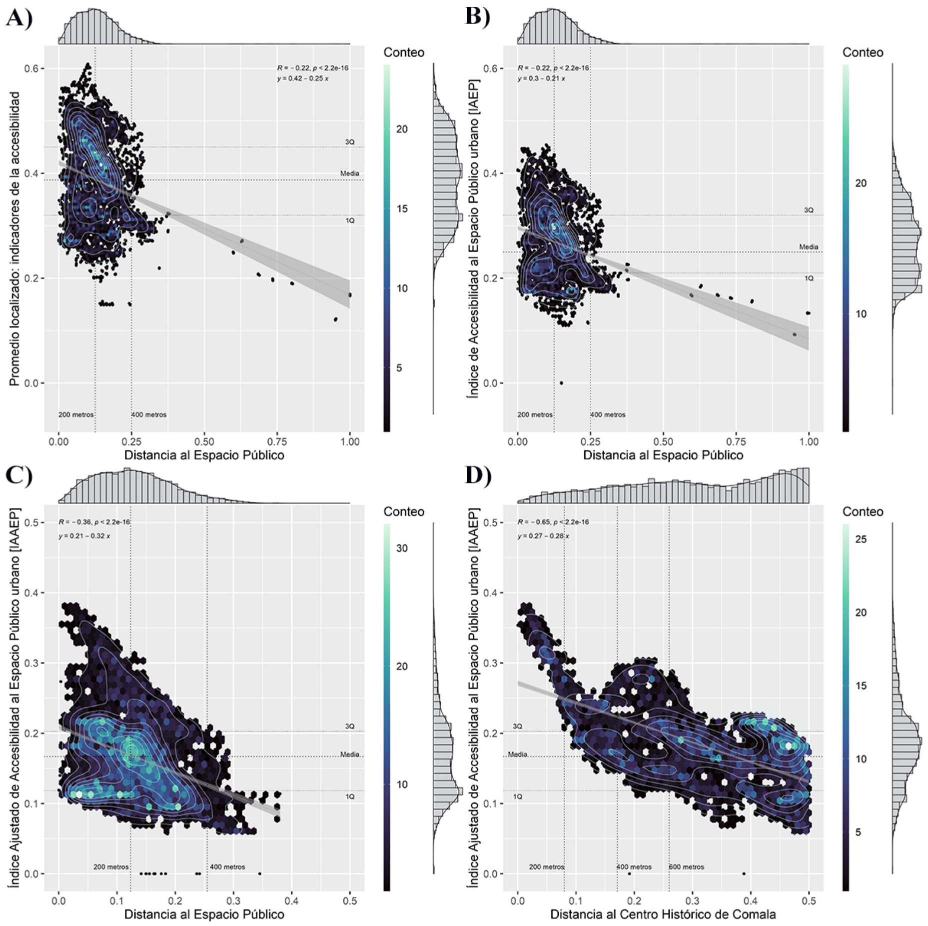


Figure 8. Statistical comparison [2D density mapping]. A: [DEP(x), S-Int(y)]; B: [DEP(x), IAEP(y)]; B) B: [DEP(x), IAAEP(y)]; D: [DCH(x), IAAEP(y)]. Source: Prepared by the authors.

The results show the functional classification of the territory, with the Historical Center [KMC 1, 5; HCA 8] the area with the highest IAAEP values, and a territorial hierarchy with evident tendencies towards centralization. The observations indicate that the KMC identified spatial subcategories with greater precision, highlighting the determination of transitional and peripheral areas with low accessibility indices and effective territorial integration [KMC 4; HCA 1].

VI. DISCUSSION

The diversity in the structure and spatial distribution of small and medium-sized cities poses relevant challenges for determining patterns, cores, and hierarchies of accessibility, especially in identifying micro-variations that evidence functional ruptures in the urban territory. The research demonstrates the effectiveness of the method for the

KMC		HCA	
Cluster	IAAEP	Cluster	IAAEP
1	0.31	1	0.15
2	0.23	2	0.23
3	0.17	3	0.11
4	0.16	4	0.14
5	0.23	5	0.18
6	0.14	6	0.19
7	0.19	7	0.01
8	0.01	8	0.24
9	0.11	9	0.11
10	0.11	10	0.12

Table 6. IAAEP in clusters [KMC/HCA]. Source: Prepared by the authors.

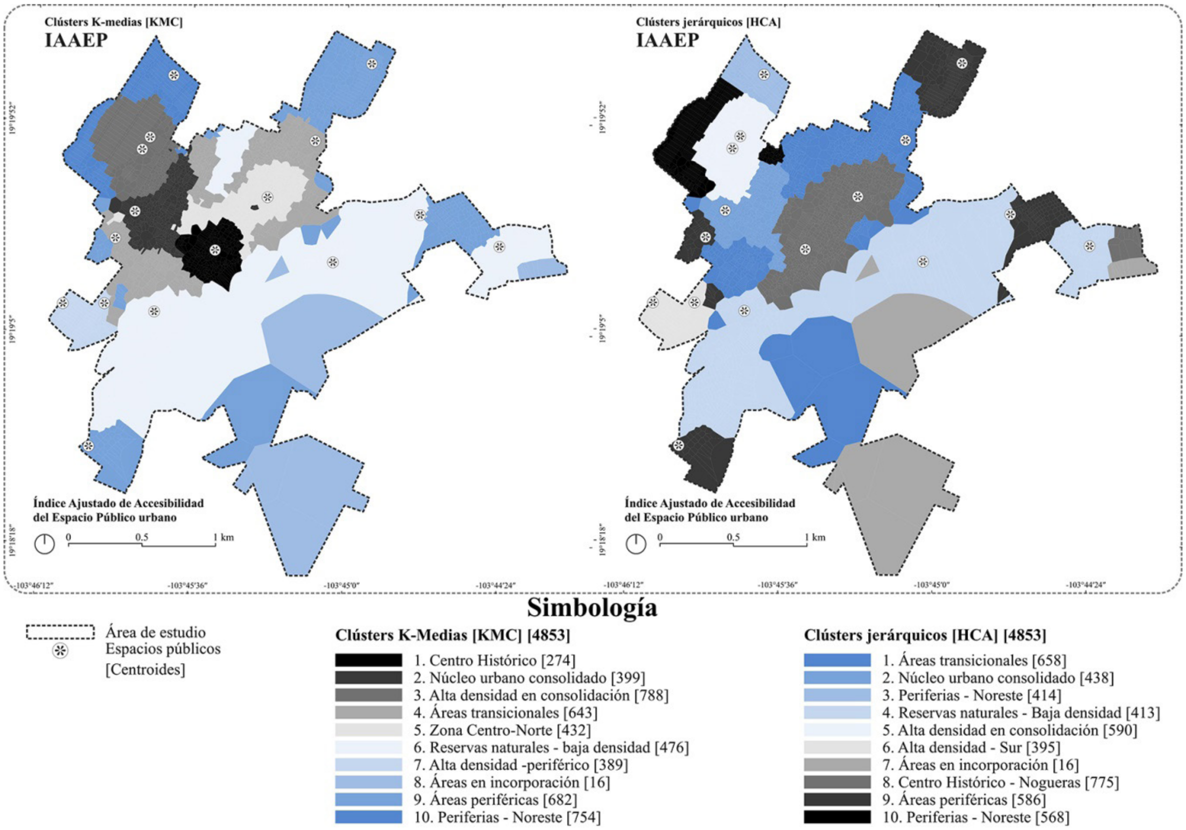


Figure 9. K-means (Left) and Hierarchical (right) clusters; IAEP-IAAEP indicators. Source: Prepared by the authors.

weighting, processing and geostatistical analysis of widely available quantitative data, as well as quantitative/subjective information derived from site evaluations, which reinforces the methodological integrality developed by considering the urban system as a whole, and incorporating criteria that articulate the components of the subsystem of public spaces as the guiding axis of human interaction.

The results highlight a focus on accessibility, the core of which is located in the Historic Center of Comala. This can be associated with the protection of their physiology and urban image, which are considered factors that protect the environment. The relevance of this phenomenon aligns with what was proposed by Vazquez et al. (2024) and Clarke et al. (2023), who emphasize the importance of the symbolic value, the historical significance, and the degree of conservation of Historical Centers in Mexico and worldwide for their consolidation as nuclei of interaction. Likewise, it was determined that the UPS exerts a positive spatial influence within a radius of < 200 meters (Figure 8), which is consistent with what was reported by Bernabeu-Bautista et al. (2023).

The distributive structure of accessibility is negatively correlated with the road network's compact patterns, which are associated with peripheral, transitional, and/or isolated sectors of Comala (Figure 7). This coincides with the results of Schön et al. (2025), who demonstrated the weakness of spatial-morphological indicators in small cities as factors influencing the use of public space, in contrast to commercial diversity [S2-CC: 0.91] and urban vitality [Q3-CC: 0.75], identified as the variables with the highest positive correlation. This relationship establishes a parallel between the urban contexts of Latin America and Europe regarding the definition of consolidated nuclei of social interaction.

The identification of the "spatial logic" linked to the urban-territorial integration promoted by the UPS is fundamental to recognizing patterns associated with the protection or vulnerability of cities. Each urban system has an underlying spatial structure that favors cohesion through the continuity of pedestrian flows, vitality, and intra-urban connectivity (Hillier & Hanson, 2009; Jin & Kim, 2024; Yu et al., 2024). The incorporation of morphological variables [E1–E3] allows analysis of the correlation between spatial configurations and their specific levels of integrated accessibility (IAAEP), thus providing structure and coherence to the study of territorial-urban typologies (Figure 9).

Despite being a small locality, the results show that only 25.03% of the population resides in consolidated nuclei with high accessibility, with a heterogeneous, irregular spatial distribution (Figure 6). This value contrasts with the records of 89.8% reported by Sdoukopoulos et al. (2024) and of 78.45% by Wang et al. (2024), corresponding to highly articulated areas in densified cities, with calculation radii of ≤600 and ≤1080 meters, respectively. These results show the need to consider potential spatial inequality even in small cities, as well as the effectiveness of the proposed methodology for identifying geostatistical micro-variances.

In comparative terms, the proposed methodology takes up indicators (Clarke et al., 2023; Fonseca et al., 2021; Mitropoulos et al., 2023) and methodological criteria (Jin & Kim, 2024; Schön et al., 2025; Sdoukopoulos et al., 2024) of contemporary urban studies, which proposes a model with high replicability and precision for the geostatistical calculation of urban accessibility, capable of integrating data from various sources and formats into a synthetic index. However, one of its main limitations is scalability, since the number of road sections in larger cities can prolong or hinder qualitative network evaluations. Future lines of research could consider the use of methods and tools for the massive and automated analysis of road images (from Street View or own captures), which would allow expanding the methodological replicability.

VII. CONCLUSIONS

This research developed a methodology to calculate the geostatistical distribution of the accessibility of Urban Public Space, identifying the specific influence of various factors in the consolidation of urban interaction and integration nuclei. According to the initial hypothesis, a heterogeneous and discontinuous spatial distribution of accessibility was observed, with a marked tendency toward centralization in the Historical Center of Comala, as well as the definition of territorial typologies based on their overall performance. In these typologies, the presence of areas affected by their functional isolation stands out, characterized by their transitional, peripheral, or marginalized condition, which reaffirms the need to address the problems related to spatial inequality, derived from both the distributive inefficiency of the UPS and the structural deficiencies in territorial-urban planning, as well as to formulate strategies for their mitigation. The research contributes to knowledge of public space accessibility as a key indicator of urban integration by illustrating technical and analytical criteria for its evaluation.

Finally, the need for urban-territorial planning based on the functional articulation of Public Space is highlighted, recognizing its influence and importance in generating nodes of human interaction that define daily activities and appropriation dynamics in urban environments.

VIII. CONTRIBUTION OF AUTHORS CRediT:

Conceptualization, I.F.M., P.C.A. and A.C.M.; Data Curation, I.F.M., P.C.A. and A.C.M.; Formal analysis, I.F.M. and P.C.A.; Acquisition of financing, I.F.M.; Research, I.F.M., P.C.A., A.C.M. and J.A.G.V.; Methodology, I.F.M.; Project management, I.F.M., P.C.A., A.C.M. and J.A.G.V.; Resources, I.F.M. and A.C.M.; Software, I.F.M. and P.C.A.; Supervision, I.F.M and J.A.G.V.; Validation, I.F.M., P.C.A., A.C.M. and J.A.G.V.; Visualization, I.F.M., P.C.A. and J.A.G.V.; Writing - original draft, I.F.M.; Writing - revision and editing, I.F.M., P.C.A., A.C.M. and J.A.G.V.

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