

Article

Green Infrastructure for Reintegrating Fragmented Urban Fabrics: Multiscale Methodology Using Space Syntax and Hydrologic Modeling

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Abstract: Green infrastructure (GI) plays a critical role in addressing urban fragmentation and flood vulnerability, especially in rapidly expanding cities where its optimal placement is essential to maximize social, ecological, and economic benefits. This study presents a multiscale methodology integrating spatial configuration and hydrological modeling to guide GI implementation in Ciudad Juárez, Mexico. The approach applies space syntax theory, fuzzy logic, and geospatial analysis across three spatial levels. At the city scale, the method evaluates street network integration and service accessibility to identify urban centers with potential for regeneration through GI. At the local scale, a 214-hectare area is analyzed using fuzzy multi-criteria decision analysis and Multiscale Geographically Weighted Regression (MGWR) to select the optimal locations for different nature-based solutions. At the microscale, spatiotemporal hydrological simulations of a 25-year return period rainfall event quantify the runoff and infiltration dynamics under different GI configurations, achieving infrastructure layouts that infiltrated over 1000 m³ of stormwater. This framework addresses the research gap on how connectivity and morphology can be combined to prioritize interventions based on flood risk data. The results offer a transferable strategy for integrating Sustainable Urban Drainage Systems (SUDSs) into complex data-scarce urban environments, supporting long-term urban resilience and multifunctional land-use planning.



Academic Editors: Tigran Haas and Laura Cirrincione

Received: 1 April 2025

Revised: 22 May 2025

Accepted: 22 May 2025

Published: 4 June 2025

Citation: Granados Aragonez, R.A.; Martinez Duran, A.; Martin, X. Green Infrastructure for Reintegrating Fragmented Urban Fabrics: Multiscale Methodology Using Space Syntax and Hydrologic Modeling. *Urban Sci.* **2025**, *9*, 208. <https://doi.org/10.3390/urbansci9060208>

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Keywords: green infrastructure; urban resilience; spatial connectivity; urban fragmentation

1. Introduction

Rapid urbanization and climate change are converging to pose unprecedented challenges for cities worldwide. While many cities face extreme fluctuations in their rainfall patterns and hydrological risks, the spatial organization of urban systems often increases these impacts. In response, nature-based solutions such as green infrastructure (GI) have emerged as critical strategies not only for flood mitigation but also for improving connectivity, public space quality, and social cohesion.

In particular, Ciudad Juárez, Chihuahua, Mexico, has experienced significant economic growth driven mainly by industrial activities due to its strategic location near the United States, creating unique cross-border urban dynamics (Figure 1). While rapid urbanization has economically benefited this transnational region, it also brings challenges associated with climate change. Its fragmented spatial structure and socioeconomic disparities make it a representative case for testing spatial models that link mobility, water risks, and urban morphology in rapidly urbanizing border cities.

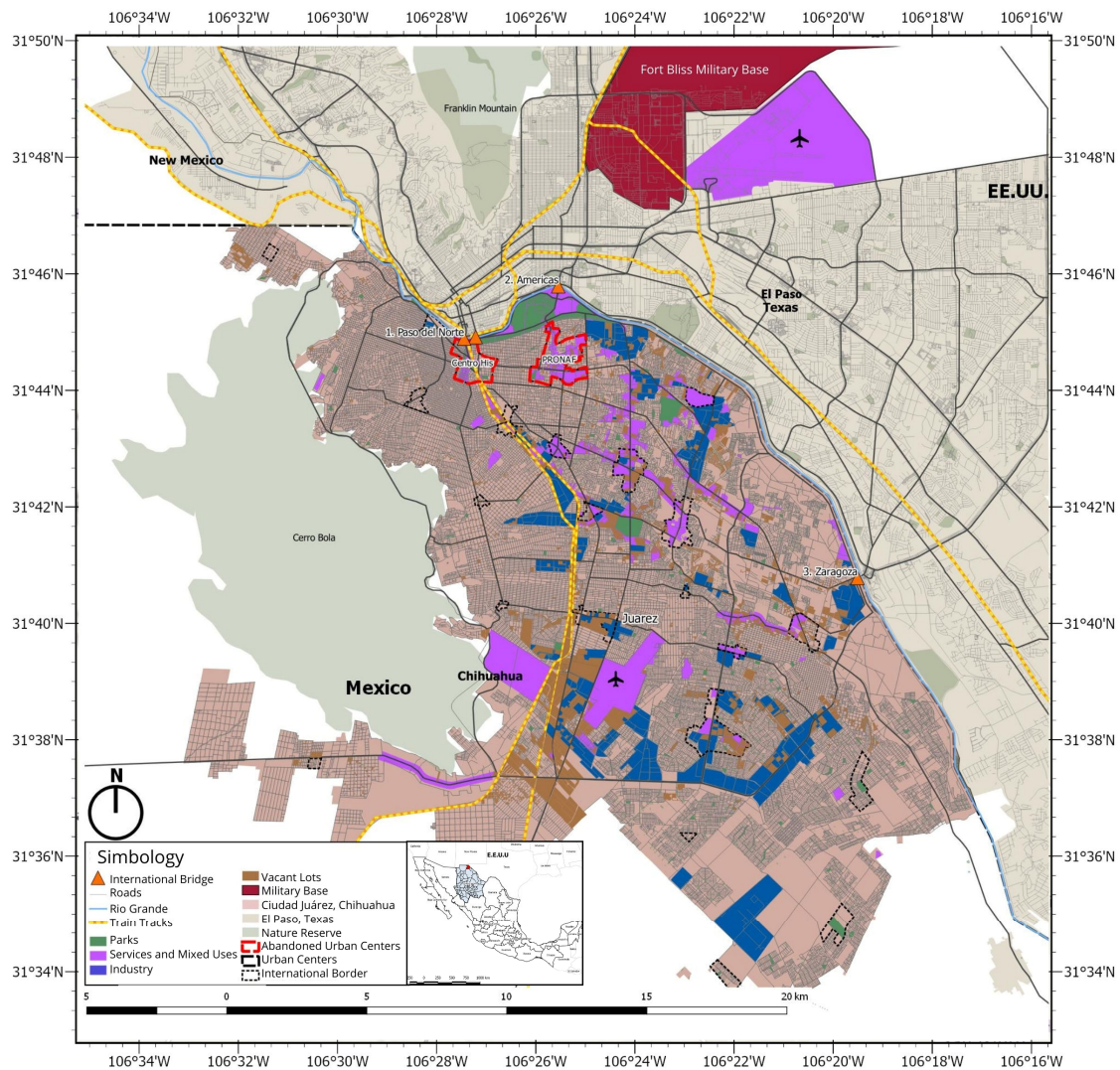


Figure 1. This shows how industrial parks in Juárez shape the city’s transportation network, creating a U-shaped route around the city whose main objective is to connect the industry to the U.S., forming a dispersed, multi-centered city.

Like other industrial cities, Ciudad Juárez struggles with morphological issues resulting from rapid and uncontrolled urban sprawl. Its fragmented urban structure and the hydrological challenges common in semi-arid regions of the Chihuahuan desert make it an ideal case to evaluate multi-scalar GI planning. Urban development without proper hydrological planning [1,2] intensifies the disruptive effects of climate change, endangering vital water resources and negatively impacting residents’ quality of life. Addressing these issues requires integrating Sustainable Urban Drainage Systems (SUDSs) into urban design while considering hydrometeorological risks.

Urban planning that prioritizes interaction with nature and interconnected spaces fosters stronger community ties and helps reduce social fragmentation. Enhancing green spaces and creating streets or public areas that encourage interaction with nature through green corridors can significantly improve residents’ physical and mental well-being [3].

Historically, the value of maintaining strong connections with nature has often been underestimated. Current urban planning practices typically prioritize short-term, low-cost solutions. However, long-term infrastructure planning incorporating sustainable solutions is essential to address the effects of climate change effectively [4]. Although initially more expensive, gradually replacing the nearly nonexistent traditional stormwater infrastructure

with GI is a practical approach. Long-term urban development strategies using GI to mitigate flooding and promote multifunctional use in public spaces can significantly enhance urban integration.

Ciudad Juárez faces additional challenges due to industrial growth that has resulted in many underutilized urban areas. This research aims to revitalize these Fragmented Urban Fabrics (FUFs) by integrating new green infrastructure and creating multifunctional networks that connect urban centers. Such integration helps combat urban fragmentation, positively influencing the environment, society, and local economy [5].

Comparable spatial strategies have been applied in cities such as México City, Bogotá, Buenos Aires, São Paulo, Santiago de Chile and Lima, where nature-based infrastructure has supported mobility, climate resilience, and social cohesion [6]. However, few studies have linked spatial configuration to hydrological modeling in a multiscale framework, despite similar urban challenges being consistent across other border cities in Mexico like Tijuana, Mexicali, and Reynosa.

While previous studies have explored the role of green infrastructure in stormwater management or pedestrian accessibility independently, few have proposed multiscale models that combine urban morphology and spatiotemporal hydrological performance in the equation. This research addresses that gap by building on existing research focused on optimizing green infrastructure placement considering multiple goals, including urban runoff management [7,8], improving water quality [9], reducing urban heat islands [10], and enhancing urban amenities. Using multi-criteria analysis [11] and geographic information systems (GISs) to prioritize areas for rehabilitation [12], based on spatiotemporal hydrological data [13], land use, topography, and other relevant physical characteristics [14].

City-scale analysis is essential for effective decision-making at smaller scales. However, many studies fail to identify critical urban areas suitable for intervention due to analyses conducted primarily at local scales or microscale. This study emphasizes the synergy achievable through integrating FUF networks based on urban morphology using “Space Syntax” theories [15] and the concept of “Spatial Capital” [16].

Consequently, this research proposes a comprehensive city-scale methodology to prioritize and strategize the rehabilitation of the degraded neighborhoods forming the FUFs, reconnecting them through ecological corridors. This strategy emphasizes the interrelation between urban form and functionality. Identifying strategic locations for interconnected green spaces can fundamentally revitalize these urban areas, enhancing spatial distribution, pedestrian accessibility, and overall urban resilience [17]. Using a multi-scalar methodology overcomes limitations in previous work, where studies often focused only on isolated interventions rather than understanding interactions between city, neighborhood, and site-specific levels.

Additionally, this study conducts detailed local-scale analyses, evaluating various GI options for specific intervention areas using multi-criteria GIS analysis and fuzzy logic to determine feasibility based on morphological and physical constraints [18]. At the microscale level, it evaluates specific sites, analyzing storm behavior and designing customized, nature-based solutions tailored to local conditions [19].

This approach has been widely validated by previous research, demonstrating that optimally placed GI networks using space syntax [20] can effectively address critical objectives for sustainable cities, including environmental equity and justice [21], and strengthen urban resilience by establishing interconnected green spaces to reduce flooding risks [22]. Thus, the methodology adopted here aligns with contemporary best practices and simultaneously addresses multiple Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 6 (Clean Water and Sanitation). By integrating spatial planning with stormwater management, the

methodology offers actionable tools for land managers, urban designers, and policy-makers addressing resilience in vulnerable communities.

2. Materials and Methods

This study adopts a multiscale spatial–hydrological methodology to guide the strategic placement of green infrastructure (GI) in fragmented urban fabrics. The approach is designed to bridge the gap between spatial connectivity, environmental performance, and policy scalability. The analysis is structured across three scales: the city scale, the local scale, and the microscale (Table 1). The methodology enables the identification of GI opportunities from urban system planning to site-specific hydrological performance, selecting systems in harmony with the physical, ecological, and social characteristics of the city.

Table 1. Multiscale methodology for green infrastructure implementation summarizing the primary activities, required information, and expected outcomes for each phase.

Scale		Process	Main Activity	Required Information	Results
City	1	Identify strategic implementation points in urban centers	Performing spatial analysis: urban accessibility models with Space Syntax and Place Syntax	Road Integration	Spatial Capital analysis for the implementation of new Green Infrastructure
				Population accessibility	
				Economic Diversification	
				Social Diversity	
				Park Accessibility	
Local	2	Describe local objectives, planning and strategy	Conduct Research: Local regulations and projects	Urban environment	Project objectives and limitations
				Urban Development Master Plans:	
				Historic Center of Ciudad Juárez	
				Recovery of the Asequia Madre	
	3	Identify areas where the implementation of green infrastructure is feasible and its possible restrictions	Analyze public spaces according to the available information: physical restrictions of the type of solution	Land use	Areas with physical conditions necessary for the use of Green Infrastructure Selection Matrix
				Slope	
				Water table level	
				Soil infiltration	
				Building typology	
				Existing infrastructure	
				Flood depth and runoff velocity	
	4	Multi-criteria structure for strategic actions	Multi-criteria decision analysis using fuzzy logic: Most reliable option according to physical, social and morphological conditions	Micro-basins critical points	Recommended area of implementation: Suitability Level
				Flood susceptibility	
				Modified Spatial Capital	
				Optimal connection Choice analysis	
				Public transport routes	
	4	Multi-criteria structure for strategic actions	Multi-criteria decision analysis using fuzzy logic: Most reliable option according to physical, social and morphological conditions	Percentage of different land use analysis	Recommended area of implementation: Suitability Level
				Multiscale Geographically Weighted Regression (MGWR)	

Table 1. *Cont.*

Scale	Process	Main Activity	Required Information	Results
Micro	5	Selection of green infrastructure for proposed areas.	Suitability Level Model	Recommendation of actions to take
			Spatiotemporal Flood Simulations	
			Space Time Cube (STC)	
			Emerging Hot Spot Analysis (EHSA)	
			Time Series Clustering (TSC)	

2.1. City Scale

The main objective of the analysis at this scale was to identify urban centers (Figure 1A) where GI would have the most significant impact based on spatial competitiveness. The methodology is based on space syntax theories, widely used since the early 1980s by architects and urban planners to simulate how spatial configurations of buildings and cities influence human movement and social interaction. Space syntax has proven a powerful theoretical and methodological framework for analyzing urban structures and dynamics, predicting human movement within 55–75%, as well as land-use distribution and other spatial phenomena [23]. Here, it helps identify urban centers where GI can provide the greatest urban regeneration benefits.

The initial phase involved creating a computational spatial analysis model of city roadways, assessing their integration and connectivity through two main metrics: Global Integration and optimal connection (Choice). These analyses are conducted using DepthmapXnet 0.35 and are visualized at different radii highlighting spatial configurations that significantly influence urban mobility. “Integration” measures how interconnected the urban environment is, highlighting more central spaces that encourage activity concentration and support the long-term success of designed or rehabilitated areas. (Figure 2, left).

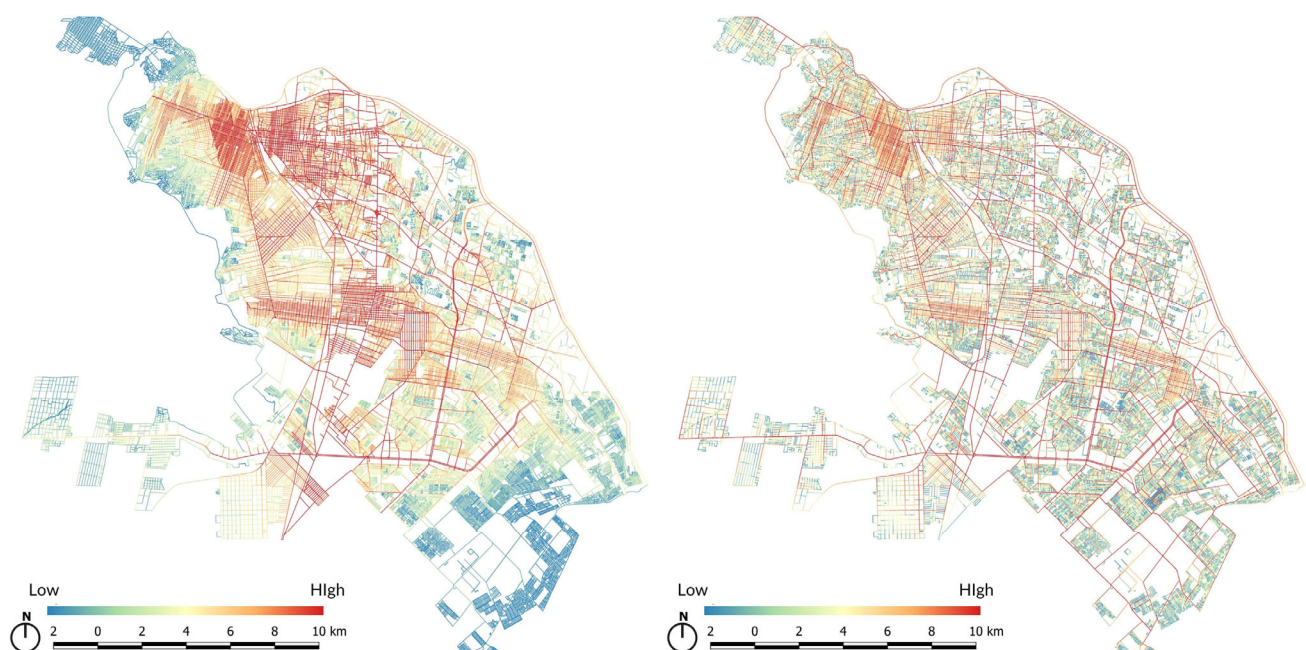


Figure 2. Integration (left) map and choice mode (right) at the global level. Prepared by the authors using road axis data from Ciudad Juárez, from the INGI, processed with DepthmapXnet 0.35.

Another analytical method involves calculating the optimal connection (choice), identifying the most frequently used routes within the city's road network. Different scales of analysis yield distinct usage patterns; a global city-level analysis highlights the main and secondary avenues (Figure 2, right). Analyses at 2500 m emphasize roads more likely used for short bicycle trips, whereas analyses at 1000 m or 500 m highlight pedestrian-scale streets [17].

Additionally, accessibility models were established following the spatial analysis method developed by Ståhle [24], using Place Syntax to identify the clustering or absence of services, businesses, facilities, or people within a specific radius, thus more effectively representing pedestrian perception than traditional measurements (Figure 3).

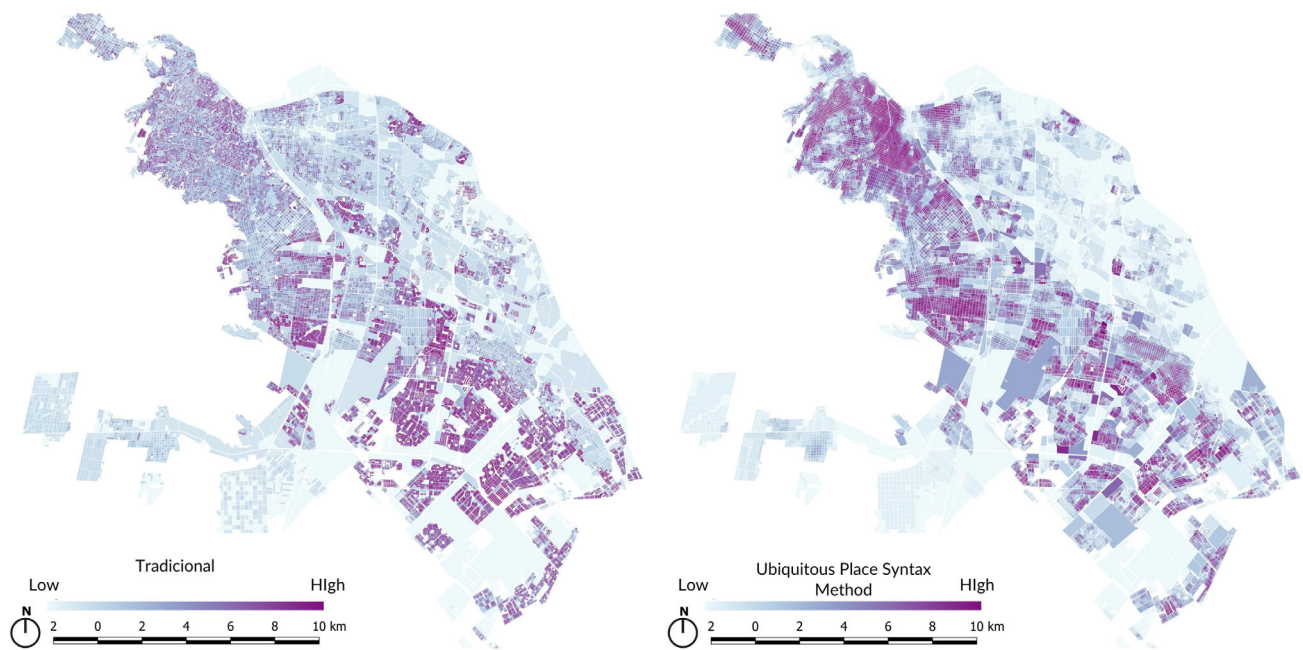


Figure 3. Traditional density map: population by block (left) and accessibility map to population density at 3 axial steps (right). Created by the authors using data on road axes and city blocks in Ciudad Juárez, from the INGI (National Institute of Statistics and Census), processed with the Place Syntax Tool (PST).

Applying Marcus's [16] spatial capital methodology to spatial data from Ciudad Juárez, this study evaluated street integration levels (Figure 4A), population accessibility (Figure 4B), and economic diversification (Figure 4C) around each block, highlighting spatial configurations favoring pedestrian use. This study also considered social diversity indicators by analyzing the co-presence of individuals with varying daily routines, ages, and social classes (Figure 4D) [25].

Lastly, following Ståhle's [26] model, which explores the relationship between urban form and user experience, studies emphasized the importance of integrating more green spaces into cities. Strategic urban design can enhance the access, quality, and functionality of these spaces, strengthening community identity and cohesion. These studies evaluate existing urban conditions (Figure 4E) and parks (Figure 4F) to measure pedestrian-friendly spaces.

These city-scale analyses produced a synthesized map highlighting priority areas for GI implementation based on spatial capital criteria (Figure 4G), as defined in previous studies by Granados [17], analyzing data from various urban centers within a 1.5 km radius of their geographic center. A full breakdown of the modeling parameters, maps, and accessibility indicators is provided in Appendix A.

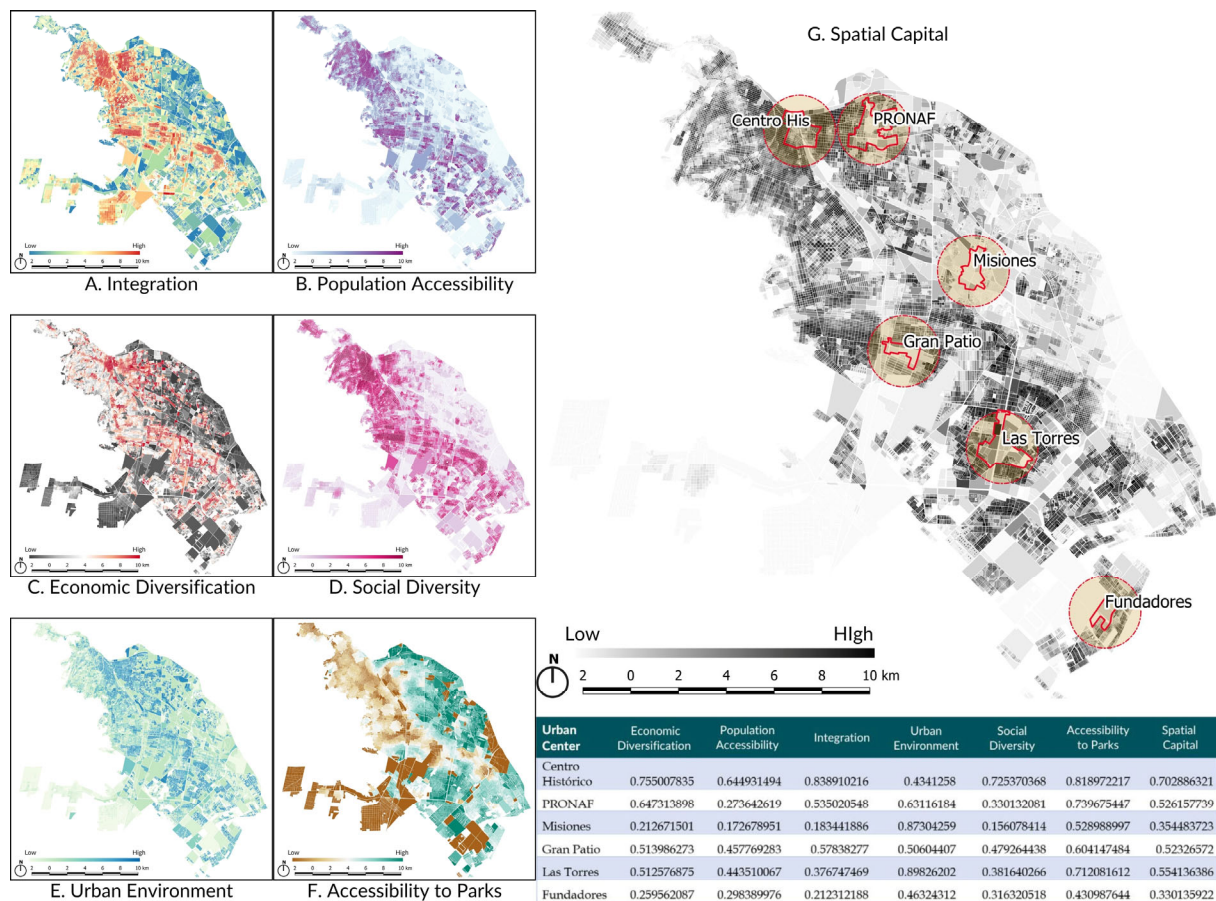


Figure 4. Pedestrian-scale accessibility studies of Ciudad Juárez modeled using the Place Syntax Tool (PST), and a summary table of the accessibility study results within each urban center.

2.2. Local Scale

2.2.1. Available Areas for Green Infrastructure

After identifying the city area with the greatest potential for rehabilitation with green infrastructure (GI) at a global level (entire city), a specific 214.24-hectare area in the Historic Center was selected for detailed local-scale study. Public spaces within the available area were divided into 1 m² hexagons to prioritize them based on their morphological conditions, such as their urban runoff absorption capacities.

Initially, a high-resolution digital elevation model (DEM) was generated using drone photogrammetry, allowing for the assessment of topography, potential water catchment areas for GI development [27], slope percentages, and building typology. An extensive review of international GI implementation manuals and guidelines informed an understanding of the physical restrictions applicable to each space. Typically, restrictions such as slopes, groundwater table depths, infiltration rates, and soil contamination levels determine the feasible types of infrastructure. However, since the study area has an average slope of 3%, a groundwater table depth of 60 m [28], type B soil with an infiltration rate of 1 to 5 cm/h [29], and no severe contamination [30], many typical physical limitations were not applicable.

Areas with physical constraints were thus defined based on proximity to buildings and underpasses, which determine their suitability for implementing GI systems requiring high infiltration capacities. A minimum distance of 6 m was maintained to minimize structural risks. Additionally, proximity within 30 m to existing natural drainage infrastructure, such as the irrigation canals (Acequia Madre) crossing through the area, was considered, since this existing infrastructure would naturally control flooding, making further investment less viable (Figure 5).

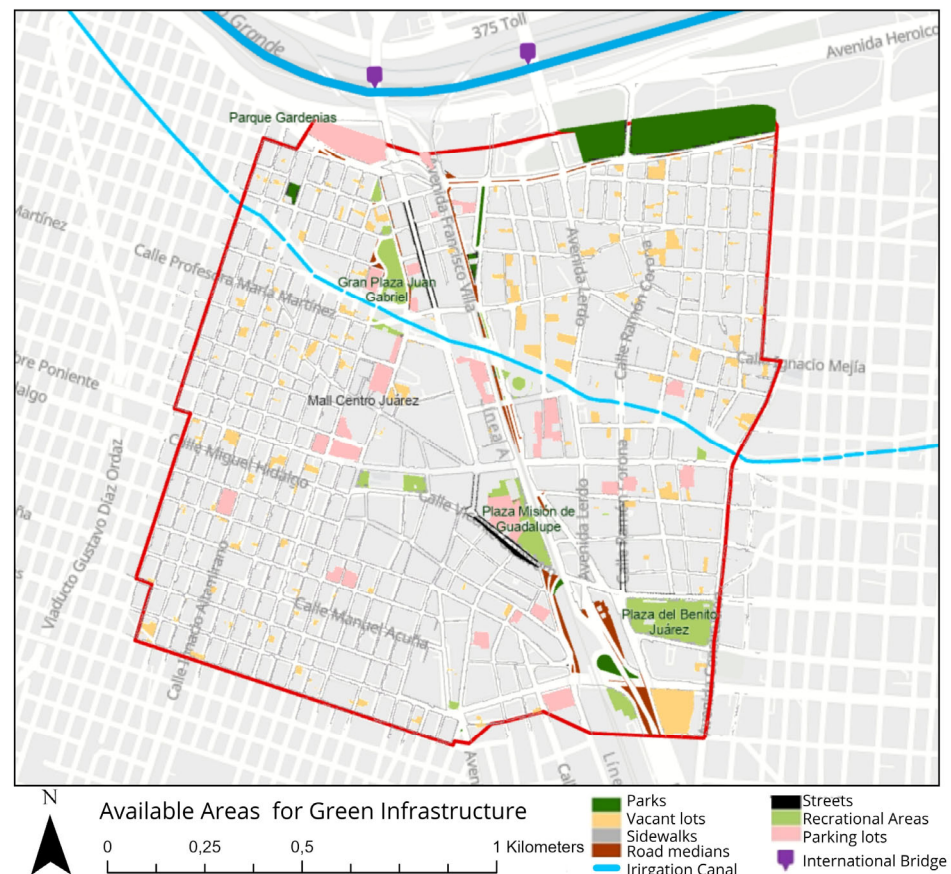


Figure 5. Local-scale study area of 214 Ha showing proposed spaces for GI implementation in the urban center “Centro Historico” of Ciudad Juárez.

2.2.2. Fuzzy Logic

Fuzzy logic provides a modeling process to help make complicated decisions, where input parameters are uncertain or derived from heterogeneous data sources. Initially developed by Zadeh [31], fuzzy set theory enables elements of belonging to a class to be of some degree of membership, but not necessarily binary as in the true/false classification. Using spatial analysis for GI planning, the technique has been useful to transform subjective criteria ranging from physical restrictions to socio-environmental needs to a suitability scale with a range of continuity.

Fuzzy logic has found application in geographic information systems (GISs) for multi-criteria decision analysis (MCDA) wherein diverse layers of information need to be merged [18,32,33]. Unlike Boolean overlays, fuzzy MCDA permits a more realistic evaluation of spatial phenomena by the allowance of gradations in suitability and the incorporation of the expert judgment necessary for the setting of thresholds and membership parameters. The method is particularly useful in urban planning, where spatial decisions must consider both quantifiable environmental conditions and sociomorphological patterns that cannot be measured against hard thresholds.

Fuzzy logic was used here to merge five spatial parameters for GI prioritization in the urban environment with landscape fragmentation. All input variables were transformed into a fuzzy membership raster from an ascending linear or Gaussian function, depending on the relationship of the variable analyzed. The fuzzification transformations were accomplished using ArcGIS Pro’s fuzzy membership tool rasterizing geospatial data and assigning a degree of membership ranging from 0 (completely unsuitable) to 1 (fully suitable). The choice of the membership function depended on the nature of the variable and is described below:

Gaussian Membership Function: This is used when there is an optimal value around which suitability is highest, decreasing symmetrically on either side. The function is as follows:

$$\mu(x) = e^{-\left(\frac{x-c}{\sigma}\right)^2}$$

where there are the following:

c = the center (optimal value);

σ = the spread of the function.

Linear Membership Function: This is applied when suitability increases or decreases linearly with the variable. The function is defined as follows:

$$\mu(x) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a < x < b \\ 1 & x \geq b \end{cases}$$

where there are the following:

$\mu(x)$ is the membership value;

x is the input variable determined by the raster;

a and b are the lower and upper values applied here as an ascending function.

The Gamma Function is defined as follows:

$$\mu_{\text{Gamma}}(x) = \mu_{\text{Product}}(x)^\gamma \cdot \mu_{\text{Sum}}(x)^{1-\gamma}$$

where

$$\mu_{\text{Product}}(x) = \prod_{i=1}^n \mu_i(x)$$

$$\mu_{\text{Sum}}(x) = \prod_{i=1}^n (1 - \mu_i(x))$$

γ is the gamma parameter ($0 \leq \gamma \leq 1$), controlling the degree of compensation between criteria. In this study, a gamma value of 0.8 was selected to allow moderate compensation, ensuring that no single criterion dominated the suitability analysis.

The Kernel density tool in ArcGIS Pro 3.4.3. was used to generate continuous raster surfaces from line and point features (e.g., streets, bus routes, and land-use points), capturing their spatial influence within a specified radius. The tool estimates density based on the following function:

$$f(x, y) = \sum_{i=1}^n \frac{1}{h^2} \cdot K\left(\frac{d_i}{h}\right)$$

where there are the following:

$f(x, y)$ is the estimated density at a location (x, y) ;

n is the number of features (e.g., street vertices or transport routes);

h is the bandwidth (search radius, set at 200 m in this study);

d_i is the distance from feature i to location (x, y) ;

$K(u)$ is the kernel function, typically a quartic kernel.

$$K(u) = \frac{15}{16} (1 - u^2)^2 \text{ for } |u| \leq 1; \quad K(u) = 0 \text{ otherwise}$$

This ensures that the features closer to a given location have a stronger influence on the resulting density, which decreases smoothly with distance. The Kernel density output raster was then normalized from 0 to 1 and transformed in this case study using a fuzzy ascending linear function to serve as an input in the fuzzy overlay process (Figure 6).



Figure 6. Fuzzy logic diagram stating grouped inputs, membership functions, overlay stages, and the final suitability output.

- A. A fuzzy logic model was then created to integrate the flood depth and runoff velocity in order to generate a flood risk map and assess the absorption capacity of SUDSs at a local scale. The simulation was conducted in ArcGIS Pro using a 25-year return period storm, representing a 6 h rainfall event with a total accumulation of 89 mm, based on a 0.5 m resolution simulation. This scenario was selected as it reflects local hydrological conditions and modeling recommendations [1]. As noted by Muthanna [34], identifying the main runoff flow paths helps pinpoint high-potential areas for SUDS implementation. In this case study, the drag factor was omitted, since the runoff velocities did not exceed the low-impact threshold identified by Yamanaka et al. [35] and were therefore considered a positive factor for intervention. Both maps were combined using fuzzy logic, first applying a Gaussian function with a mean of 0.75 m and dispersion of 0.5 to the flooding depth raster (Figure 7A), gradually reducing values in areas with no flooding or extreme flooding conditions requiring other hydrological solutions. Similarly, a linear function was applied to the maximum runoff velocity values of $0.27 \text{ m}^3/\text{s}$ (Figure 7B). Both layers were then combined using a fuzzy gamma function at 0.8 through the fuzzy overlay tool, balancing the influence of both factors and flexibly integrating zones with high flood and runoff susceptibility (Figure 8A).
- B. For morphological constraints, a modified spatial capital analysis identified the most urbanistically sustainable pedestrian-level spaces lacking green areas [17]. This value was calculated by summing and averaging five accessibility models used to create the spatial capital (integration, population accessibility, economic diversification, urban environment, and social diversity). The values obtained from the park accessibility model were subtracted from the modified spatial competitiveness result, normalizing values from 0 to 1 using a linear ascending function for fuzzy logic analysis (Figure 8B).

- C. The optimal connection (choice) analysis of the streets was used at an influence distance of 2500 m to determine the circulation preference at the local level, thus helping to connect the urban centers most likely to create pedestrian dynamics in the area, [17]. This was conducted by converting the streets into a raster using the ArcGIS Pro “Kernel Densit” tool by setting a search radius at 200 m. This tool is normally used in urban studies to capture the influence effects of urban elements [36]; in this case the choice value at 2500 m from each road was able to be used in the fuzzy logic model using an ascending linear function (Figure 8C).
- D. To evaluate the relationship of the 88 public transport bus routes in our study area with the traffic they would generate, the Kernel density technique was used at 200 m, generating a raster that identifies the areas with the greatest accumulation of public transport routes, highlighting the southern area where buses avoid entering the historic center. Thus, an ascending linear function was used to relate the flow of pedestrians who would walk towards them, acting as an indirect indicator of pedestrian movement [23], since most routes do not have established stops. Therefore, integrating the unique characteristics of the density of public transport lines is considered relevant since they cross strategic areas near the international bridge, serving as attraction nodes for non-residential pedestrian flow, which includes tourists or people transiting to the US (Figure 8D).
- E. The distribution of pedestrian movement can also be explained by the number of commercial fronts that are established in the streets of the study area [23]. This is another of the main factors influencing future activity in the area, regardless of what small changes the municipality may make in trying to create new commercial fronts around them [37]. Therefore, a methodology has been used to explore the m2 of the different land uses within a 25 m buffer of the 1047 vertices of the streets analyzed in the study area. This value is reasonable to capture the urban typology of each street since the smallest blocks in the study area measure 50 m in width. The land-use variables obtained from the Historic Center Urban Development Plan were grouped into seven different categories (commerce, services–amenities, housing, parks and recreation, vacant and unused land, industrial, and under construction) to obtain the percentage of land-use types for each street segment. A kernel density raster was then created at 200 m with the percentage of commerce–service–amenity land use for the street segments, thus measuring their level of attractiveness in the study area using an ascending linear function (Figure 8E).
- F. The integration of the five fuzzified layers was carried out using the fuzzy overlay tool with the gamma operator, which integrates restrictive and compensatory logic. A gamma value of 0.8 was chosen in order to offer moderate compensation between factors so that no one factor would be able to overshadow the composite suitability measure (Figure 8F).

In this case, the model identifies flood-prone lands as being highly suitable for GI measures, reversing the traditional way of considering such lands as constraints. This decision follows the aim of tackling hydrological weaknesses using SUDSs. Additionally, spatial configuration indicators based on space syntax theory [15] were used in the analysis to quantify the underlying morphological rationality of the street network. This addresses an essential methodological gap in the literature, as urban connectivity is rarely incorporated in flood resilience and GI planning models. By combining network analysis with environmental, accessibility, and land-use factors, this fuzzy logic approach introduces a reproducible and adaptable system for guiding GI implementation in data-poor, rapidly urbanizing contexts.

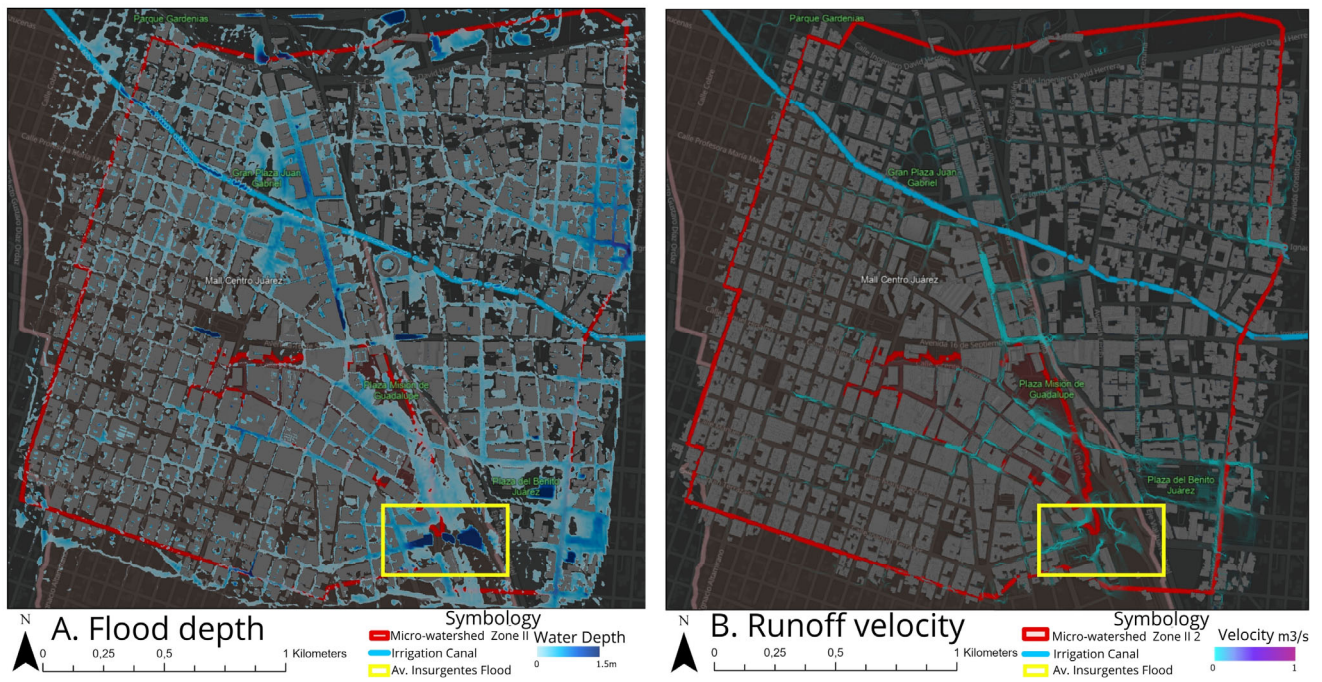


Figure 7. Flood risk categories used for the fuzzy logic model, (A) Flood depth and (B) Runoff velocity, highlighting the flood-prone areas of micro-watershed “Zone II 2 Centro” and Insurgentes Avenue’s flooded underpass.

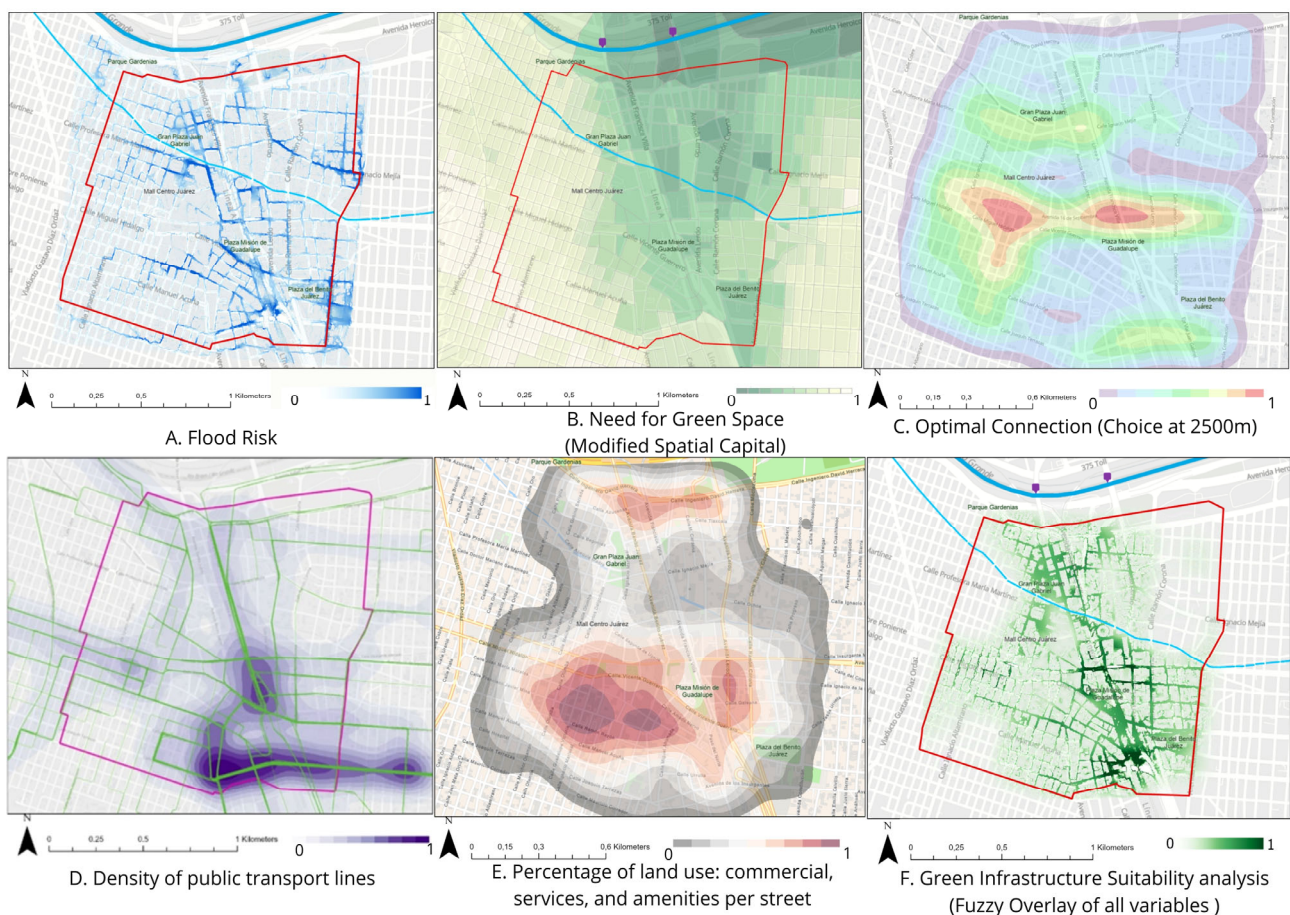


Figure 8. Study area showing the flood risk (A), modified spatial capital (B), optimal connection choice at 2500 m (C), public transport line (D), commerce–service– amenities (E), maps used in the fuzzy approach to make the GI suitability analysis (F).

2.2.3. Automated GI Selection Matrix

Green infrastructure (GI) strategic placement can be effectively guided by automated GIS-based models that apply rule-based logic to align GI typologies with site-specific physical and hydrological conditions. In this study, the most appropriate GI type for each 1 m² hexagon in the intervention area was selected using a geospatial decision matrix implemented through Attribute Selection and spatial analysis tools in ArcGIS Pro. This matrix evaluates the flood depth, runoff velocity, infiltration restrictions (due to proximity to sensitive infrastructure), and area typology, based on spatial layers generated in previous stages.

The decision-making logic is structured using Boolean classification rules, applying an if/then hierarchy that encodes criteria thresholds following the matrix detailed in Table 2. This approach enables a streamlined, scalable, and replicable method for matching GI types to localized urban conditions. It offers a comprehensive and systematic framework for flood mitigation through nature-based solutions, validated by its growing application in contemporary research. Several studies have implemented similar GIS-based decision logic to optimize GI placement, demonstrating its practicality and scientific grounding [38–40].

Table 2. Selection matrix of green infrastructure typologies [41–46].

Green Infrastructure (GI)	Flood Level (m)	Runoff Velocity (m ³ /s)	Infiltration Restrictions	Area Type	Infiltration Rate (mm/h)	Maximum Infiltration (mm)	Description
I-DIP (Permeable Pavement with Geo-cellular Deposits)	<1	N/A	Yes	Sidewalks, Streets, Parking lots, Impervious recreational areas	100	1000	Mixed system with permeable pavement and underground geo-cell storage. High storage capacity.
D-PAV (Mixed Permeable Pavements)	0.3–1	N/A	No	Sidewalks, Streets, Parking lots, Impervious Recreational Areas	50	200	Permeable pavement that combines tree pits and concrete tiles with gravel and clay. It facilitates water infiltration and allows tree roots to grow. Ideal for urban areas with vegetation.
I-PAV (Simple Permeable Pavement)	>0.3	N/A	No	Sidewalks, Streets, Parking lots, Impervious Recreational Areas	30	100	Permeable pavement used near buildings. It infiltrates directly into the soil without a deep layer of gravel and clay mixture, ideal for urban areas where foundation damage must be avoided.

Table 2. *Cont.*

Green Infrastructure (GI)	Flood Level (m)	Runoff Velocity (m ³ /s)	Infiltration Restrictions	Area Type	Infiltration Rate (mm/h)	Maximum Infiltration (mm)	Description
I-ZAN (Infiltration Trenches)	>1.5	<0.05	Yes	Green Areas, Road Medians, Vacant lots	100	500	Infrastructure with a high infiltration capacity that controls runoff speed, preventing erosion and serving as the first line of defense in integrated systems.
I-BIO (Bio-retention Strips)	0.3–1.5	>0.05	Yes	Green Areas, Road Medians, Vacant lots	50	200	They use a specifically designed soil layer where native vegetation grows and that helps maximize the storage and filtration of storm water into underground drainage systems.
I-JAR (Rain Garden)	>0.3	>0.05	No	Green Areas, Road Medians, Vacant lots	50	100	They use a specifically designed soil layer where native vegetation grows to maximize the infiltration, storage and filtration of storm water into underground drainage systems.
F-Est (Infiltration Ponds)	<1.5	N/A	Yes	Green Areas, Road Medians, Vacant lots	50	1000	Designed with a highly permeable substrate, they have a high water storage and filtration capacity. They are ideal for recharging aquifers. They can be used in areas larger than 45 m ² with a 1:2 ratio.

Table 2. *Cont.*

Green Infrastructure (GI)	Flood Level (m)	Runoff Velocity (m ³ /s)	Infiltration Restrictions	Area Type	Infiltration Rate (mm/h)	Maximum Infiltration (mm)	Description
I-CUN (Vegetated Swale)	0.3–1.5	N/A	No	Green Areas, Road Medians, Vacant lots	30	150	Designed with containment barriers to channel water towards high infiltration systems.
I-POU (Infiltration Wells)	<1.5	N/A	Yes	Green Areas, Road Medians, Vacant lots	100	1000	Structures excavated in the ground, designed to infiltrate water into aquifers. In areas smaller than 10 m ² , the ratio is 1:2.
Semi-permeable Urban Areas (spaces with some vegetation, compacted soil)	Base Model	Base Model	Base Model	Green Areas, Road Medians, Vacant lots	5	20	Ciudad Juárez has an arid climate, with predominantly sandy and clayey soils, assigned the lowest value of a type B soil (NRCS) because urbanized areas tend to compact over time.

2.2.4. Multiscale Geographically Weighted Regression (MGWR) Models

Multiscale Geographically Weighted Regression (MGWR) is a spatial statistical technique used to find how relationships between variables change across a geographic space. Unlike traditional regression models [23] that assume relationships are constant across the study area, MGWR allows each explanatory variable to operate at its own spatial scale, capturing spatial heterogeneity more accurately [47]. This is particularly useful in urban morphology and land-use studies, where local variations in accessibility, connectivity, or socio-environmental context can strongly affect outcomes.

In the latest urban research, MGWR has been successfully combined with space syntax measures to analyze how network connectivity influences urban outcomes. For example, Wang et al. [48] used integration values to explore how street connectivity contributed more strongly to land quality in some districts than in others. Similarly, Zhang et al. [49] used MGWR with space syntax metrics set at a 3 km radius to analyze how well-connected green corridors have a positive effect inciting people to use them for jogging more often in Shenzhen. Cao et al. [50] also used MGWR to map spatial variation in housing prices and its correlation to proximity to parks and well-integrated streets, confirming that network morphology impacts urban value differently across a city.

In this study, MGWR is applied in ArcGIS Pro to confirm the relationship between optimal connection (choice) and various land-use typologies in Ciudad Juárez's historic center, joining spatial configuration theory into GI planning. Following earlier studies that used configurational measures to predict land use [51], we tested the relationship between street connectivity and land-use intensities at three different scales.

The percentages of five land-use categories (commerce, services–amenities, housing, parks and recreation, vacant and unused land) were calculated for each street segment. Three MGWR models were then created using choice values at 2500 m, 1000 m, and 500 m radii as the dependent variable. Then, inverting the process generated nine different MGWR models using the land-use categories as the dependent variables and the “Choice” values of the street as the explanatory variables. All the variables were normalized from 0 to 1 prior to modeling. Industrial and under-construction land-use categories were excluded from the choice dependent analysis, and so were the parks and commerce percentages for the land-use dependent analysis due to irregular spatial distribution and a lack of statistical significance, which introduced instability in preliminary models.

2.3. Microscale

In this third approach, the Zone II.2 Centro micro-watershed was used as a case study. The area was identified by the Ciudad Juárez Risk Atlas [52] as one of the most vulnerable and at-risk areas for flooding, due to its location being within the hydraulic system that forms the Mariano Escobedo Stream. This creates a large floodplain and the accumulation of storm water in the overpass located on Insurgentes Avenue. This can be mitigated by implementing flood control systems, taking advantage of the available spaces in the Guadalupe Mission Plaza and surrounding areas (Figure 9A). Similar spatially constrained drainage contexts have been addressed with decentralized GI retrofits in Latin American cities such as Barranquilla, where SUDSs were proposed instead of storm drains [7].

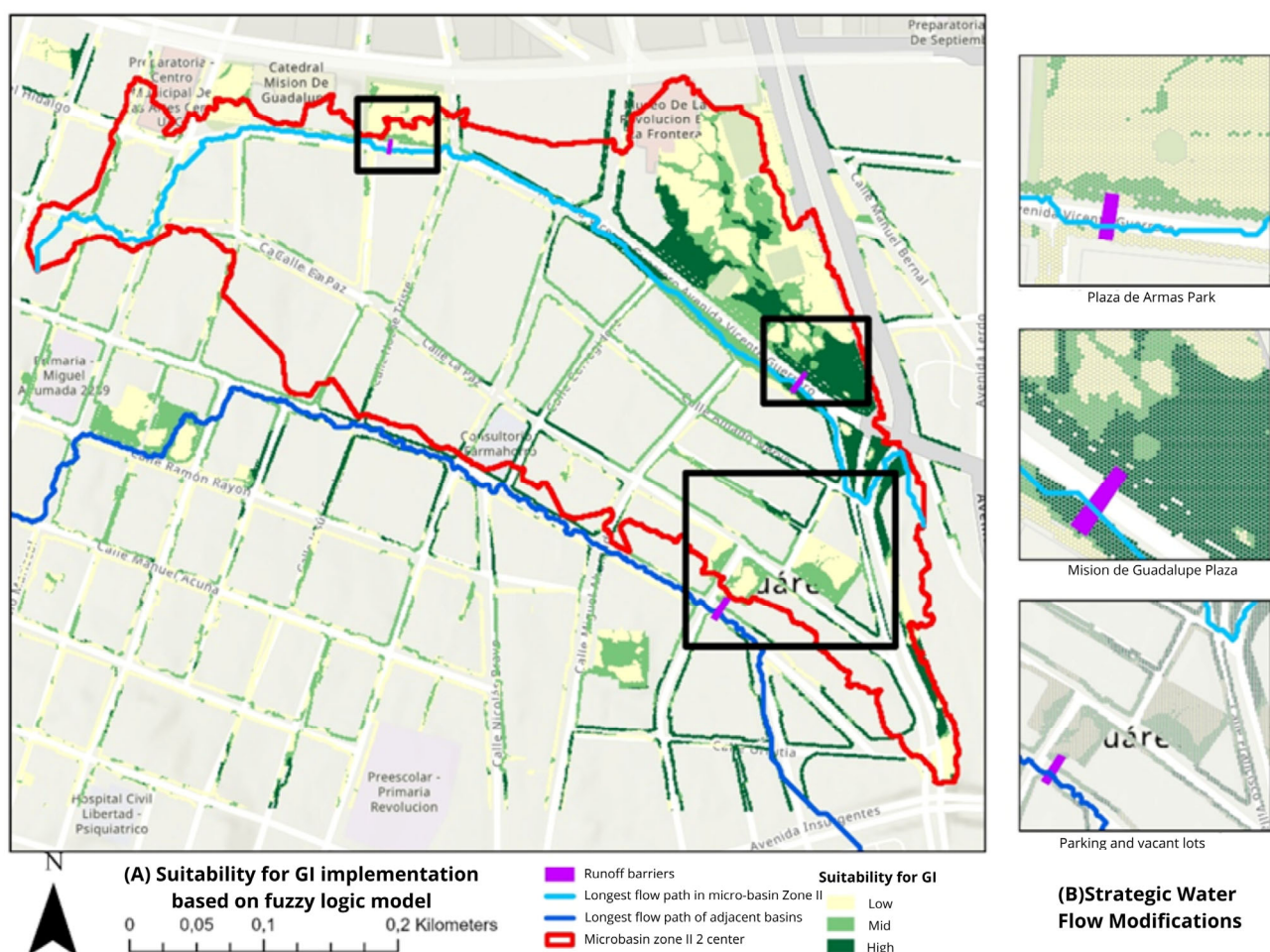


Figure 9. Suitability map (A) and how several spaces could potentially be modified to absorb the main urban runoff in the area (B).

For this purpose, the design of a sustainable urban drainage system similar to that of the case originally defined by Schutze et al. [53] was considered, which proposes controlling floods using GI, which are connected to the mixed drainage system, since there is no functional storm drainage network in the study area. These types of hybrid infrastructure systems are the most effective in developing countries considering the resilience they demonstrate in technical implementation, economic, and environmental aspects [54].

To evaluate the influence of the SUDSs at this scale, we relied on the suitability map obtained from the fuzzy logic analysis. We selected the areas that could be modified with slight topographic modifications, increasing their flood retention capacity. A high-resolution digital elevation model (DEM) was created by performing a photogrammetric survey of the study area, which clearly captured the terrain's topography at a 10 cm resolution. High-resolution DEMs are widely used in SUDSs siting to identify microtopography and flow paths for runoff interception, especially where flow monitoring is unavailable [35].

This allows us to analyze the main runoffs within the micro-watershed and nearby watersheds with more precision than the local-level analysis. In this way, we proceeded to evaluate how water could be channeled, using speed bumps or other infrastructure, to improve the performance of the proposed GI (Figure 9B).

A hydrological analysis was then performed with ArcGIS Pro's flood simulator to measure flood reduction over time, subjecting a base model and a model with GI to a designed storm with a maximum intensity of 14.83 mm/h for 6 h. This design-storm approach is common in data-scarce regions, offering a valid basis for modeling runoff and GI performance in the absence of calibration [55].

The infiltration rate and maximum infiltration of each type of green infrastructure proposed in the study area are used and compared to the base simulation, which considers all permeable areas as semipermeable urban spaces. The results of the two multidimensional flood level models are subtracted, and zonal statistics are calculated within each hexagon in the study area. This allows us to analyze flood dynamics over time and measure how GI reduces runoff peaks.

To analyze the efficiency of GI, three Space–Time Cubes (STC) (Figure 10A) models were created in ArcGIS Pro (base model, GI model, and flood-level difference model). This allows us to represent how the flood level varies over time in each space available for GI implementation. The Emerging Hot Spot Analysis (EHSA) (Figure 10B) tool was then used on the STC models, detecting where GI successfully reduces water accumulation, as well as patterns in absorption over time. Spatiotemporal flood tools like STCs and EHSA are increasingly used to detect trends and identify vulnerable zones in flood-prone urban areas [13,56].

Finally, the Time Series Clustering (TSC) tool was used in the STCs, which allows us to group the GI into cluster classifications with similar infiltration behaviors or abrupt changes in their floodwater infiltration performance. This helps us evaluate which systems need to be modified to absorb new floodwater volumes after the terrain has been modified, showing how long the water can infiltrate before reaching its saturation capacity.

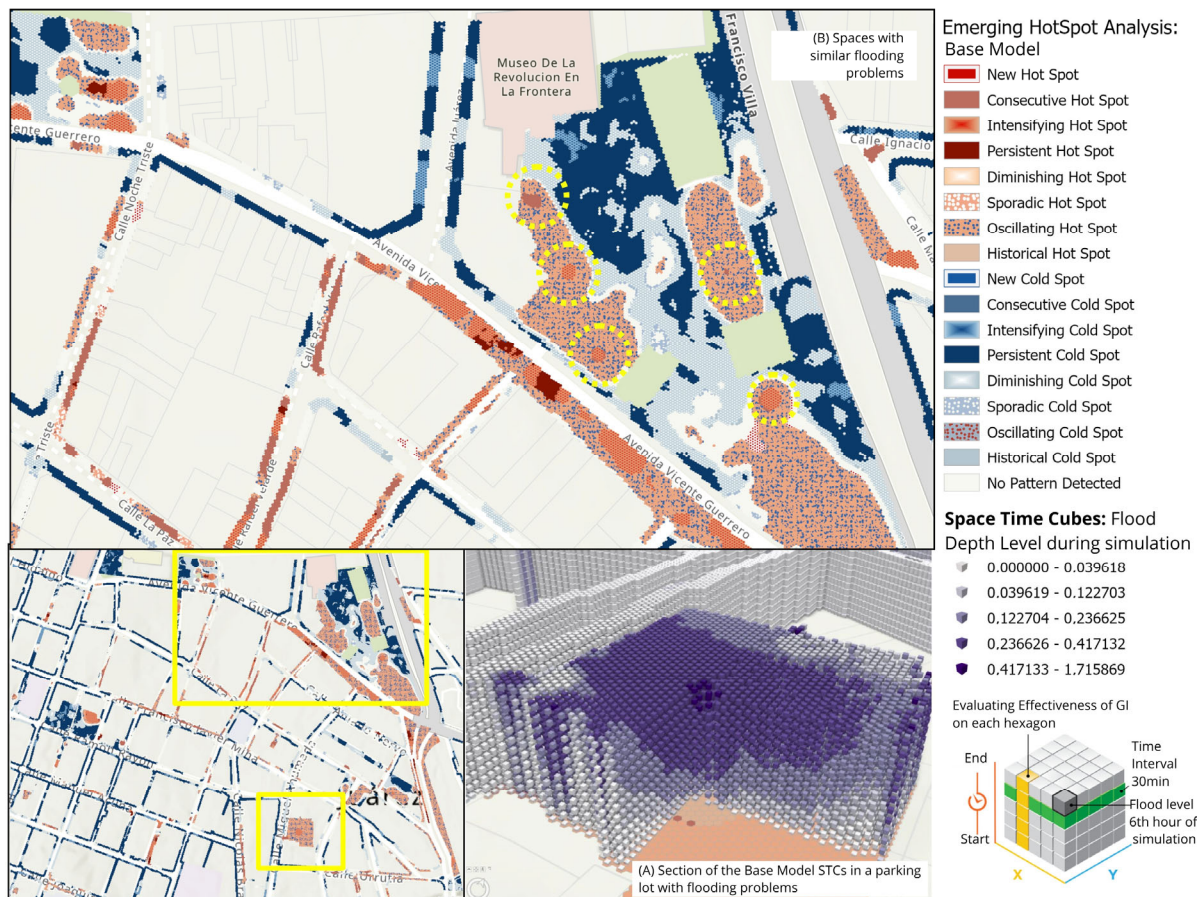


Figure 10. This shows the flood level with a cross-section of the base model STCs in a parking lot, marking towards the center an area where flooding has increased in intensity over time, with 90% of the storm being flooded (A). Therefore, the EHSA analysis classifies them as an intensifying hot spot in the center, with a persistent or hot oscillating flood pattern around it, which means that the flood depth is gradually increasing, as in other areas in the study area (B).

3. Results

The development of a multiscale, multi-criteria analysis is necessary to effectively and holistically integrate GI into the city. To present a methodology that would identify the areas that would best contribute to managing the natural water cycle in an established urban environment, its pre-existing urban dynamics had to be taken into account, along with an analysis of its spatial configuration at different levels to address both environmental and spatial planning challenges simultaneously [57].

This section presents the results of applying this methodology at the city scale, local scale, and microscale, combining spatial analysis tools (such as space syntax, fuzzy logic, and MGWR) with hydrological modeling and geospatial simulation techniques. By integrating land-use patterns, urban forms, and runoff behavior, the results provide a robust framework for locating, prioritizing, and adapting green infrastructure to specific urban conditions. Moreover, spatiotemporal tools like Space–Time Cubes (STCs), Emerging Hot Spot Analysis (EHSA), and Time Series Clustering (TSC) allow the assessment of GI performance over time, offering insights into which systems remain effective and which require redesigning. The findings are organized by scale, demonstrating how each level contributes to a comprehensive urban resilience strategy.

3.1. City Scale Results

The initial phase of the process involved identifying spaces with potential for implementing GI at the city level, integrating space syntax theories as a diagnostic tool to assess spatial accessibility and connectivity patterns. These theories, developed by Hillier [15], revealed that the centralized structures underlying the city's road network correlate with morphological transformations throughout its history. The city's initial urban growth spurt took place until the 1970s, when tourism was the predominant economic activity in the city. This caused these neighborhoods to present a grid-like layout with narrow, short streets, and the main objective was to create a link between the historic center, the PRONAF area, and the international bridges to the United States.

Due to their spatial configuration, their roads today continue to have a high level of integration with the rest of the city. This is reflected in the high level of pedestrian accessibility in all studies, except for the study of park accessibility due to the lacking urban regulations at the time [17], as shown in the spider chart in Figure 11.

Spatial Capital: Pedestrian Accessibility of Urban Centers

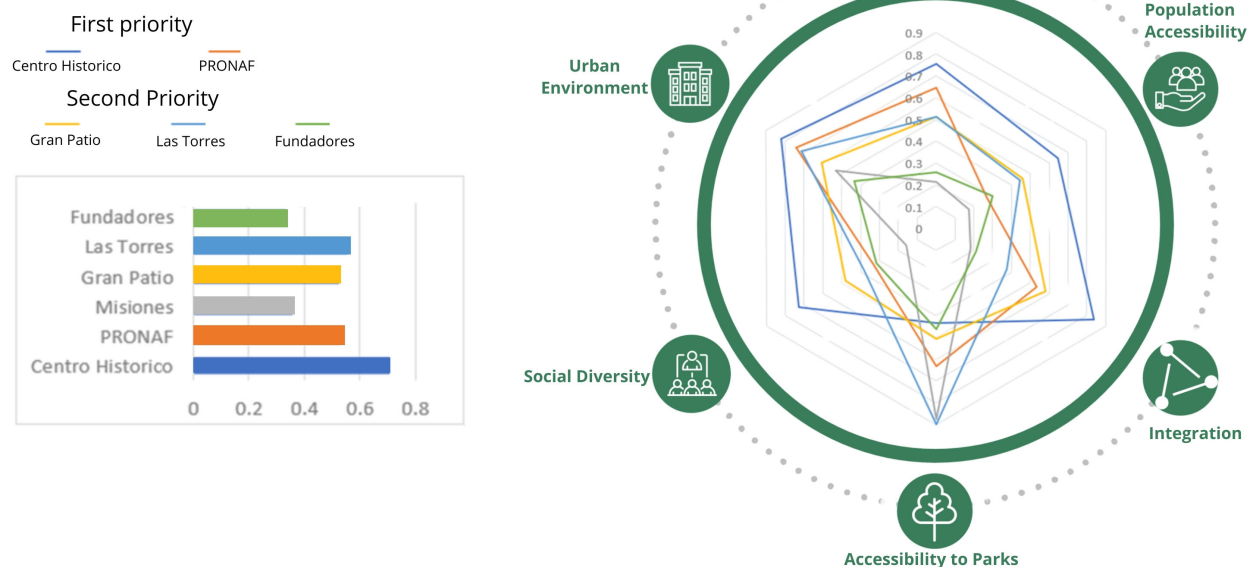


Figure 11. Graph showing quantitative data how the “Centro Historico” urban center has the highest spatial predisposition to create more sustainable urban areas at the pedestrian level, so it is ranked as the urban center with the highest spatial capital as shown on the bar chart.

Analyzing the main challenges facing these urban centers and potential ways to address them is essential for sustainable urban development. The results indicate that the first step could be the strategic implementation of green spaces, which would counteract the current problem of unused lots in the area connecting the historic center and the PRONAF area. These vacant spaces generate deterioration and insecurity in the neighborhood, which in turn diminishes the desirability and value of surrounding properties in the event of an urban reform project [58].

Transforming these areas into green spaces could have the opposite effect [48], paving the way for future plans toward a more pedestrian-friendly city by creating green corridors linking the two urban centers (Figure 12). Given the short distance between them (approximately 2500 m), there is robust potential to encourage active mobility and reduce dependence on motorized transport [49]. Moreover, the presence of a human-scale urban grid, characterized by permeable street patterns and mixed land uses, enhances walkability

and supports densification and rehabilitation efforts in these key corridors [51]. Therefore, these areas represent strategic zones where the city should prioritize investment in sustainable infrastructure and spatial reintegration [36,48].

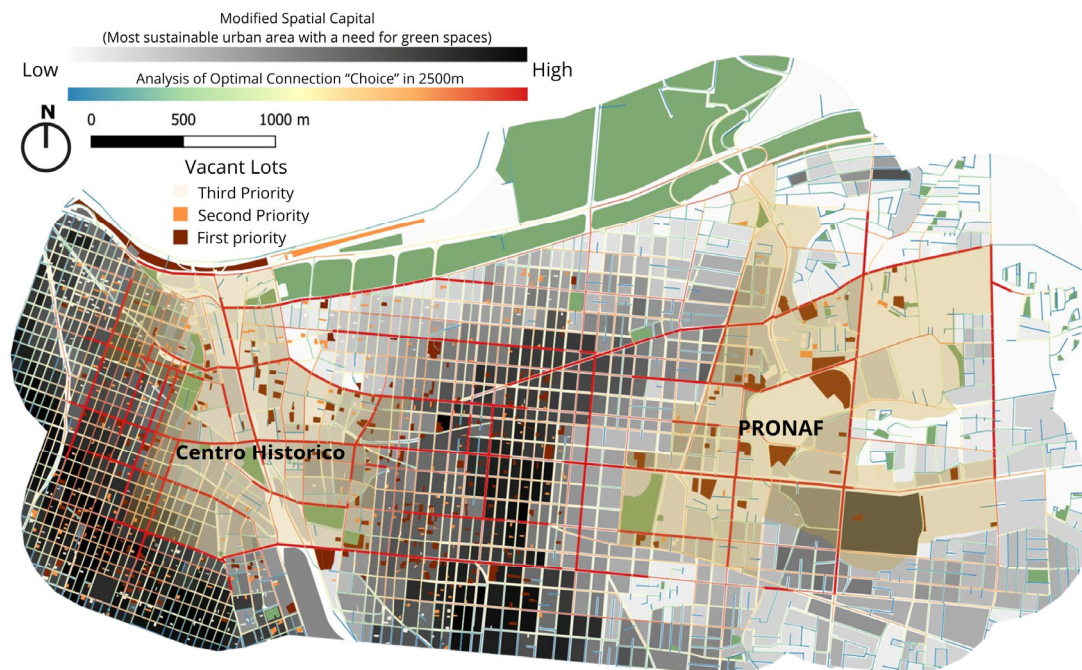


Figure 12. Map showing which blocks would be most effective in implementing new green areas to connect the two urban centers (Centro and PRONAF), highlighting in red the 10% of roads most likely to be used by pedestrians or cyclists according to the choice analysis at 2500 m and unused lots classified by level of rehabilitation priority.

3.2. Local Scale Results

At the local scale, green GI implementation opportunities in the historic center were first identified using hydrological modeling and spatial suitability analysis. By combining fuzzy logic with a geospatial decision matrix, this study evaluated the flood risk, runoff dynamics, and land-use conditions to determine the best GI types for each location. This process generated an initial proposal for GI distribution based on terrain, drainage needs, and proximity to urban infrastructure (Figure 13).

The most implementable type of GI in the study area was identified as the infiltration permeable pavement (I-PAV), which is possible to implement in 265,000 m² of sidewalks since it allows controlled infiltration close to buildings, followed by its implementation in 54,672 m² of parking areas. Also, the implementation of 43,519 m² of permeable pavement with a retention system is recommended, which integrates tree pits and interlocking concrete with a sublayer of gravel and clay, which has the highest infiltration rate and resistance in conditions with a high level of sediment accumulation [59]. This, together with its multifunctionality of infiltrating, storing, and channeling excess rainwater through pipes towards the mixed drainage, makes it a priority system since it will also improve mobility and appearance in the area [38].

Currently, there are a total of 127,428 m² of permeable surfaces for implementing GI in the study area, which are neglected, giving a poor urban image to the area. Most of these are only used as passageways leading to commercial centers or to crossings into the US. These could be rehabilitated, improving the city's aesthetics and biodiversity, using a combination of GI according to its infiltration and runoff detention needs. It was estimated that a total of 123,799 m² of rain gardens and 11,207 m² of bioretention strips could be

implemented in the study area. And in this way only using more technical infrastructure such as infiltration wells as a last option due to their implementation and maintenance costs (Figure 14).

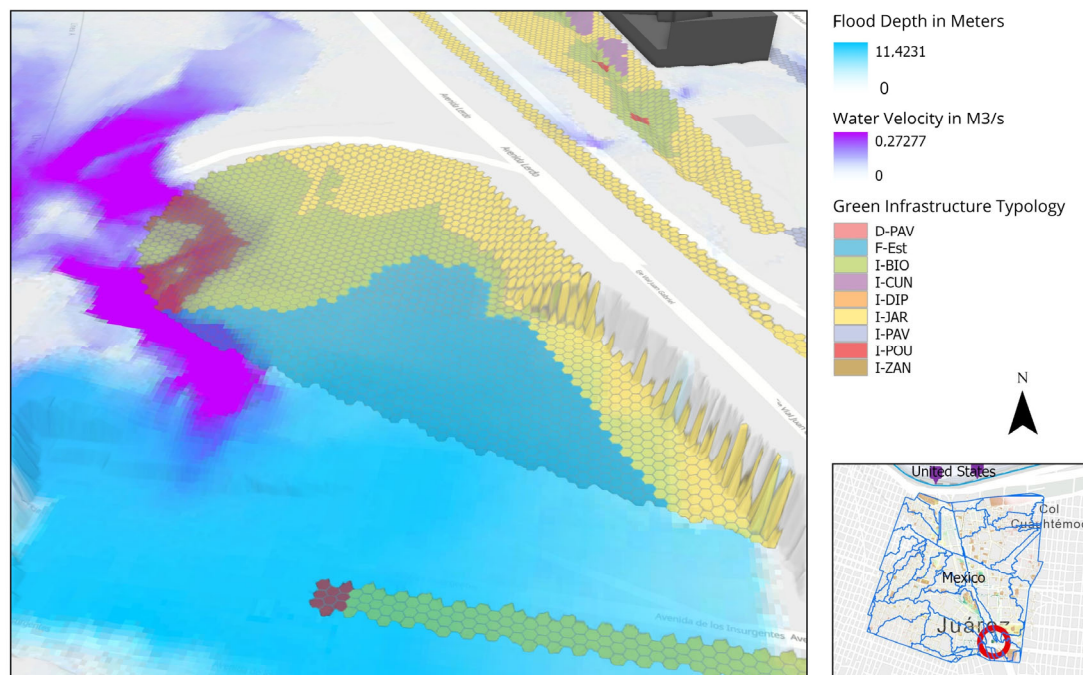


Figure 13. This shows how the GI is strategically placed by the Automated Selection Matrix to help reduce runoff with infiltration ditches before it reaches other systems, reducing the washout of the upper layers of other types of vegetated infrastructure.

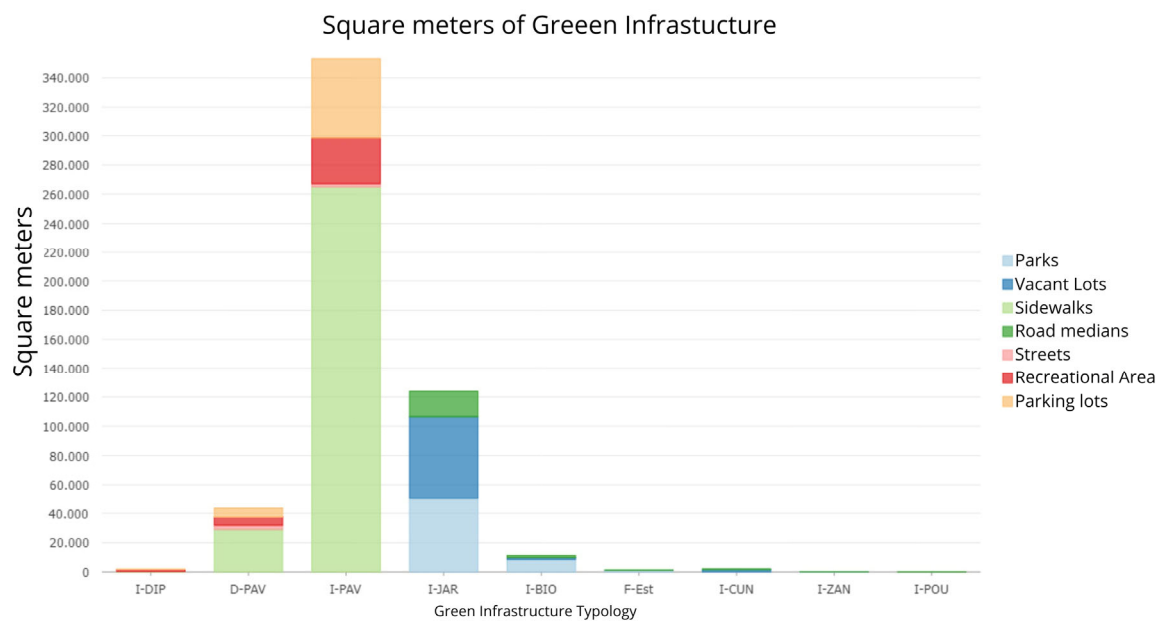


Figure 14. Quantification of types of green infrastructure proposed at the local level.

To strengthen the spatial logic of GI placement and to prove if space syntax theories functioned according to previous studies, MGWR analysis was conducted. This allowed us to assess how different land uses correlate with street connectivity at multiple spatial scales (choice 500 m, 1000 m, 2500 m), validating the relevance of key corridors for strategic GI intervention.

The MGWR results confirm that streets with high choice values at 2500 m and 1000 m are key to commercial activity in the area. The model also explains approximately 54.23% of the variability in the vacant-lot percentage values. This is a concrete result for this type of analysis and suggests a significant correlation between streets with an optimal connection (choice) at 500 m and the distribution of vacant lots. Thus, this validates the hypothesis that spatial configuration plays a central role in urban functionality in the historic center, since low-traffic areas are more likely to end up abandoned. Thus, highlighting the importance of integrating this information into GI planning for strategic investment, the relationship between land uses, and the optimal connection values allows for prioritizing the most relevant streets for urban connectivity and sustainable regeneration.

- Areas with high accessibility within 500 m (choice 500 m) would be ideal for community-oriented green infrastructure (small urban parks or community gardens).
- Areas with high accessibility within 1000 m (choice 1000 m) can serve as green infrastructure that complements commerce, such as tree-lined streets, wide pedestrian areas, and market spaces.
- Areas with high accessibility within 2500 m (choice 2500 m) could have more iconic green infrastructure, marking urban landmarks to connect the two urban centers (large urban parks, vegetated civic plazas, green corridors).

3.3. Microscale Results

It was shown that the geomorphology within the micro-watersheds in the study area follows a dendritic drainage pattern, where runoff follows short, irregular courses, partially following the reticular structure of the urban fabric. This results in the underutilization of runoff storage capacity in the nearest catchment area, since the few available areas of permeable surfaces where GI implementation is possible are at a higher level than the sidewalks. Therefore, another type of ground-level infrastructure must be proposed in these spaces, thus diverting runoff inward and increasing their infiltration capacity. This type of microscale terrain-based retrofit is consistent with the SUDS practices applied in other semi-arid cities, where minor topographic changes have been shown to improve runoff interception without major infrastructure investment [44].

Thus, the terrain was modified by simulating three 30 cm high physical barriers in strategic locations, channeling the main runoff from the study area to the catchment areas. A spatial statistical analysis was then performed, allowing us to quantify the influence of GI with high precision. The micro-topography was altered using a 10 cm resolution DEM, and depressions were modeled 20 cm below the sidewalks based on runoff flow directions, as recommended in SUDS implementation guidelines [46]. By modifying the relief of the possible catchment areas and using the GI typology proposed at a local scale, 1085.72 m³ of water can be infiltrated into the micro-basin until the catchment areas overflow and the storm water runoff ends up at the critical flooding point in the Insurgentes Avenue (Figure 15).

The GI works in much of the study area, reducing flooding and creating a safer and more hospitable environment. However, some specific areas become saturated and redirect water, causing new flooding hot spots, since terrain modification had not been considered when proposing the GI at the local scale. Therefore, using a combination of the EHSA and TSC analyses reveals which GI is functioning correctly and which areas require system improvements.

In this study, the EHSA tool was configured to identify statistically significant hot spots using a fixed time-step of 30 min in a 1 m² hexagonal grid, following best practices in space-time flood modeling [13,60]. This allowed for the identification of both persistent and newly emerging hot spots, offering a detailed understanding of temporospatial GI effectiveness.

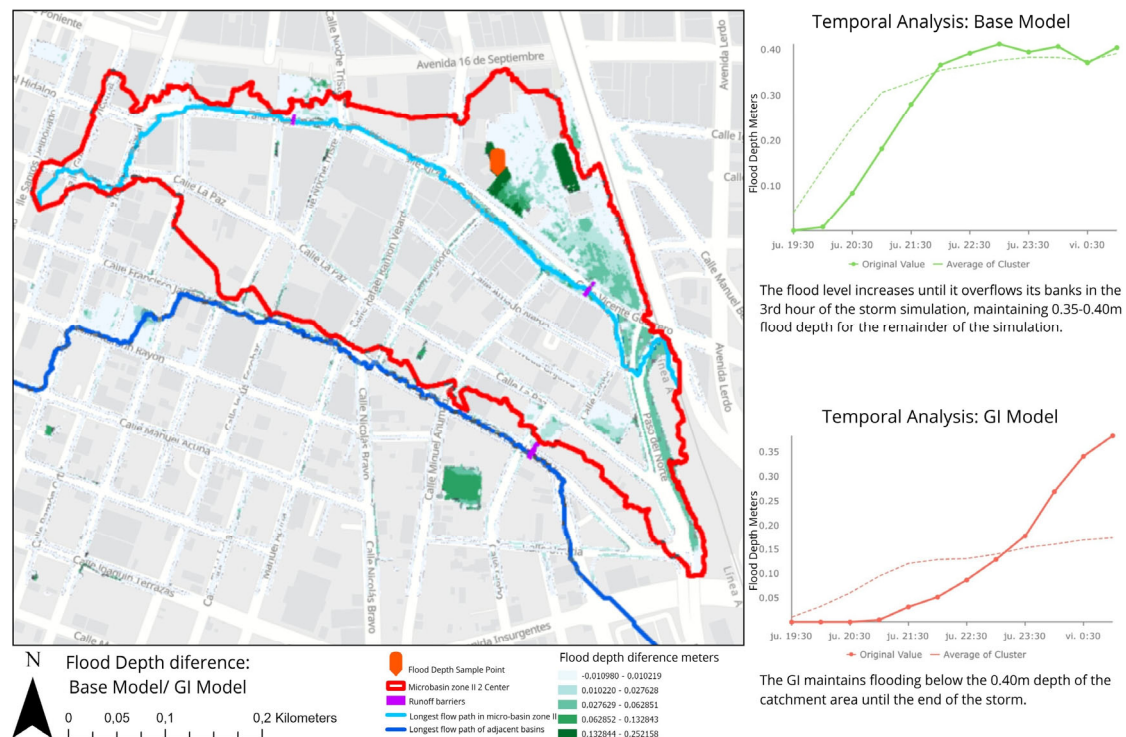


Figure 15. The difference in flooding between the base model and GI model, performing a temporal analysis within a parking lot with flooding problems.

The results from TSC show that in the Functional Cluster of GI, the percentage of hot spots in critical flooding is generally lower, indicating that these GIs are successful in reducing flooding. In contrast, the Dysfunctional Cluster category shows a higher percentage of time when the infrastructure is flooded, suggesting that these GIs are unable to efficiently manage the amount of runoff or become saturated quickly. Time Series Clustering has been used in flood resilience studies to evaluate GI performance over storm events [60]. In this case, the clustering patterns clearly differentiate zones that require structural upgrades from those where GI is working as intended.

Therefore, in impermeable spaces, 1953 m² of mixed permeable pavement (D-PAV) and 4796 m² of simple permeable pavement (I-PAV) present flooding issues. It is suggested to change these GI systems by implementing more cellular storage systems (I-DIP) or infiltration wells. Similarly, it is recommended to replace the flooded 3751 m² of rain gardens (I-JAR) with bioretention strips (I-BIO), which have a higher runoff absorption capacity (Figure 16).

Using the EHSA allowed us to evaluate the impact of GI in two scenarios. On the Base model (Figure 17B), areas with recurrent flooding were identified as “Intensifying Hot Spots”, since they remained flooded during 90% of the simulation. These areas are surrounded by zones where water accumulation fluctuated until it overflowed the catchment area, which are labeled as “Oscillating Hot Spots”. Following the implementation of green infrastructure (Figure 17C), a 38% reduction was observed in areas with intensifying flooding, transforming them into zones of oscillating hot spots. This led to a 318% increase in areas classified as new hot spots.

This means that while flooding in these areas did not disappear entirely, storm water accumulated more gradually and to a lesser extent, only peaking during the final 30 min of the 6 h storm simulation. Such a change indicates that the GI systems successfully delayed peak flooding and increased infiltration time, buying critical time during intense rainfall events, which is an important outcome for urban flood resilience planning.

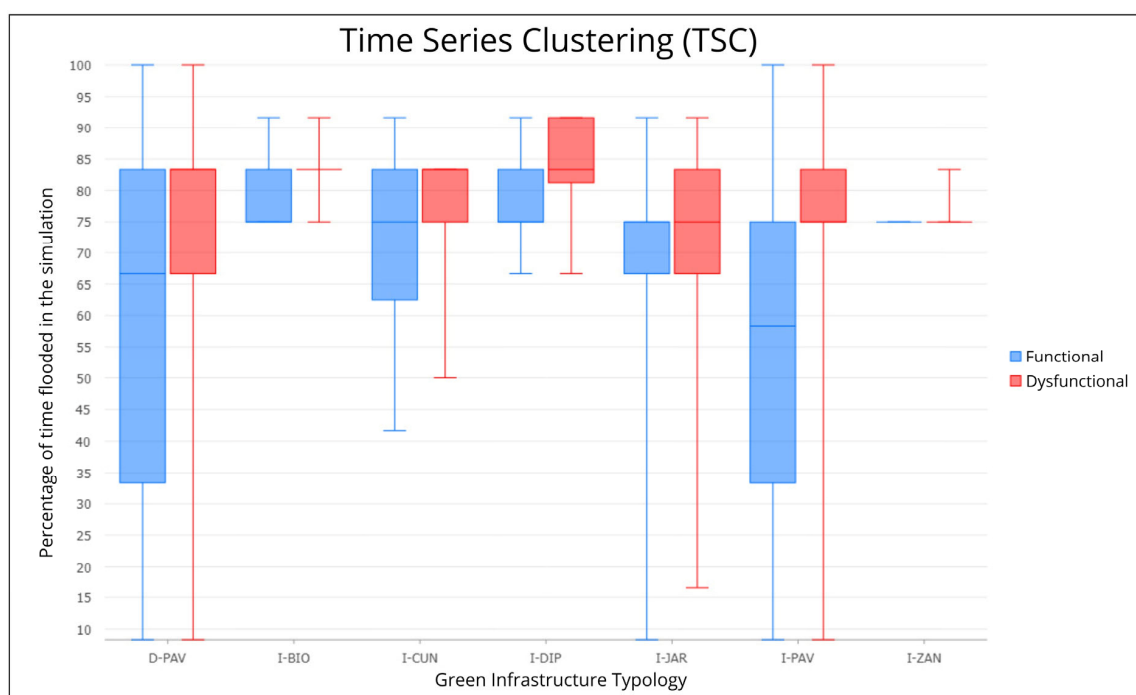


Figure 16. This shows the temporal effectiveness of GI, divided into two behavioral clusters (functional and dysfunctional), identifying what GI needs to be upgraded.

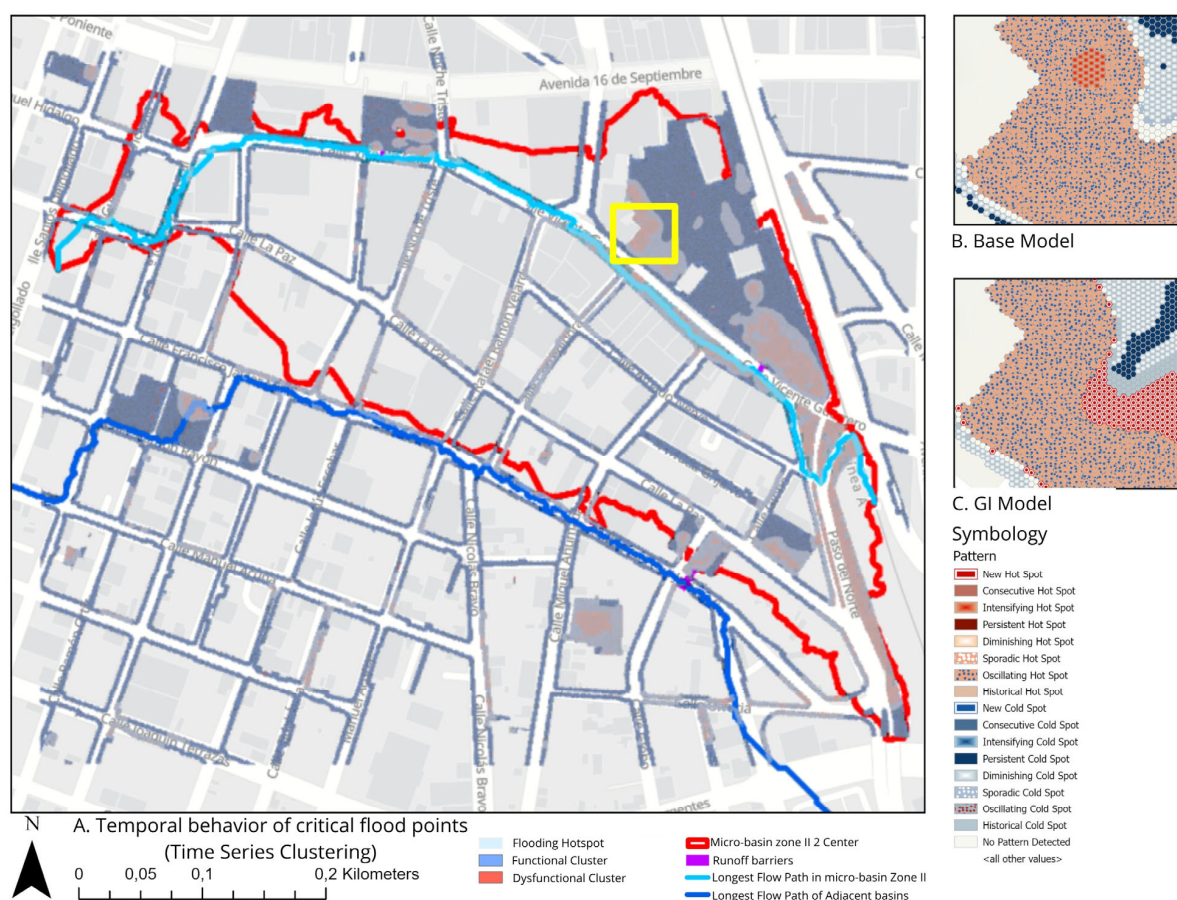


Figure 17. Map of critical flooding points using TSC; the GI category that needs to be improved is identified in red (A). Also shown are the EHSA analyses of the base model (B) and the GI model (C), highlighting the reduction in flooding time per 1 m2 hexagon of GI.

In summary, the results across the three scales exhibit the usefulness of joining spatial connectivity analysis with hydrological simulations. The findings confirm that GI can be optimized by spatial context: from macro level connectivity interventions (green corridors), to targeted GI typologies (permeable pavements, rain gardens), to precise site-scale retrofits that reduce flood tenacity over time.

4. Discussion

Overall, the methodology employed in this study successfully identified areas with the highest potential for integrating green infrastructure (GI) within fragmented urban fabrics, maximizing the social, ecological, and economic benefits of GI as a tool for mitigating hydrometeorological risks. By combining spatial configuration analysis and hydrological modeling across multiple scales, this approach effectively addresses a critical gap in current urban planning research. Although the integration of spatial morphology and storm water modeling has been widely recommended in the recent literature as a strategy to enhance multifunctionality and urban resilience [13,57,60], its application in practice remains limited. This study demonstrates that such a combined methodology is not only feasible but offers significant advantages for planning adaptive, site-responsive GI strategies in complex data-scarce urban environments.

Based on the morphological analysis carried out on the city-scale study [15,16], two main urban centers (historic center and PRONAF) were identified as the best areas to focus efforts to evaluate the potential implementation of GI. These centers were selected due to their spatial predisposition to create a sustainable environment and the potential benefits of creating flood risk mitigation strategies to help rehabilitate them. This supports similar findings by Cao et al. [50] and Zhang et al. [49], who used MGWR to show how green corridors and well-connected areas increase land value and promote active transportation and demonstrate that choice-based network connectivity at 500 m and 2500 m radii aligns with local commercial and pedestrian dynamics in the historic center [51].

Additionally, studies by Li et al. [36] demonstrate that routes between two centers are not only influenced by high-demand areas, such as transportation or commercial hubs, but that users prefer areas with green corridors and will often choose them over other routes. This highlights the importance of GI promoting connectivity and comfort for cyclists and pedestrians, since creating more accessible routes will attract more users and reactivate the economy. Considering that, the municipal government of Ciudad Juárez is planning the city's first bike-sharing system in the study area. Therefore, the choice-type analysis helps predict cyclist traffic in this zone [61], with assisting in validating a strategic rehabilitation plan being crucial for certain roads and facilitating sustainable urban mobility.

At the local level, different spaces within the historic center were evaluated to determine their potential for implementing different types of GI. Considering fuzzy MCDA to assess the benefits provided by GI [18,32,33], it is possible to identify where to focus rehabilitation efforts by conducting a sustainable urban analysis using geospatial tools. This approach is aligned with methods used by Failache et al. [39] and Gulshad et al. [40], where spatial and performance-based criteria were combined with rule-based logic to prioritize GI placement, demonstrating the scientific advantages of automated matrix selection models.

On the other hand, a viable and high-potential alternative is implementing strategies for renaturalizing the canal system within the study area. Creating adaptation plans for areas adjacent to these canals using riparian restructuring techniques [62] would provide essential goods and services to resolve hydrometeorological risks in the urban center. Despite having less than the recommended 30 m distance between the river channel and first constructions in some sections, these solutions could be implemented in 22.64 hectares adjacent to the canals, contributing to the functional beautification of these zones. Thus,

this creates new recreational areas that mitigate pollution effects in the streams and adapts them as biological corridors within the urban fabric.

While leaving the analysis of private spaces for future studies, the following points are determined: Buildings that can implement green roof solutions could be analyzed. The presence of roofs with a slope of less than 10% could be prioritized for implementation in public, commercial, and industrial buildings. Residential buildings, on the other hand, could implement roofs with reflective materials and rainwater collection cisterns, reducing flooding and heat islands in the area. Making these nature-based retrofits is particularly effective in semi-arid regions [44], where surface-level GI is limited.

Finally, at the micro level, the results from the previous scales were used to identify the best possible solution, based on the specific geospatial constraints of each area, in terms of topography, hydrology, land use, and mobility patterns. This generated multiple benefits, such as flood risk mitigation, improved mobility and public spaces, as well as improvements in the quality of life and social well-being of these communities. By using spatiotemporal tools like STCs and EHSA, this analysis not only mapped outcomes but revealed the evolution of flood hot spots in time, a method increasingly advocated for adaptive GI planning [13,56] and which shows promise for future disaster planning due to its high spatial and temporal precision.

5. Conclusions

This study demonstrated that a multi criteria, multiscale approach integrating spatial configuration and hydrological modeling can be effective in informing the implementation of green infrastructure (GI) in fragmented urban settings. By integrating space syntax, fuzzy logic, and storm water simulation, the proposed framework facilitates data-driven, context-sensitive planning at the city scale, local scale, and microscale.

The model was successful in not only identifying where GI must be implemented but also in what typologies are most appropriate based on urban form and hydrological function, re-establishing the underlying research objective of improving connectivity and flood resilience in semi-arid, data-poor urban areas.

The proposed methodology is implementable in other Mexican border cities (Figure 18) and transferable to similar international settings that are experiencing rapid urbanization, spatial disarticulation, and climate exposure [63]. It aligns with global sustainability agendas, particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

Yet, given the scarce availability of high-resolution hydrological data, synthetic storms and USDA soil infiltration rates were employed, though these are sufficient for simulating runoff and would be significantly improved through calibration against empirical field data. Likewise, the inclusion of community engagement and sociospatial feedback loops would be able to improve social equity in GI planning.

Future applications need to expand the model by integrating additional environmental and social criteria, such as urban heat island effects, long-term maintenance costs, and community preference, with the application of tools like the Fuzzy Analytic Hierarchy Process. The continued integration of spatiotemporal tools (e.g., STCs, EHSA) and spatial network measures will further promote adaptive and evidence-based GI planning in the face of evolving urban and climatic stressors.

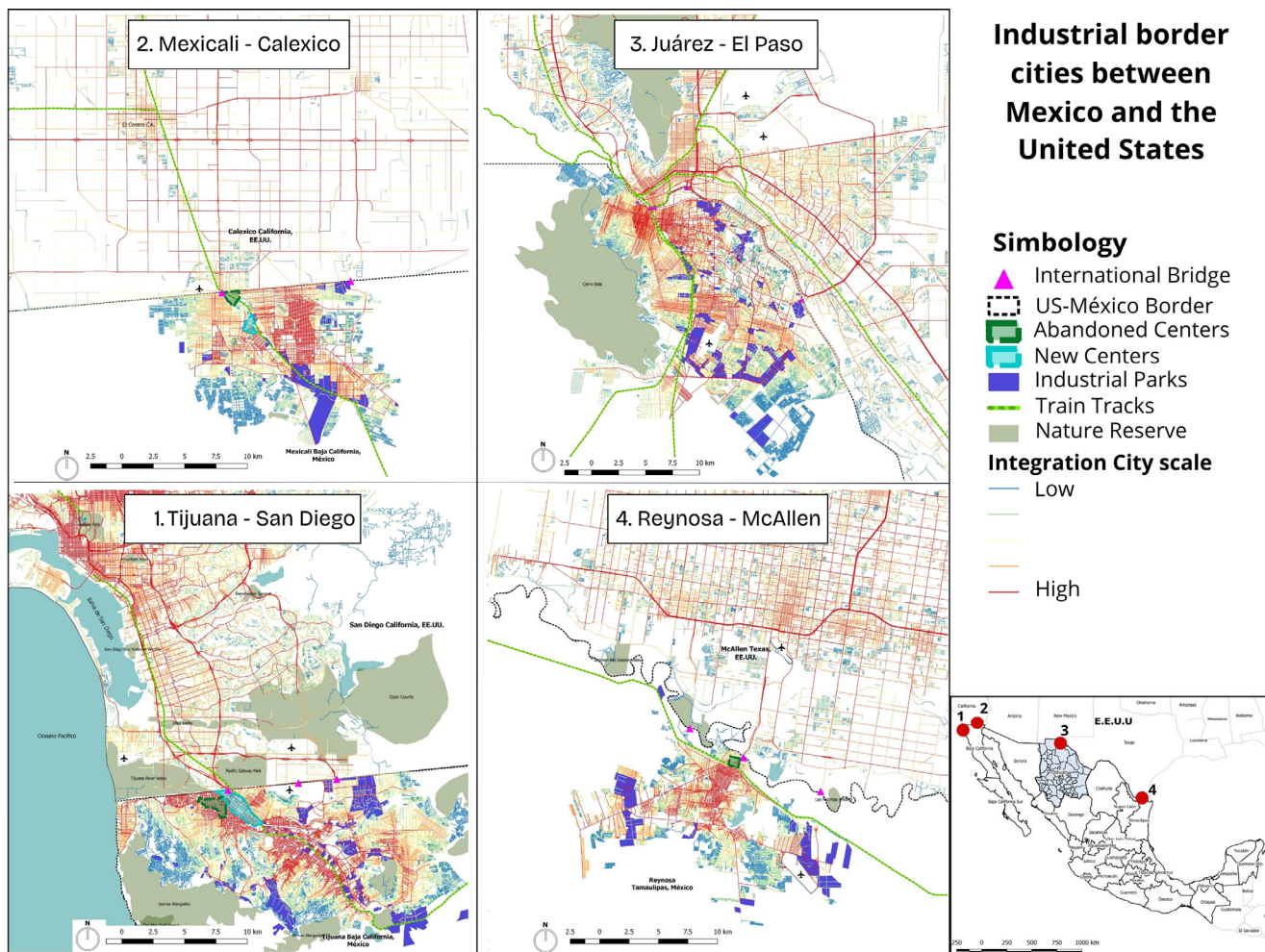


Figure 18. These border cities present a series of defining factors that contribute to their current state of urban fragmentation: their physical and topographical environment, their foundational urban layout, their railroads, their bond to the international bridges, and their industrial parks, making them suitable for a rehabilitation strategy using a multiscale approach.

Author Contributions: Conceptualization, R.A.G.A. and A.M.D.; methodology, R.A.G.A. and A.M.D.; software, R.A.G.A.; validation, R.A.G.A.; formal analysis, R.A.G.A.; investigation, R.A.G.A.; resources, R.A.G.A.; data curation, R.A.G.A.; writing—original draft preparation, R.A.G.A. and A.M.D.; writing—review and editing, A.M.D. and X.M.; visualization, R.A.G.A. and X.M.; supervision, A.M.D. and X.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CONACYT, grant number 671391, and the APC was funded by FUNITEC, La Salle, Universidad Ramon LLull.

Data Availability Statement: The high-resolution elevation data used in this study were generated by the authors through a photogrammetric drone survey of the study area. Base maps were sourced from Esri for visualization purposes only. Due to file size and storage limitations, the full raw datasets (e.g., orthophotos, point clouds, and DEMs) are not publicly available; however, processed outputs including suitability rasters, fuzzy logic layers, and hydrological model results are available from the corresponding author upon reasonable request. Additional spatial and statistical datasets were obtained from public sources. Urban and demographic data from INEGI (Instituto Nacional de Estadística y Geografía) and planning documents from IMIP (Instituto Municipal de Investigación y Planeación de Ciudad Juárez) are openly accessible through their official websites: <https://www.inegi.org.mx>; <https://www.imip.org.mx>.

Acknowledgments: Gratitude is extended to the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONACYT) for the scholarship that supported the development of this Ph.D. research. Special thanks are also extended to La Salle, Universitat Ramon Llull for their support with the APC funding. Finally, sincere appreciation is expressed to everyone whose contributions made this research possible.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

GI	Green infrastructure
FUFs	Fragmented urban fabrics
SUDSs	Sustainable drainage systems
SDGs	Sustainable Development Goals
STCs	Space–Time Cubes
EHSA	Emerging Hot Spot Analysis
MCDA	Multi-criteria decision analysis
MGWR	Multiscale Geographically Weighted Regression
INEGI	Instituto Nacional de Estadística y Geografía
DENUE	Directorio Estadístico de Unidades Económicas
INV	Inventario Nacional de Viviendas
IMIP	Instituto Municipal de Investigación y Planeación

Appendix A. Urban Morphological and Accessibility Modeling at the City Scale

This appendix summarizes the spatial analysis methodology used to identify the strategic areas for green infrastructure (GI) implementation across Ciudad Juárez, based on space syntax theory and urban accessibility modeling.

Appendix A.1. Spatial Configuration Analysis

The spatial configuration and constant traffic on the city's roads are important factors for the sustainable development of its urban fabric. Depending on the efficiency of connectivity within this network, a space with improved accessibility is created, leading to a better quality of life. This can be predicted using the theories and analytical techniques of space syntax, which have been used since the early 1980s by architects and urban planners to simulate how the spatial arrangement of buildings or cities influences the results of human movement and social interaction within their spaces [15]. This type of analysis is based on “graph theory”, reconceptualizing it in terms of the geometric shape of the city to measure the relative proximity of a location to all locations in the road network. In this way, we can observe how every urban environment is interconnected and how the evolution of urban fabrics is guided by a process of large-scale changes in the accessibility of these spaces. In this sense, a spatial structure with more connections reflects a more central space, which facilitates the conditions for a concentration of activities in the area, helping to sustain the long-term prosperity of the spaces to be designed or renovated.

In order to correctly identify the different variables that would increase the spatial capital of the analyzed urban areas, models of the level of “integration” or centrality of the entire city's roads are first created using space syntax, which is called a “global” level analysis. In this study, the links between the elements of a network were analyzed by transforming them into an axial map. In this case, the interconnecting segments and nodes that make up the city's roads are calculated. This calculates their integration or centrality among all the streets, thus predicting their usage potential. In other words, this would be

the distance or measurement from each element of the network to all the other elements. Therefore, each element would be integrated when its distance was shorter than the rest of the network, giving it a more central value. On the other hand, it would be given a more segregated value, which would be when it is located in a peripheral position or without a broad relationship with the rest of the urban network.

The other way the program processes is through the optimal connection measure or “Choice”, in which, based on a “global” analysis of the city, it calculates the shortest path or one with the least angular deviations between all the nodes and segments of the network to get from one place to another. This identifies the roads that are most frequently used to navigate the city’s road structure, such as main and secondary avenues. On the other hand, there are dead-end streets, since they do not establish any connection to the road network other than their own.

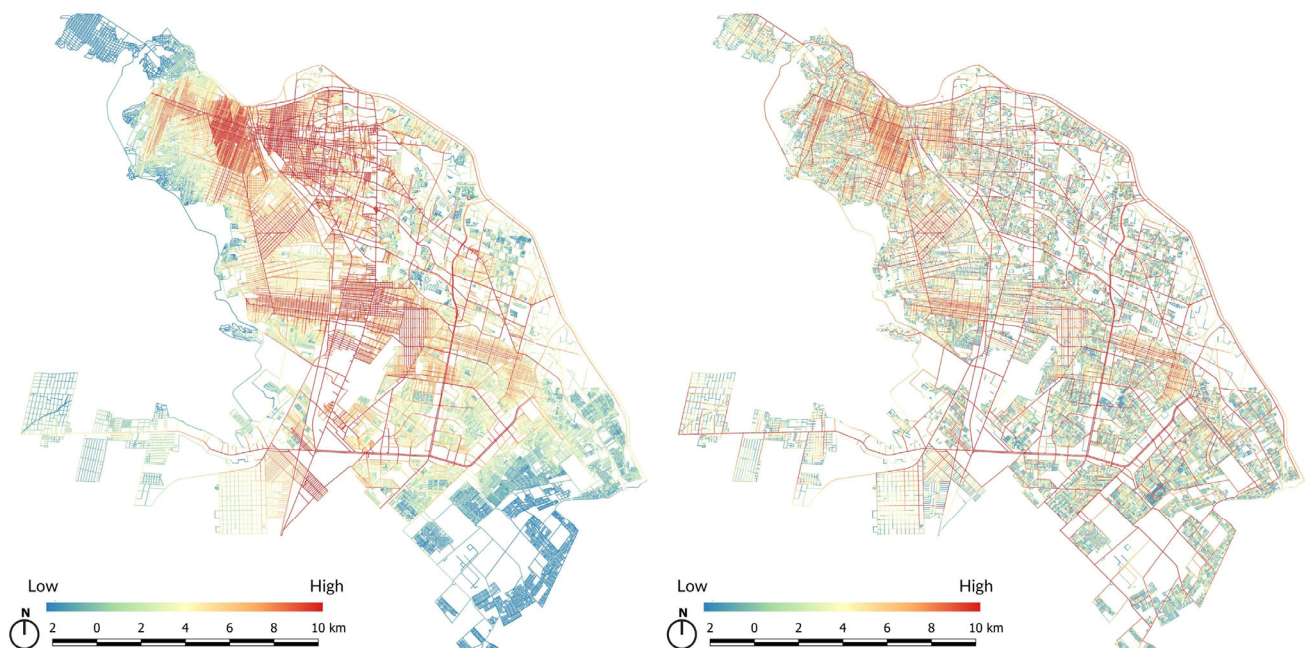


Figure A1. Integration (left) map and choice mode (right) at the global level. Prepared by the authors using road axis data from Ciudad Juárez, from the INGI, processed with DepthmapXnet 0.35.

Appendix A.2. Accessibility and Attraction Modeling

The study of the relationship between the attractiveness and accessibility of an element in urban space is one of the main research objectives in urban morphology. This is because, to shape more sustainable cities, it is essential to conduct various urban accessibility studies, which focus on two main variables: the distance and attractiveness of a location. These concepts are linked to the economic theories of Von Thunen from the late 19th century, which basically explain that the rent of a location varies with the distance of the location from its market.

For a long time, these studies were limited by a lack of data and the tools to analyze them. This is due to the complexity of incorporating a model that properly integrates the daily activities of urban life and a person’s cognitive perception of the environment that surrounds them. Recently, research related to measuring the accessibility of a place has been advanced to another level with the spatial analysis method developed by Place Syntax [24].

This is important since an urban analysis is usually conducted not only based on its level of spatial integration, as space syntax does, but also on the capacity of these roads to provide access to people or a certain type of service.

This is why Place Syntax developed different types of urban accessibility analyses. The first involves analyzing a point of origin or node on the axial map, measuring the accessible distance to a specific attraction. This distance is georeferenced using points or plots of land, which is called “Attraction Distance”. The other possible analysis is the “Attraction Reach” method, which calculates the total number of attractions that can be reached within a certain radius from a point of origin or node on the axial map. This method can yield interesting results, identifying the concentration or absence of services, shops, or people within a specific radius, giving a more realistic perspective on how a person perceives urban space.

Appendix A.2.1. Integration

By generating city models with these tools, the level of attraction of each block is measured using the integration values of its roads within a radius of three axial steps on the axial map. Space syntax calculates these values based on the number of changes in direction, or geometrically speaking, the number of angular deviations in the path. According to Ståhle [24], this is the most appropriate distance measure for simulating short trips, such as those made on foot in cities with a curvilinear loop, cul-de-sac, and organic tree-lined and grid-like variations in their urban morphology, as these measures more accurately predict human behavior than the traditional metric method of measuring distance.

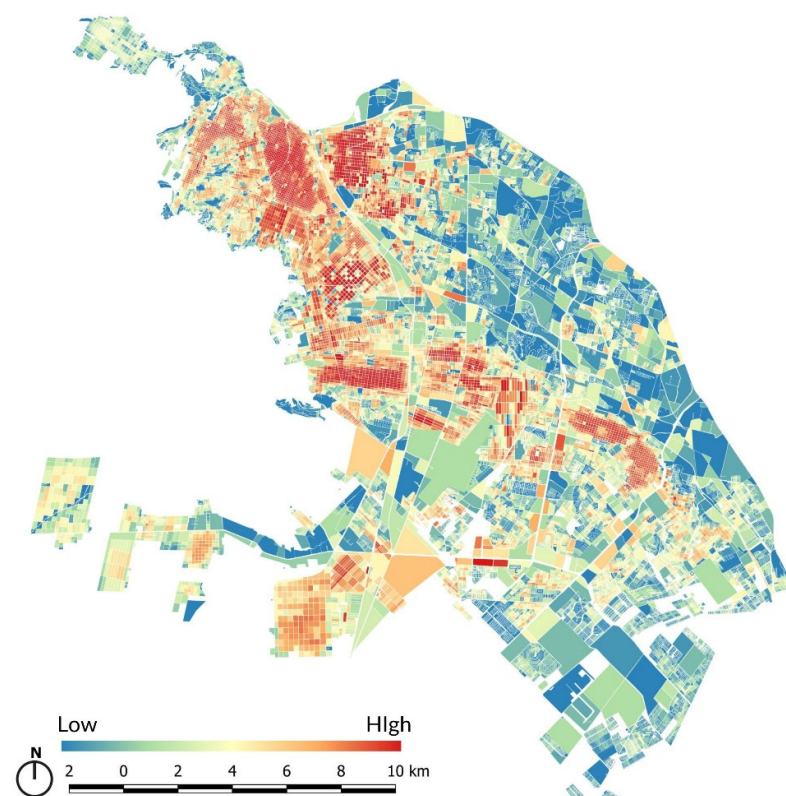


Figure A2. “Attraction Reach” analysis map at the 3 axial steps’ level of road integration, highlighting the most pedestrian-friendly spatial configurations.

Appendix A.2.2. Population Density

Population density analyses are among the most studied aspects for achieving more urbanistically sustainable cities. According to Frey [64], a functional city should achieve values between 60 and 80 inhabitants/ha, standards that are far from being achieved in Ciudad Juárez due to its current dispersed city model, where only 37 inhabitants/ha are achieved. By refocusing the traditional way of measuring population density data, which

is typically the density within a geographic unit (such as neighborhoods, properties, or blocks), through the level of population accessibility available at different attraction ranges, it is possible to capture the values that measure the description of population density in the ubiquitous form developed in the space syntax methodology within each block.

Conducting this type of study in the city reveals a difference between the traditional method of measuring population density per block (left) and the accessible population density within three topological steps (right), which, according to Ståhle [24], represents a more realistic version of how a subject perceives population density in urban space during short walks around their neighborhood (Figure A3).

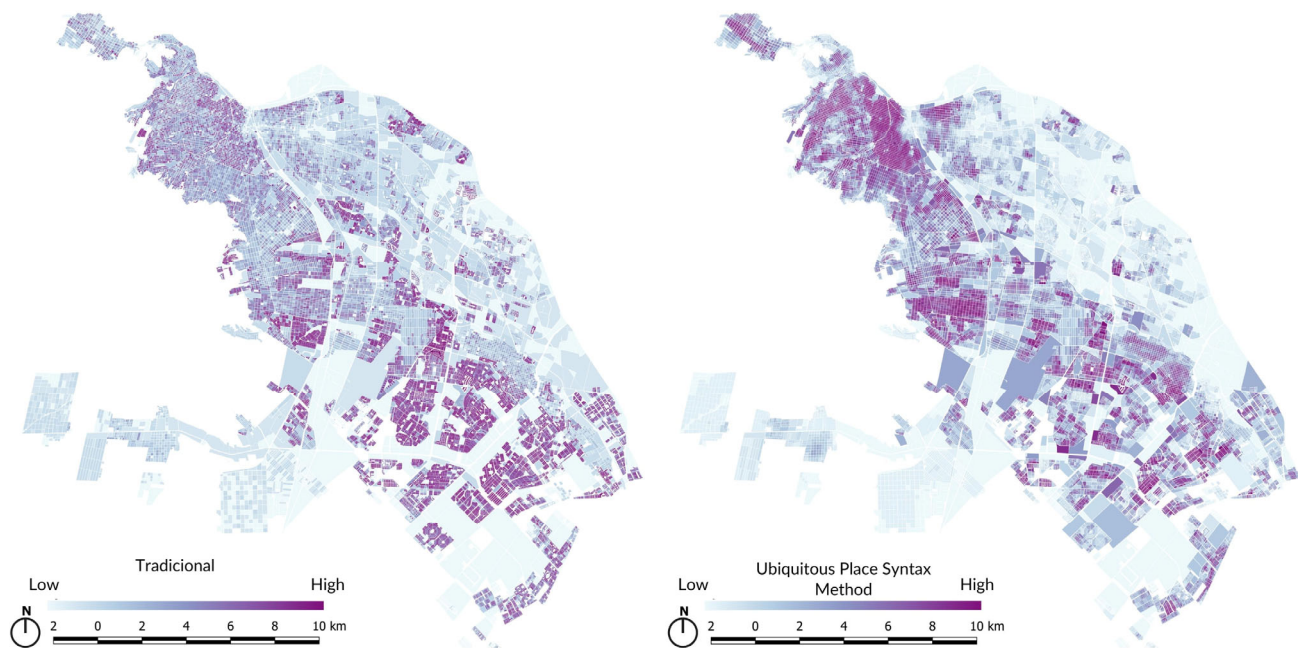


Figure A3. Population density map by block (**left**) and accessibility map to population density at 3 axial steps (**right**). Created by the authors using data on road axes and city blocks in Ciudad Juárez, from the INGI (National Institute of Statistics and Census), processed with the Place Syntax Tool (PST v3.2.2.).

Appendix A.2.3. Economic Diversification

Using the method described previously, Place Syntax can also be used to calculate the accessibility to the diverse contents in an urban space. In this article, it is used to evaluate the presence of different economic establishments within a three-axial-step distance, obtaining an analysis of which area of the city has the greatest pedestrian accessibility for businesses. The National Statistical Directory of Economic Units (DENUE) database contains a total of 41,435 georeferenced economic establishments in the city, which are divided into a large number of different categories; therefore, the entire database is used for this exercise. These are defined as different destination points in the PST, using blocks as origin points and using the city's axial road map to run the "Attraction Reach" analysis for each block within three steps. Because this process is strongly influenced by the level of accessibility of each block, it is necessary to normalize it by dividing the analysis result by the square footage of all blocks captured by the analysis (Figure A4).

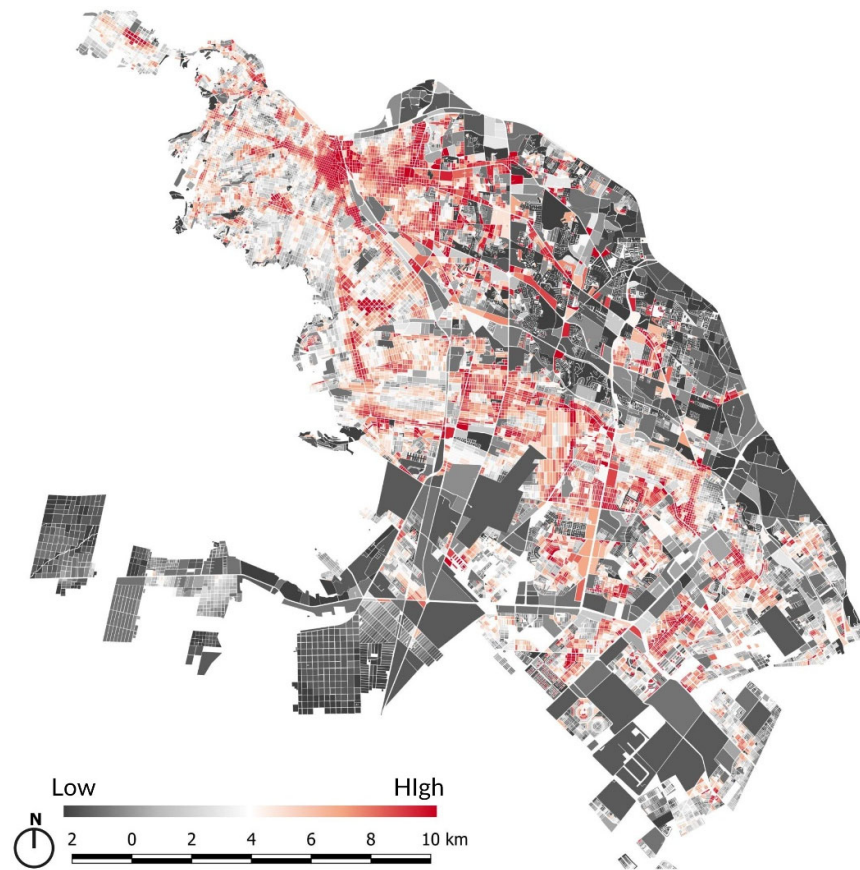


Figure A4. Map of accessibility to economic diversity in 3 axial steps.

Appendix A.2.4. Social Diversity

Because people's daily routines are the fundamental basis that guides the functions of social organization within cities, it is necessary to analyze how different age groups and social classes are distributed in an urban environment. By applying Place Syntax techniques to social studies of the population, a way is created to measure the co-presence of different people in urban space.

The segregation and concentration of marginalized groups in different sectors of the urban fabric is one of the most serious problems facing cities, as it limits the range of diverse activities and opportunities that a given sector offers. Planning cities that foster geographic proximity between diverse social groups creates spaces with greater diversity, enhancing cohesion, trust, and security within them.

According to Marcus [25], this level of co-presence is linked to the type of social network generated by different urban structures. Spatial configurations designed with lots of cul-de-sacs minimize social contact with visitors from outside these neighborhoods due to the low number of people who would be available to pass through these spaces. This generates networks of more homogeneous groups, creating a type of social bonding in which neighborhood members are not as open to socializing with people outside their social circle. In contrast, more permeable spatial configurations give rise to a more accessible network of population groups, creating social networks more inclined to social bonding, a result in which more heterogeneous groups are linked, promoting social diversity, in which individuals generate a sense of willingness to work and cooperate with one another.

Based on age diversity and the urban marginalization index within each block, two main indicators are developed to assess the accessibility of social diversity, which will define the co-presence attraction value within each block. First, to obtain indicators of social diversity by age range, we used information from the databases provided in the National

Housing Inventory (INV) published by INEGI. This index describes the population of each block in four age categories: 0–14 years, 15–29, 30–59, and 60 and older. These categories were used to determine the balance between the age categories using the diversity index developed by Simpson [65] as an indicator. The index measures values between 0 and 1, where 0 corresponds to a population with little variation by block within its age range (Figure A5 Left).

To evaluate socioeconomic indicators within the city, we used the INEGI urban marginalization index (IMU) database. This index captures various census concepts within each of the city's Basic Geostatistics Areas (AGEBs), which are comprised of approximately 50 blocks. This analysis examines school attendance conditions, access to healthcare services, and various housing aspects, resulting in the level of deprivation experienced by the population of each AGEb. This value is then normalized from 0 to 1 and applied within each block for this study. As can be seen, there is a strong social and economic divide in the city, with a concentration of marginalization toward the city's peripheries, represented in lighter colors (Figure A5, Center).

The study conducted by Marcus [25] is taken as a reference, which establishes that a radius of six axial steps captures between 97 and 100% of the people who, when surveyed, consider themselves local residents of the analyzed city center, thus imposing this as a radial limitation in the Place Syntax for the study of social diversity in the case of Ciudad Juárez. Two separate analyses of the blocks are then run at six axial steps, assigning the weight generated by each block based on the values obtained in the two studies described above. Finally, the results are summed and then divided by the number of indicators to normalize them using the six-axial step population density attraction analysis, yielding the co-presence capacity within each block (Figure A5 Right).



Figure A5. Age-balance maps (left), urban marginalization index (center), and co-presence capacity maps (right) for city blocks. Prepared by the authors using INGI data processed with the PST.

Appendix A.2.5. Accessibility to Parks

Providing green areas that are accessible, safe, and inclusive for all city residents is an important requirement for its sustainable development. In addition to being essential tools for controlling environmental issues such as reducing the heat island effect and flooding within the urban fabric, they are one of the main pillars for how neighborhoods develop economically and socially. A city with active public spaces creates a humanizing effect on its streets, helping its inhabitants develop a sense of identity and community cohesion.

The dispersion of urban fabric has created cities that suffer from serious social and environmental problems directly linked to the garden city model imposed in the 21st century. This makes it necessary to create green spaces that are more efficiently integrated into the urban structure. Using Place Syntax and park accessibility measurement techniques, new metrics are being developed that describe how the population perceives the lack or need for green spaces in their community [26]. This is because the traditional way of

measuring accessibility to green areas considers the accessibility factor through the metric distance to the park, considering the park's surface area as the attraction value. In contrast, this new methodology uses the axial distance to the park as the distance, and attraction is the multiplication of the park area by the use value of the site.

Although there is no "Use of place" study in Ciudad Juárez, which analyzes how individuals appropriate the green space by considering the diversity of activities carried out there, the analysis is limited to quantifying attraction, simplifying it to only using the area of the analyzed park. To conduct this study, "Attraction Distance" analyses are first run, with no distance limitation from each block to all the city's parks. These provide the results of the proximity of each city block to a park in the three different ways of defining distance within the program (columns 1–3 in Table A1).

The next type of accessibility analysis performed is the "Attraction Reach" analysis, 500 m from each park. The area of each park is added as an attraction weight to determine how many square meters of green space are accessible within 500 m of each block (columns 4–6 in Table A1).

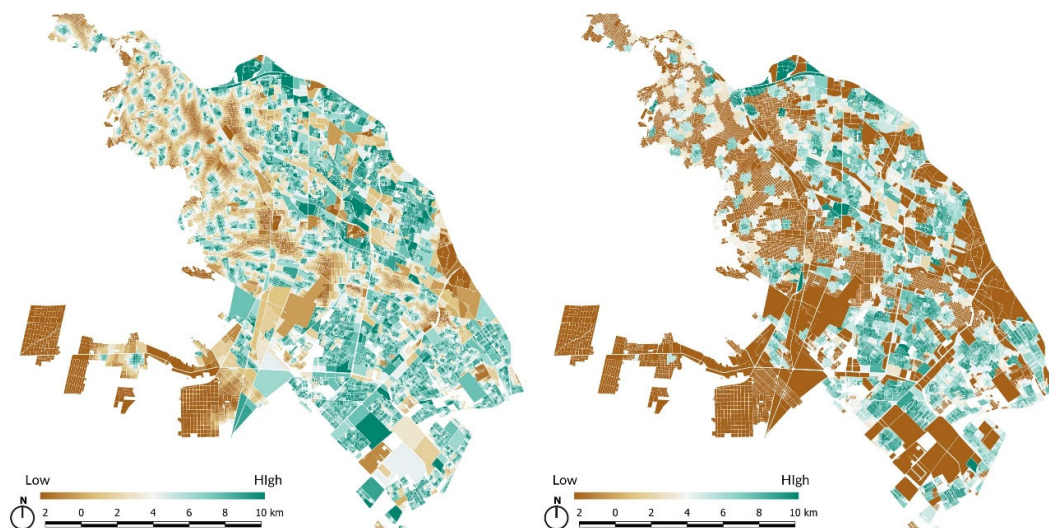


Figure A6. Classifying proximity in axial steps from each block to the nearest park (**left**) and parks accessible within 500 m walking (**right**) measured by the parks' squared meters as the attraction weight to each city block. The presence of parks is marked green. Prepared by the authors using the park database of the Municipal Research and Planning Institute (IMIP) and processed with the PST.

Finally, the city was studied using the "Attraction Reach" method again, within a 1000 m walking distance to the parks. This distance is limited by the distance a person is willing to walk to a recreational green area. In this analysis, in addition to weighting the attraction of each park's surface area, each one is also weighted by their distance in axial steps from the green area to each block. The results of the two studies are then divided to obtain the combined value within each block (column 7 in Table 1). The accessible population of each block is then calculated using the same formula, thus obtaining the combined values that, when divided, give the square meters of accessible green area by the accessible population in each block within 1000 m (column 8 in Table 1).

Table A1. Sample of the median value for all city blocks across the city. Columns 1–3 show the distance to the nearest park for the different ways of defining the PST distance; columns 4–6 show the square meters of parks accessible within a given radius. Column 7 shows the combined value, and column 8 shows the combined value for the population accessible within a 1 km walk.

Straight “Bird’s Distance” to Green Space	Walk Distance (Following Road) to Green Space	Distance to Park from Each Block in Axial Steps (s)	m ² of Green Space on “Bird’s Distance”	m ² of Green Space in “Walking Distance”	m ² of Green Space in 3 Axial Steps (s)	Combined 1 km Walking Distance (w)	Combinad 1 km (w)/Combinad Accesible Population 1 km (w)
225.98 m	380.71 m	5.00	10,899.63 m	2870.06 m	0.00 m	26.91 m	2.77 m

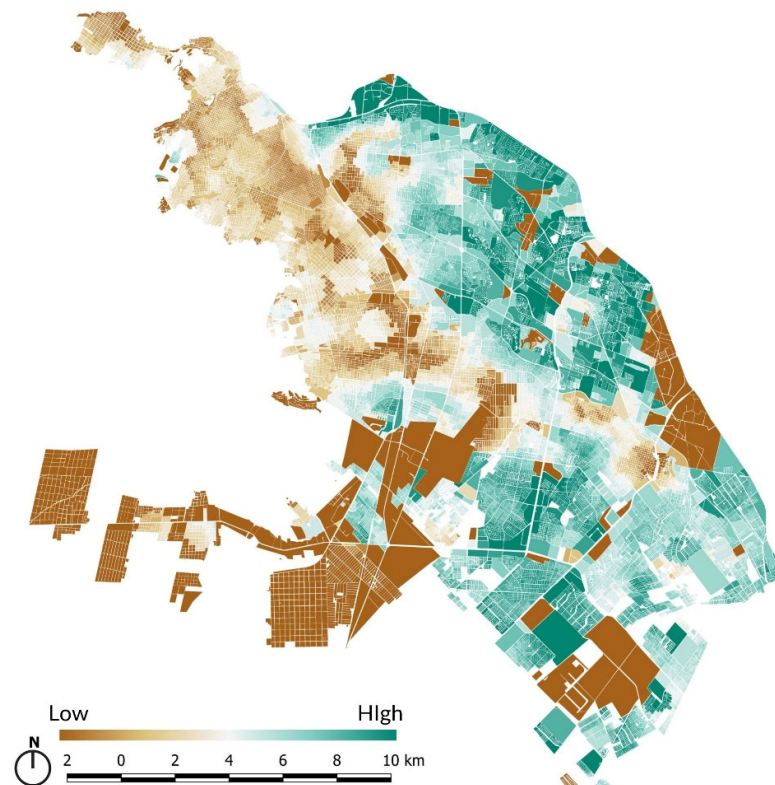


Figure A7. Map of the combined method value (column 7 of Table 1), which most accurately determines the level at which residents of each city block would perceive the presence of green areas in their neighborhoods. The perception of a high presence of parks is marked green. Prepared by the authors using the IMIP park database processed with the PST.

Appendix A.2.6. Urban Environment

The rapid expansion of the city has led to the creation of a large number of neighborhoods with poor quality in their urban environment. A methodology was developed to describe the pre-existing road infrastructure conditions of each block using the spatial data set of the National Housing Inventory (INV). The results are calculated to determine which ones could be more pedestrian-friendly. Five indicators are taken into account: whether the streets have any type of paving, sidewalks, curbs, vegetation, and street lighting. A value of 1 is assigned to the block if it is fully covered, 0.5 if it is only partially covered, and 0 if the infrastructure is lacking or if the data to assess it are non-existent. The result is divided by the number of indicators.

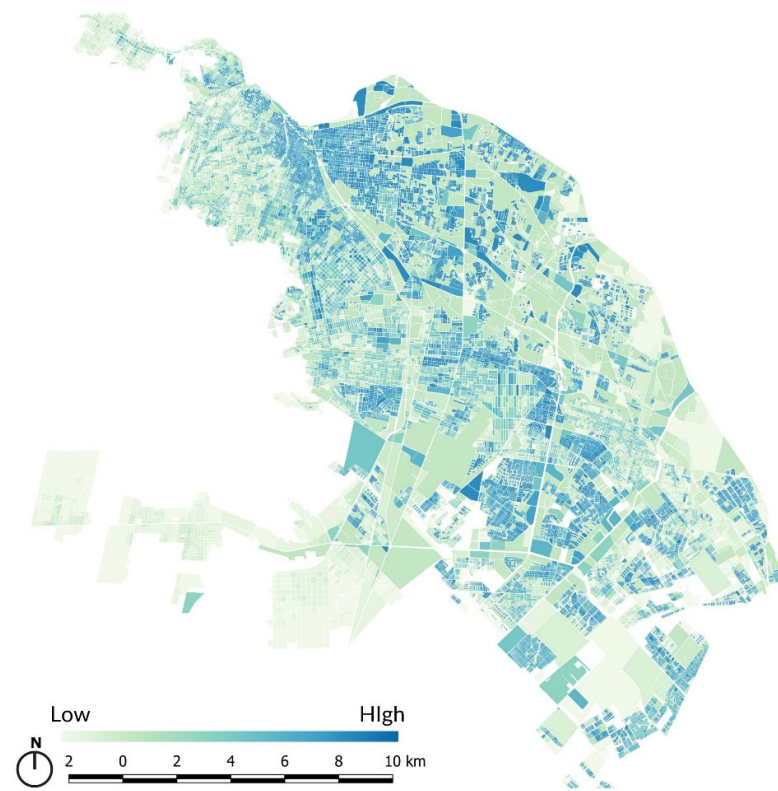


Figure A8. Map of the urban environment infrastructure of the city blocks. Prepared by the authors using data from the INV.

Appendix A.3. Identification of Urban Centers with Highest Spatial Capital

The ability of an urban layout to provide its inhabitants with more urbanistically sustainable spaces at a pedestrian scale is directly linked to the previously discussed urban models. These models allow us to understand how the spatial configuration and urban activity in these spaces relate to each other, showcasing the opportunities each urban layout offers to create a multifunctional mixed neighborhood. This allows us to propose the system by which the spatial capital of each urban center will be measured.

This classification is consolidated by measuring each of the city's 22,231 blocks using the six accessibility studies conducted. The results for each block are then scaled into 10 quantile intervals to normalize extreme values. Each interval contains a total of 2223 blocks, which are normalized from 0 to 1. The result is then multiplied by 0.1, and then the decimal is added depending on the interval in which each block falls (example: the first 10% of blocks with the highest value in the entire city are assigned a decimal of 0.9, and the next lowest 10% are assigned a decimal of 0.8), thus normalizing the values for the entire city from 0 to 1.

In order to study the characteristics of each urban center, without referring to a global or city-wide scale, we first analyze the data obtained in the previous exercise within a 1.5 km radius of its geographic center (Figure A9). This allows us to create models with an area of approximately 706 hectares, completely surrounding the area designated by the IMIP as the city's urban centers. We then obtain the total square meters of the blocks analyzed within this study for each urban center to determine the percentage that each block represents within the study area. This value is then multiplied by the normalized value from the previous accessibility studies, reflecting how much each block is devalued depending on the lack of accessibility in the previous six studies.

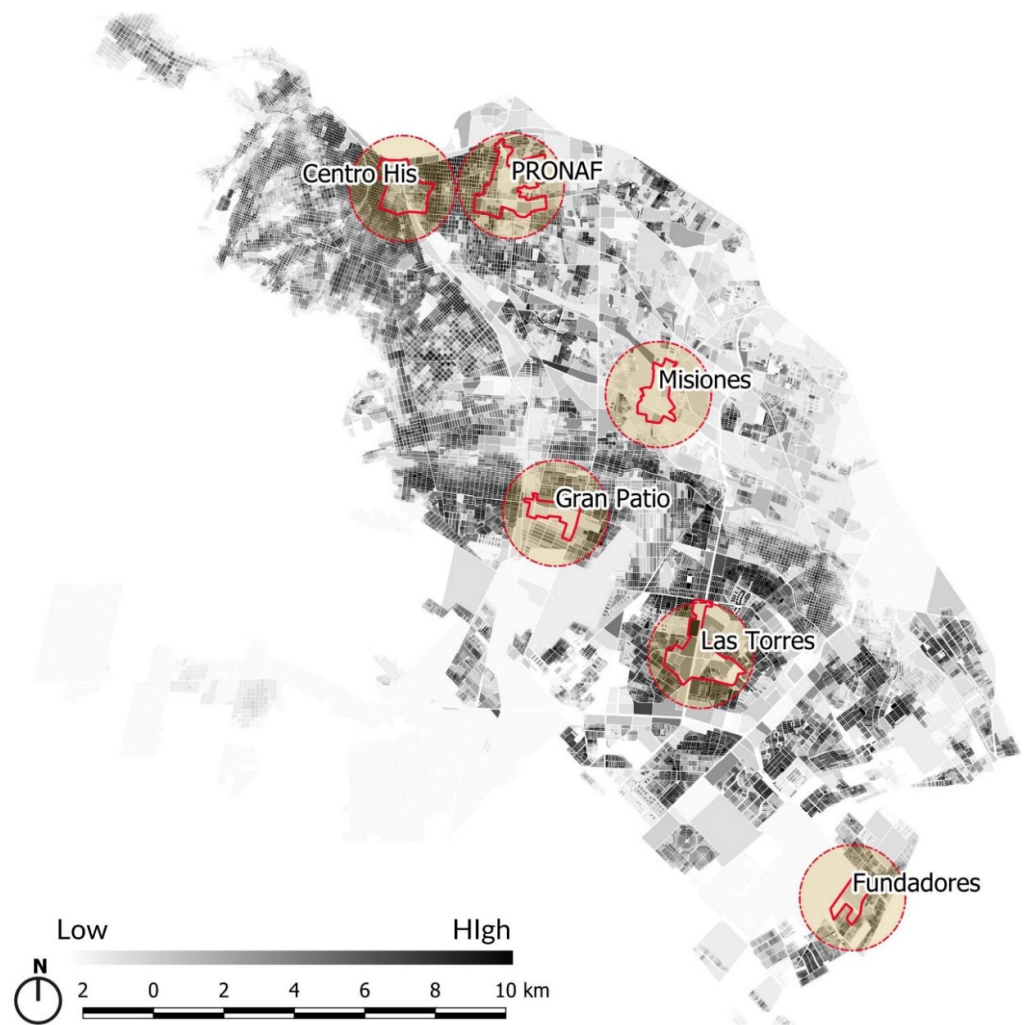


Figure A9. Spatial capital map of the city showing the urban centers with the circumference of the study area. Prepared by the authors based on IMIP and INEGI data.

Finally, the results of the six analyses for all blocks within each urban center are added. These results are then summed and divided by the number of studies, thus obtaining the value that determines the spatial capital of each urban center in the city.

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