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Evaluation of Geographic Accessibility in Areas without Road Infrastructure through GIS Simulation

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Abstract. Spatial accessibility to services allows for the assessment of people's access to opportunities, especially in disadvantaged areas. This study employs the simulation of hypothetical scenarios using Geographic Information Systems (GIS) to analyze future accessibility to healthcare services, aiming to evaluate their potential impact and contribute to long-term strategic planning that reduces spatial inequalities. The proposed methodology models hypothetical hospital locations in areas with high levels of marginalization and no road infrastructure. In this context, Euclidean distance was used as an alternative to estimate proximity since, although road-based distance provides more realistic data, its application is limited in these regions. The scenario results show that the strategic location of new healthcare facilities in disadvantaged areas can significantly improve accessibility levels in the future, thereby contributing to a better quality of life for the population.

Keywords. Simulation in GIS, Euclidean distance, Spacial accessibility to services.

1 Introduction

Spatial or geographic accessibility is defined as the ability of individuals to travel from an origin to a specific destination. In other words, geographic accessibility refers to the ease with which people can reach facilities and urban opportunities based on their proximity and availability [1]. This concept encompasses the spatial distribution of points of interest, as well as the population's ability to overcome distance and mobility barriers [2], [3].

Spatial accessibility to services is a key aspect in assessing their quality within a region. Adequate accessibility not only facilitates access to services but also contributes to the overall well-being of the population. In this regard, analyzing the distribution of points of interest in a specific area through accessibility allows for the identification of barriers that limit their reach. This analysis enables experts to develop strategies that promote greater equity and efficiency in service provision, particularly in disadvantaged areas.

Various studies have used distance as a criterion in accessibility assessments, ranging from straight-line calculations to more complex approaches that consider street infrastructure [4]. Among the approaches used to evaluate accessibility, Euclidean distance, Manhattan distance, and road network-based distance stand out. The road network-based distance measures the actual travel path along streets from an origin to a destination. This measure accounts for the connectivity of a region’s road network, providing a more realistic approximation of travel routes compared to traditional distance metrics [5].

To calculate this type of distance, GIS and mapping applications are commonly used, allowing for the identification of the most efficient route while considering factors such as road curvature, street direction, traffic, and network connections. These tools offer options that include traveled distance, estimated travel time, and real-time transportation modes.

The presence of road infrastructure has been shown to have a positive and significant impact on the acquisition of goods and services for housing improvements, contributing to poverty reduction. Studies have demonstrated that the initial paving of streets in disadvantaged neighborhoods significantly increases property values [6]. Additionally, road infrastructure generates substantial economic benefits for cities and countries by promoting economic growth, reducing transportation time and costs, and facilitating access to essential services such as markets, education, employment, and healthcare. Together, these factors greatly enhance the population's quality of life [7].

However, some rural areas face serious limitations in terms of accessibility to services and opportunities, particularly when compared to urban areas, due to their dispersed development and peripheral location. In these regions, the absence of road infrastructure is directly linked to a lack of essential services such as healthcare, education, and food supply. This lack of infrastructure poses a significant challenge for rural communities, as it restricts mobility and complicates planning and decision-making for the future implementation of services [8]. As a result, the absence of infrastructure not only hinders access to key resources but also negatively impacts the social and economic development of the region.

For this reason, accessibility analysis is particularly challenging, as the most disadvantaged areas often lack infrastructure. This limitation prevents an accurate assessment of access to services in these regions, making it difficult to plan and implement strategies to improve accessibility.

The objective of this research is to evaluate spatial accessibility to hospitals in rural areas without road infrastructure by simulating hypothetical future scenarios. This involves considering the placement of new healthcare facilities in currently underserved areas to analyze how accessibility could improve and to identify priority areas for development. The evaluation is based on the concept of distance as a key factor in measuring proximity to healthcare services.

This study highlights the application of scenario simulation using GIS, not only to assess current accessibility but also to model future scenarios and evaluate the impact of new infrastructure. The Euclidean distance measure was used as it provides a simple and effective approach to evaluating accessibility without requiring existing road infrastructure. Hypothetical scenarios will be constructed based on data from the marginalization index and the degree of road pavement in rural areas.

This approach not only allows for the simulation of potential improvements in service accessibility but also provides valuable insights for future service planning and optimization. By analyzing these scenarios, it will be possible to anticipate how future urban developments may influence the population's quality of life and support informed decision-making for strategic planning aimed at achieving more equitable and efficient sustainable development.

This paper is structured as follows: Section 2 presents related work, Section 3 describes the implemented methodology, Section 4 discusses the results, and Section 5 provides the discussion and conclusions.

2 Related Works

The study of geographic accessibility is often approached using variables that consider distance, availability, and distribution of services. This section will review state-of-the-art works focused on accessibility to various services in socially disadvantaged areas, as well as studies that employ scenario simulation or sensitivity analysis.

The work by [9] identified areas with limited access to education in developing countries, which they referred to as "education deserts." In this study, an open-source algorithm was used to locate populated areas without access to schools. The methodology includes geolocating schools and populations, calculating straight-line distances between each population unit and the nearest public school, as well as evaluating accessibility with threshold levels. The study generated detailed maps with information about the population and the minimum distance to public primary schools.

The research by [10] modeled travel time to the nearest primary healthcare center using a cost-distance analysis in areas where access is difficult. The model incorporates variations in land use, climate, and elevation, excluding barriers such as bodies of water and protected areas. Additionally, a cost-distance algorithm was applied that considers walking, cycling, and motorized transport, assuming the population can access a health center in less than an hour. The study highlights the model's usefulness in detecting spatial inequalities in healthcare access.

The research in [11] evaluates accessibility to pharmacies in various communities to identify areas with greater need. The study calculates the travel time from the population to the nearest pharmacy, considering different thresholds. The results reveal a higher presence of independent pharmacies and franchises in urban areas, while rural areas predominantly have independent pharmacies, though in smaller numbers, limiting access to these services in those regions.

In [12], spatial accessibility to urban medical services was evaluated using an enhanced two-step floating catchment area (2SFCA) method. The traditional method was compared to a refined version that integrates age-differentiated demand and supply based on medical specialty, adjusting travel times with Gaussian attenuation functions. The results showed that the traditional method overestimated accessibility in more than 70% of communities, while the refined method revealed significant inequalities, especially in pediatrics and obstetrics-gynecology. The study highlights the importance of considering demographic and spatial factors in health service planning to improve equity and efficiency in the distribution of urban medical resources.

The study in [13] analyzed accessibility to hospitals, considering cold weather's impact on urban mobility and the distribution of medical services. It used a weighted spatial barrier model to assess how snow and ice affect hospital access, revealing that the best resources are concentrated in the urban center, while peripheral areas suffer greater accessibility reductions in winter. The results show that improvements in hospital distribution and road infrastructure are necessary to ensure equitable access to health services in cold regions.

On the other hand, the study in [14] evaluated spatial accessibility to healthcare services, considering the impact of travel time uncertainty. To achieve this, a reliability-based enhancement of the two-step floating catchment area (2SFCA) method was proposed. This approach enabled a more precise assessment of spatial disparities in healthcare access. The results revealed significant impacts of travel time uncertainty on medical care accessibility, with variations depending on location and time of day across different scenarios.

The research in [15] developed a comprehensive method to estimate and compare accessibility to public green spaces and exposure to different types of land cover, aiming to improve measurement in studies on the relationship between the natural environment and health. To assess accessibility, international recommendations on optimal distances and land characteristics were followed. Additionally, the distribution of access and exposure was analyzed along an urban-rural gradient and correlated with territorial-level marginalization. A sensitivity analysis was also conducted, considering a threshold that defines the maximum acceptable distance for access to these spaces.

In [16], physical accessibility to healthcare centers was evaluated, taking into account the impact of roads. This analysis considered a simulation of scenarios based on travel times, considering both walking and motorized transport modes. The results showed that the use of motorized transport significantly improves accessibility, increasing population coverage.

In the study by [17], spatial accessibility to Emergency General Surgery services was analyzed, along with the behavior of patients choosing more distant hospitals instead of the closest one (bypass). Using hospital, demographic, and geospatial data, a gravitational model was applied to measure accessibility and a Bayesian hierarchical model to assess factors associated with bypass. The results indicate that better accessibility reduces the likelihood of bypass, while factors such as living in rural areas, having private insurance, and suffering from

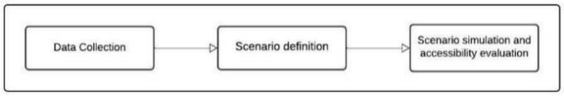

Fig. 1. Procedure for simulation with GIS

complex diseases increase this likelihood. Spatial patterns were identified where bypassers tend to cluster in areas with dense road networks but low hospital accessibility.

A sensitivity analysis was conducted by varying hospital criteria, the definition of bypass, and the inclusion of patients with complex diseases, confirming the robustness of the model. These findings could contribute to improving resource planning and equity in access to services.

3 Methodology

Geospatial data encompasses a wide range of information about the physical and natural environment of the Earth's surface. These data have gained significant importance in various applications [18]. In particular, simulation with Geographic Information Systems (GIS), which combines the analytical capabilities of GIS with modeling techniques to address geographic and social issues more efficiently. Its goal is to model, analyze, and predict spatial phenomena in both hypothetical and real scenarios.

Through simulation with GIS, it is possible to explore complex dynamics involving multiple variables, which facilitates a better understanding of the territory and improves decision-making in various contexts [19]. Fig. 1 shows a diagram of the Procedure for Scenario Simulation with Geographic Information Systems and distance measures, used for this case study.

3.1 Data Collection

In this study, the geographical area of interest is limited to Mexico City, which stands out as a financial, cultural, political, and economic hub, both nationally and internationally. The city spans an area of 1,495 km^2 and has a population of 9,209,944 inhabitants, representing 7.3% of the national total. Predominantly urban, 99% of its territory is urbanized, while only 1% is rural.

Despite its urban nature, Mexico City faces significant challenges related to access to basic services. In 2020, important social deficiencies were identified, such as access to social security, healthcare, education, and food. These issues are especially critical in rural areas, where there are limitations in opportunities and road infrastructure, which affect the development and well-being of its inhabitants [20-23].

In this analysis, various sources were consulted, such as the National Institute of Statistics and Geography, the Open Data Portal of Mexico City, and the Ministry of Health of Mexico City [24-26].

The extracted information included geospatial data on neighborhoods, municipalities, and blocks, with blocks being defined as groups of residences that form the population's residential units. Data from public hospitals was also collected. Subsequently, a data cleaning process was carried out, which involved selecting relevant attributes, standardizing the information, and manually correcting erroneous data.

Fig. 2 shows the geographic distribution of hospitals in the municipalities of Mexico City. In total, there are 32 hospitals spread across the 16 municipalities providing care to the community. Each municipality is composed of neighborhoods. In general, rural areas are concentrated in the southern part of the city, while urban areas and the majority of the population are located in the central and northern parts.

3.2 Scenario Definition

Residents, especially in rural areas, face limited access to healthcare services due to insufficient infrastructure and medical coverage. This study considered public sector hospitals as key points for evaluating accessibility.

These hospitals, managed by the Ministry of Health of Mexico City, provide medical care to the population without social security coverage from any institution [27].

This context highlights the importance of analyzing healthcare accessibility in an environment marked by significant social challenges faced by the population.

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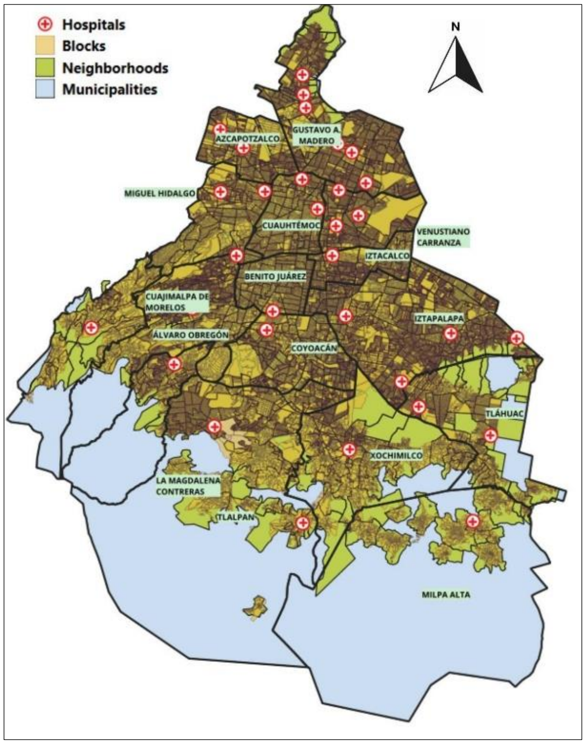

Fig. 2. Map of México city

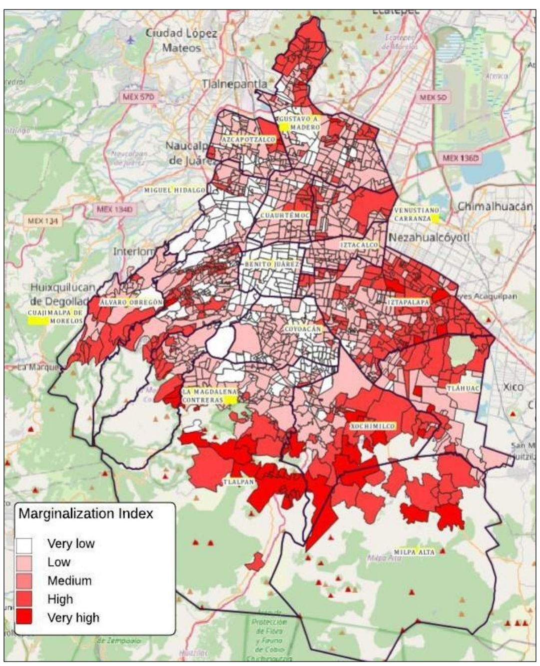

Fig. 3. Marginalization Index

To identify the most disadvantaged areas in the context of healthcare that lack road infrastructure, two key indicators were used: the marginalization index and the degree of accessibility to paved roads. These indicators helped detect significant deficiencies in disadvantaged areas from a social, demographic, economic, and spatial perspective, identifying those regions with higher marginalization and very low availability of paved roads.

The degree of accessibility to paved roads measures how easily a neighborhood can access this infrastructure, considering geographical and social factors such as the presence of roads, location, terrain slope, vegetation, land use, public transportation, and time, among others [28], [29]. On the other hand, the marginalization index measures the level of social deprivation in a locality based on factors like access to education, housing, basic services, and income [30].

Fig. 3 shows the cartographic representation of the marginalization index of the neighborhoods, highlighting that the most disadvantaged are located in municipalities in the southern part of the city. Fig. 4 presents the map of accessibility to paved roads in Mexico City. In this map, red-colored areas indicate zones with very low levels of paved road infrastructure. This information coincides with the location of the municipalities with the highest marginalization in the southern part of the city.

As a result, four municipalities in Mexico City were identified, where areas with higher levels of poverty, rural zones, and limitations in road infrastructure were observed. The municipalities are: Milpa Alta, Xochimilco, Tlalpan, and La Magdalena Contreras. Based on our objective, these municipalities were selected to define the scenarios and assess accessibility.

To analyze how accessibility could change based on scenario simulations, two important elements were established: (1) the geographic location of new hospitals in each municipality, defined as destination points, and (2) the geographic center of each municipality, considered as the origin point to estimate population movement. Both elements allow measuring the relationship between them through distance and evaluating accessibility. This approach enabled modeling the potential impact of new infrastructure

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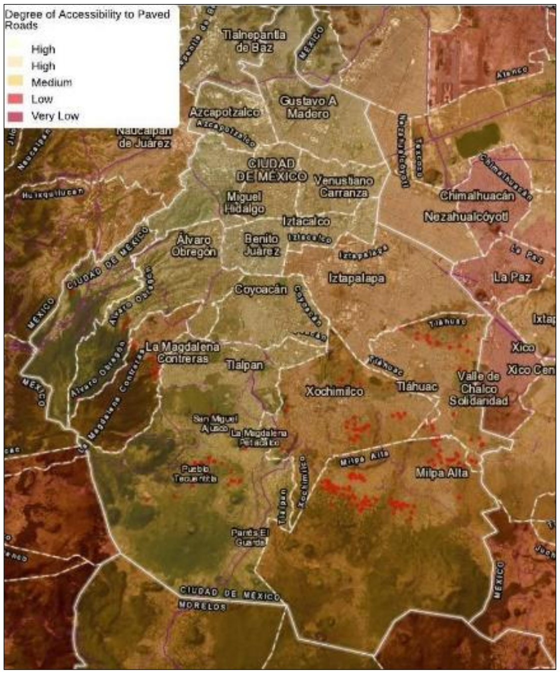

Fig. 4. Degree of Accessibility to Paved Roads

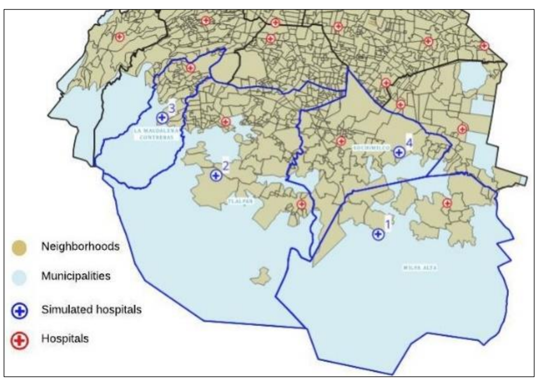

Fig. 5. Definition of Scenarios

hypothetically on rural community accessibility, and analyzing how the connection between the population and the new health services would improve in the future.

To determine the geographic location of the new hospitals in the areas of interest, the weighted geometric centroid method was used. This method allowed modeling strategic spatial configurations that optimize the location of new hospitals in areas without road infrastructure. This method not only determined the locations but also considered factors such as population density, the existence of current hospitals, and the specific needs of the area. The calculations were performed using the Python programming language, and the graphical visualization was carried out using QGIS software version 3.34.1. As a result, four scenarios were defined, with four new hospitals strategically located in each of the municipalities of Milpa Alta, Xochimilco, Tlalpan, and La Magdalena Contreras.

These hypothetical hospitals were located in disadvantaged areas, with the purpose of evaluating the potential level of accessibility to health services in the future. Fig. 5 shows the map with the proposed location of the new hospitals.

3.3 Scenario Simulation and Accessibility Evaluation

Among the most common approaches to assess geographic accessibility to services, Euclidean distance stands out as the primary metric [31-33]. Its use for evaluating accessibility in areas without road infrastructure is justified by its simplicity and effectiveness. This metric allows estimating the proximity between neighborhoods and services in the absence of defined routes, and it is computationally efficient, easy to implement in spatial analysis, and suitable for processing large volumes of data; making it ideal for quick and accurate assessments [34].

For this reason, the assessment of accessibility through scenario simulation was carried out considering a neighborhood-level aggregation. To properly interpret the results and gain a deep understanding of the impact of evaluating accessibility from the concept of distance, it is essential to understand the mathematical formula that supports the Euclidean distance measure. The Euclidean distance [35] is calculated using the following equation:

$$d(u,v) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}, \quad (1)$$

where $d(u,v)$ represents the distance between the origin point and the destination; $u = (x_1, y_1)$ are the coordinates of the origin point, and $v = (x_2, y_2)$ are the coordinates of the destination. This measure reflects the straight line connecting both points, thus representing the shortest distance between them in a two-dimensional space within

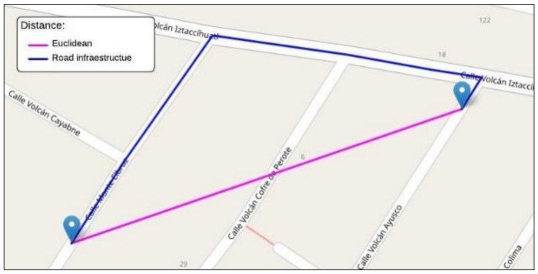

Fig. 6. Accessibility measures from an origin point to a destination.

Table 1. Average Euclidean distance of the some neighborhoods

Neighborhoods	Id Hospital	Euclidean distance (km)
ARENAL	26	6.504
CENTRO DE AZCAPOTZALCO	24	0.374
JUVENTUD UNIDA	32	5.744
LA FAMA	17	10.832
EL OLIVO	28	7.923
EMILIANO ZAPATA	1	2.626
XICALHUACAN	14	2.543
19 DE MAYO	21	3.009

Geographic Information Systems (GIS). It is important to note that, in GIS, the distance calculation is performed using geographic coordinates (latitude and longitude), allowing for an accurate representation of locations on the Earth's surface. Fig. 6 graphically illustrates both the Euclidean distance and the distance based on road infrastructure, calculated from an origin point to a destination. Each measure not only reflects mathematical differences but also has practical implications in terms of accessibility.

To calculate the Euclidean distance between hospitals, the simulated hospitals, and the centroid of the neighborhoods, the Python programming language was used along with the Geopy and Pandas libraries. Specifically, the geodesic function from *geopy.distance* was employed to obtain the geodesic distance, which takes into account the Earth's curvature. Additionally, the euclidean and cityblock functions from *scipy.spatial.distance* were used to calculate distances in a Cartesian space and in an urban environment, respectively. The geographic center of the neighborhoods, commonly known as the centroid, was calculated using QGIS software. These calculations were carried out for all neighborhoods in Mexico City to measure accessibility.

Table 1 presents some data on the Euclidean distance calculated in kilometers from the centroid of the neighborhoods to the existing hospitals and the simulated hospitals. For better understanding, Fig. 7 shows the cartographic representation of the calculated distances and the location of the hospitals, highlighting the municipalities of interest where the scenarios were defined.

The distances obtained in kilometers allowed for estimating the geographic proximity of each neighborhood to the hospitals, determining how close or far they are. Based on these distances, the average distance from the center of each neighborhood to the hospitals within each municipality of Mexico City was calculated, which allowed for the evaluation of accessibility through an indicator that follows the rule: the greater the distance, the lower the accessibility; the shorter the distance, the higher the accessibility.

The values of the average distances calculated were classified using the Jenks optimization method, which minimizes the variance within classes and maximizes the variance between them [36]. This approach allowed for grouping the distances to the services into five categories, aligning with the criteria used in indicators presented by official sources, such as the Social Development Index of Mexico City and the Measurement of Poverty [37], [38]. Thus, an accessibility indicator was generated, providing a precise and clear evaluation of the spatial accessibility of neighborhoods to hospital services.

The results yielded two indicators. The first was obtained from the actual data, i.e., with the hospitals currently located. The second indicator considered the data of the currently located hospitals plus the new hospitals located through the scenario simulation, in order to compare the current and projected future accessibility.

Fig. 8 presents the accessibility indicator for Mexico City, which measures geographic proximity through the Euclidean distance to the hospitals as they are today. On the other hand, Fig. 9 shows the city's accessibility indicator, including the simulated hospitals from the four scenarios in the

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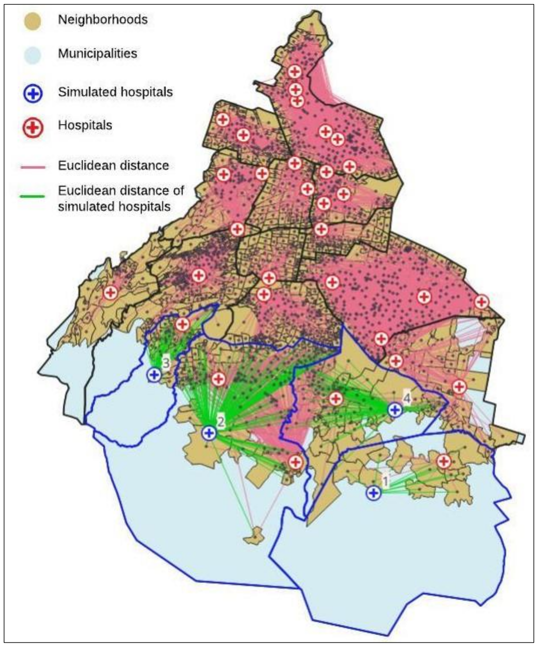

Fig. 7. Euclidean distance of the neighborhoods

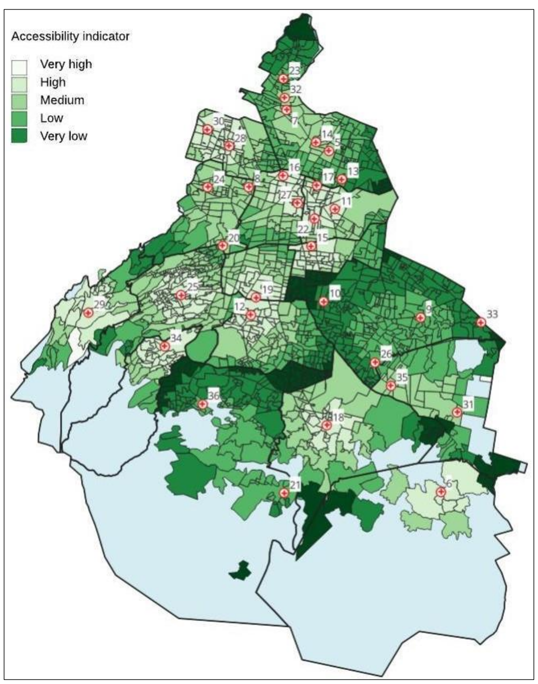

Fig. 8. Accessibility indicator with real data

neighborhoods of Xochimilco, Milpa Alta, Tlalpan, and La Magdalena Contreras. Additionally, Fig. 10 and Fig. 11 present the histogram of the indicator data with real data and the indicator with real data plus the simulated data, respectively. Both show the distribution behavior of the data, the segmentation of the five categories, and the values within each class.

This analysis facilitated the identification of the level of accessibility and its current behavior, as well as how it could behave in the future in marginalized areas lacking road infrastructure.

4 Results

The following presents the results of the four scenarios in the context of accessibility, in which four new hospitals were generated, one in each neighborhood, with the aim of analyzing the future spatial accessibility to hospitals. It is important to note that, currently, each neighborhood already has at least one hospital; however, they still face deficiencies in various aspects. One way to observe how accessibility to services could improve is through a future simulation.

The current spatial accessibility indicator reveals that, from a proximity perspective, the level of accessibility to hospitals is generally high. However, by strategically adding a new hospital to improve future accessibility, it is observed that the accessibility level of neighborhoods in the municipalities of interest increased, as the reduction in distance enhances access, driven by the increase in supply. Fig.12, 13, 14, and 15 show the accessibility level results in the simulated scenarios for each neighborhood in the municipalities.

From this analysis, it can be observed that locating hospitals in areas without road infrastructure could promote the expansion of road networks, which in turn would facilitate the population's access to a greater supply of services in the future. The presence of new health units, accompanied by adequate access roads, would drive connectivity and promote the development of other essential urban facilities.

These findings highlight the importance of territorial planning based on spatial analysis, which ensures equitable access to health services and supports sustainable urban development. Road infrastructure plays a crucial role in social and

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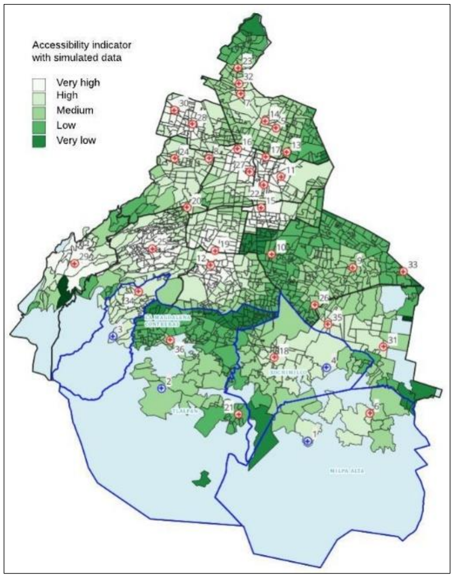

Fig. 9. Accessibility indicator with real data and simulated data

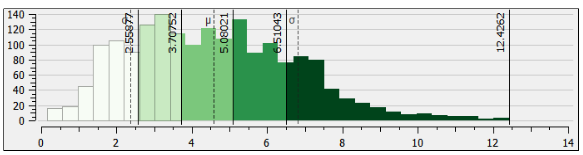

Fig. 10. Histogram of the indicator for the real data

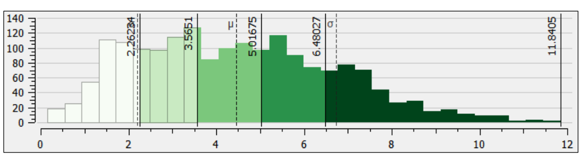

Fig. 11. Histogram of the indicator with real data and simulated data

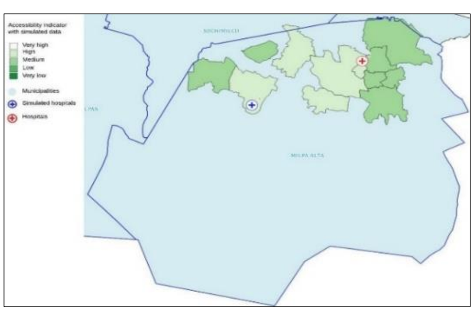

Fig. 12. Scenario 1: Municipality of Milpa alta

territorial integration, as it facilitates the connection between rural and urban areas, thus reducing spatial inequalities. Additionally, it represents a significant economic advantage by boosting local development and improving the population's quality of life.

The scenario simulation in the context of accessibility, using Geographic Information Systems (GIS), allowed for the evaluation of the potential impact of installing new health units. In this case, the GIS modeling employed geospatial and analytical tools to represent accessibility to points of interest.

The accessibility analysis not only provides a reference for the current situation but also allows for anticipating how accessibility could evolve with the development of new services or improvements in road infrastructure. This prospective approach is essential to understanding urban and rural dynamics, as well as their impact on the availability and proximity of essential services for the population.

5 Discussion and Conclusions

The results highlight that several areas of Mexico City, particularly Milpa Alta, Xochimilco, Tlalpan, and La Magdalena Contreras, face significant social and spatial challenges. Among these, limited accessibility to healthcare services stands out due to the social conditions of the community, which is further impacted by insufficient road infrastructure. This restricts the population's mobility and hampers their timely access to medical care.

Given this issue, it is essential to implement strategies that contribute to improving accessibility. A viable option is the simulation of future scenarios through spatial models, which allows for the evaluation of the potential impact of new healthcare units and improvements in road infrastructure. As reflected by the accessibility indicator, the strategic inclusion of new hospitals showed an improvement in accessibility, suggesting that the planned expansion of the healthcare network could significantly reduce spatial inequalities and improve medical coverage in these marginalized neighborhoods in the future.

The analysis highlights the importance of road infrastructure not only for improving access to

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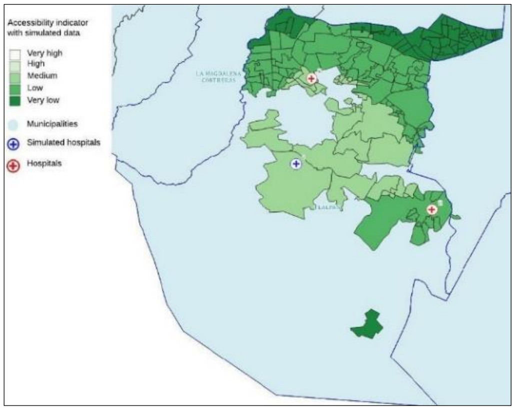

Fig. 13. Scenario 2: Municipality of Tlalpan

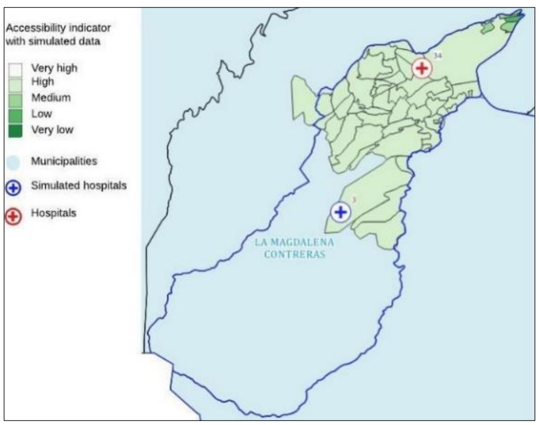

Fig. 14. Scenario 3: Municipality of La Magdalena Contreras

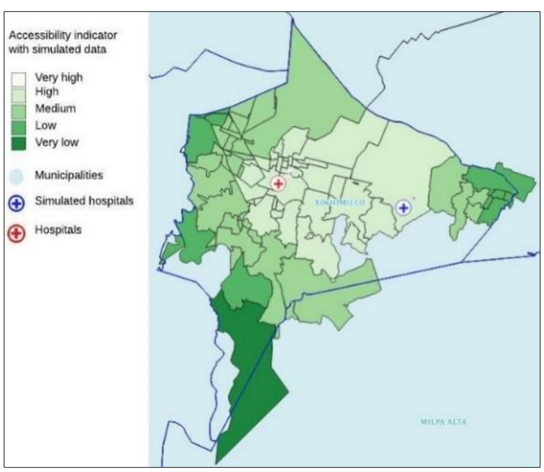

Fig. 15. Scenario 4: Municipality of Xochimilco

essential services but also as a key factor for economic and social development. The strategic placement of hospitals in marginalized neighborhoods, with high demand for care and low road connectivity, has proven to be an effective tool for reducing inequalities in access to healthcare services. In this context, it is crucial for public policies to consider road infrastructure as an essential component for improving quality of life in marginalized communities.

While the use of Euclidean distance is useful in scenarios where detailed information on the actual road network is unavailable, it is important to recognize its limitations. This measure does not capture the complexity of real routes, such as geographic constraints or the availability of transportation, but provides a valuable initial estimate for territorial planning. In this regard, its application allows for the establishment of preliminary scenarios that can serve as a foundation for the development of sustainable road networks and the expansion of healthcare service infrastructure.

As future work, it is proposed to strengthen the validation of scenarios using real data and collaboration with local communities, ensuring that solutions are viable and effective in a real-world context. Additionally, an integrated analysis is sought that not only considers distance but also other factors. The integration of technical and social aspects in urban planning and the improvement of road infrastructure are fundamental to promoting more equitable and sustainable development. Furthermore, extending this analysis to other services is also a priority.

In conclusion, this study proposed an innovative approach by applying Geographic Information Systems (GIS) with simulation to model future scenarios in the context of accessibility to services, allowing for the evaluation of the impact of new infrastructures. Additionally, it addressed the methodological challenge of analyzing accessibility in areas without road infrastructure by using Euclidean distance as a simplified and effective alternative, which is currently difficult to measure from a perspective that includes road infrastructure. Moreover, the weighted centroid was used to optimize hospital locations, improving strategic planning in rural and marginalized areas.

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