

From Constraints to Urban Growth: Satellite-Based Monitoring of Guayaquil's Urban Expansion with Sentinel-2

David Freire-Granda^{1,2}, Andrés Velastegui-Montoya^{2,3,4}, Yasmim Carvalho Guimarães⁵, Eduardo Soares Nascimento⁶, Marconi de Arruda Pereira⁷, Leonardo B.L. Santos⁸, Cesar Ivan Alvarez⁹ and Eddy Sanclemente^{2,3}

¹ Faculty of Mechanical Engineering and Production Sciences, ESPOL Polytechnic University, ESPOL, Campus Gustavo Galindo, Km. 30.5 Vía Perimetral, Guayaquil, 090902, Ecuador – davfreir@espol.edu.ec

² Laboratory of Geoinformation and Remote Sensing, ESPOL Polytechnic University, ESPOL, Campus Gustavo Galindo, Km. 30.5 Vía Perimetral, Guayaquil, 090902, Ecuador

³ Faculty of Engineering in Earth Sciences, ESPOL Polytechnic University, ESPOL, Campus Gustavo Galindo, Km. 30.5 Vía Perimetral, Guayaquil, 090902, Ecuador – (dvelaste, esanclem)@espol.edu.ec

⁴ Centro de Investigación y Proyectos Aplicados a las Ciencias de la Tierra, ESPOL Polytechnic University, ESPOL, Campus Gustavo Galindo, Km. 30.5 Vía Perimetral, Guayaquil, 090902, Ecuador

⁵ Graduate Program in Natural Disasters (Unesp/CEMADEN), São José dos Campos, Brazil – yasmin.guimaraes@unesp.br

⁶ Postgraduate Program in Cartographic Sciences (PPGCC), Department of Cartography, School of Technology and Sciences São Paulo State University (FCT-UNESP), 19060-900 Presidente Prudente, São Paulo, Brazil – e.nascimento@unesp.br

⁷ Department of Technology, Universidade Federal de São João del-Rei (UFSJ), Campus Alto Paraopeba, Ouro Branco, Minas Gerais, 36490-972, Brazil – marconi@ufsj.edu.br

⁸ National Center for Monitoring and Early Warning of Natural Disasters (Cemaden), Estrada Dr. Altino Bondensan n° 500, São José dos Campos, SP, 12247-016, Brazil – santoslbl@gmail.com

⁹ Centre for Climate Resilience, University of Augsburg, Universitätsstrasse 12a, 86159 Augsburg, Germany – cesar.alvarez@uni-a.de

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Abstract

Urban expansion is a global phenomenon that poses significant challenges for territorial planning and environmental sustainability. In Guayaquil, Ecuador's largest and most populous city, accelerated urban growth has been recorded, particularly in peri-urban areas. This study analyzes the transformation of Guayaquil's urban boundaries between 2016 and 2024, aiming to identify peri-urban zones and their basic infrastructure using Sentinel-2 satellite imagery and Geographic Information Systems (GIS). For this purpose, the analysis integrates Sentinel-2 satellite imagery from 2016, 2020, and 2024 with Geographic Information Systems (GIS) and official data on electricity, potable water, and sanitary sewer systems. The spatial assessment focused on areas beyond the official urban perimeter, highlighting Monte Sinaí as a significant growth zone. Results show an increase of 697.03 hectares of urbanized land during the study period, mainly concentrated in Monte Sinaí, Villa Bonita, and Costa Sol. However, 57.63% of properties in Monte Sinaí lack access to basic services such as electricity, drinking water, or sewage systems, indicating shortcomings in planning and infrastructure provision. The research demonstrates that urban expansion in Guayaquil is heterogeneous and unregulated, with a pronounced gap in basic service coverage. This research contributes meaningful insights that may be used to implement sustainable and equitable strategies for urban development.

1. Introduction

Urban expansion is a global phenomenon in which cities grow and extend into peripheral areas to accommodate population growth and improve quality of life (Zhan et al., 2025). This process offers several benefits, such as creating new residential areas, diversification of services, and economic stimulation in formerly rural zones (Roy et al., 2025). However, urban expansion also entails challenges in terms of sustainability and planning (Liang et al., 2025; Tian et al., 2025). Controlled urban expansion can yield significant long-term benefits despite these challenges, enabling more balanced and better-distributed development (Jamal & Ali, 2023).

In Ecuador, urban expansion is an increasingly relevant issue due to the accelerated growth of cities (Espinoza Jaramillo, 2023). In this context, municipalities play a crucial role in territorial planning and land management, overseeing the distribution of urban and rural spaces (Narváez Benalcázar, 2023). Municipal competencies in terms of land-use planning include regulating land use, promoting adequate infrastructure, and preventing unregulated expansion (Hugo Del Pozo Barrezueta, 2016). These responsibilities must be adapted to the specific needs of each locality, aiming to find solutions that balance growth with environmental protection.

The urban boundaries in Ecuador are established by the municipalities based on their management capacity and the development of the consolidated urban area. These boundaries are essential to prevent uncontrolled expansion and delineate urban zones from rural ones (Metzger & Bermúdez, 1996). Municipalities define these limits through urban development and land-use planning strategies to control urban growth and promote efficient land use (SOT, 2021). However, continuous population pressure tests the effectiveness of these boundaries, often resulting in the occupation of unauthorized areas (Paulina & Segura, 2010).

One of the main problems associated with uncontrolled urban expansion is the growing demand for basic services such as potable water, electricity, sewage, and transportation (Yu et al., 2025). As cities expand, existing infrastructure is often unable to meet the needs of the new population (Yerkenhazı et al., 2025). This phenomenon affects residents' quality of life and poses a challenge for local authorities in terms of planning and sustainability.

As an irreversible change in land use, urban expansion affects land cover and ecosystems (Liu et al., 2019). Remote sensing and Geographic Information Systems (GIS) are key tools for monitoring and predicting these growth patterns (Agapiou et al.,

2015). Moreover, advanced technologies such as remote sensors have become a valuable resource for the accurate and continuous monitoring of urban expansion (Masha et al., 2025). Sustainable urban planning also plays an essential role in protecting heritage and environmental sites from expansion pressures (Gillespie, 2009). Likewise, integrated tourism management in expanding urban areas balances economic development and cultural and natural conservation (Fletcher et al., 2007). In this context, the research question arises: Which peri-urban regions in Guayaquil are experiencing the most significant growth, and what is the status of their basic infrastructure?

In this context, this study aims to assess the transformation of the urban boundaries of the city of Guayaquil between 2016 and 2024 through the temporal analysis of Sentinel-2 satellite images, with a focus on identifying peri-urban areas and their basic infrastructure. This research employs a methodological approach that combines remote sensing technologies and spatial analysis to evaluate urban expansion in Guayaquil. By integrating satellite data and official maps, the study has successfully examined the city's growth and its implications for territorial planning without delving into the technical specifics of the process.

This work may serve as a guide for controlling urban expansion by enabling municipalities to manage population growth and promote local economic development. Satellite-based monitoring supports territorial planning and environmental protection, thereby strengthening the provision of infrastructure and basic services for sustainable development.

2. Materials and Methods

2.1 Study Area

Guayaquil is located in the coastal region of Ecuador and is the country's largest and most populous city, covering an approximate area of 344.5 km². By 2022, its population exceeded 2.65 million inhabitants (Fig. 1) (INEC, 2022). Its geographical coordinates (latitudes -1.9551 to -2.2983 N and longitudes -79.9890 to -79.9511 W) position it as a strategic hub for commerce and economic activities. The city has a tropical dry climate, with an average annual temperature of 27 °C and rainfall concentrated between December and May (Mejía C. et al., 2023).

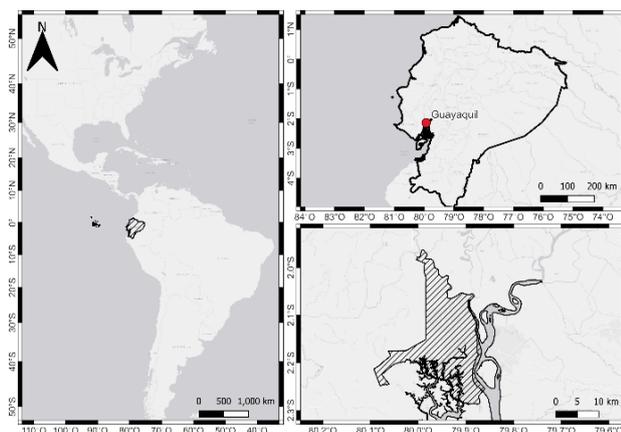


Fig. 1. Guayaquil's geographical location in Ecuador and South America, showing its official urban boundary according to the municipal zoning ordinance map.

2.2 Workflow

The methodology consisted of three main steps (Fig. 2): 1) Geo-information acquisition through public and open-access geoportals; 2) Processing and photo-interpretation, conducted using QGIS software version 3.34.1; and 3) Spatial geoprocessing, also carried out in QGIS.

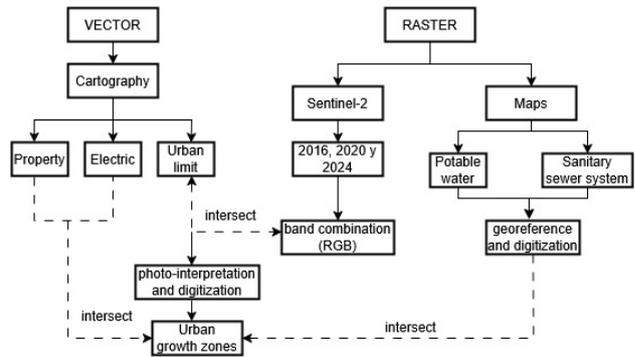


Fig. 2. Methodological flow for the acquisition and processing of vector and raster data, integrating Sentinel-2 images (2016, 2020, 2024) and official maps to analyze urban growth zones in Guayaquil.

2.2.1 First Step: Geo-information Acquisition

The first step involved acquiring cartographic and raster data to analyze urban expansion in Guayaquil. Sentinel-2 satellite imagery (RGB, 10 meters spatial resolution) for 2016, 2020, and 2024 was obtained from the Copernicus platform, ensuring adequate temporal coverage to assess urban change over the past decade. In parallel, official cadastral maps were collected from the Geoportal of the National Institute of Statistics and Censuses (INEC) (INEC, 2022); data on electrical infrastructure (location of poles, service lines, and transmission lines) were acquired from the Geoportal of the National Electricity Corporation (CNEL EP) (CNEL EP, 2024). Additionally, potable water and sanitary sewer system coverage maps were extracted in PDF format from the INTERAGUA website (INTERAGUA, 2024), and the official urban boundary of the city from 1991 was integrated, as published in the Municipal Ordinance (OM) available on the Guayaquil Municipality portal (GAD Guayaquil, 2005). This initial phase of data acquisition serves to create a robust cartographic base, enabling a precise assessment of urban changes and their implications for territorial planning and the city's sustainability.

2.2.2 Second Step: Processing and Photo-interpretation

During the second step, satellite images were processed and photo-interpreted to precisely delineate urban expansion within the study periods (Cao et al., 2025). Sentinel-2 images were spatially clipped to fit the area of interest, defined by the study zone, using the open-source software QGIS as the primary tool. For proper visualization and analysis, RGB band combinations (Red, Green, and Blue) were employed for each year's images, allowing natural color representation and facilitating the visual identification of urbanized areas (Lin et al., 2023). Through a detailed photo-interpretation process, existing urban zones for each date were identified and compared against official urban boundaries (Tuno et al., 2024). Areas exceeding these boundaries were manually digitized in polygon format for subsequent spatial analysis.

The outcome of this step is an accurate visual representation of urban expansion, which will serve as the foundation for the following phases of analysis and evaluation. This step of processing and photo-interpretation is crucial for transforming satellite images into usable and comprehensible data, allowing not only for the observation of territorial evolution but also for identifying areas requiring intervention in terms of urban planning and the provision of basic services.

2.2.3 Third Step: Spatial Analysis

The third step involved geoprocessing, which was applied to the collected and processed cartographic information to conduct a focused territorial analysis. From the digitized polygons representing expansion beyond official limits, the most significant area, Monte Sinaí, was selected for a more detailed study. A spatial intersection was performed between the Monte Sinaí polygon and cadastral maps to identify affected properties within this zone. Potable water and sanitary sewer system coverage maps were digitized and georeferenced, converting the information into vector formats compatible with GIS (Barrantes-Chaves, 2025). Finally, further spatial intersections were executed between these vector layers and electrical infrastructure data (poles, service lines, and transmission lines) with the Monte Sinaí properties, integrating relevant data for territorial assessment and urban management within the study area.

This third step serves to draw conclusions regarding the need for intervention in specific areas and to propose more efficient urban policies. The integration of various spatial data in this phase enables an accurate depiction of how urban expansion is influenced by the lack of infrastructure, facilitating the formulation of strategies to enhance territorial planning and service provision.

3. Results

The analysis of urban expansion in Guayaquil between 2016 and 2024 reveals heterogeneous growth, mainly concentrated in the city's peripheral areas, such as Monte Sinaí, Villa Bonita, and Costa Sol. This phenomenon, identified through Sentinel-2 satellite imagery and detailed spatial analysis, is presented as follows.

Expansion of the Urban Area

According to Figure 3, which shows the spatiotemporal dynamics of urban expansion in Guayaquil from 1991 to 2024, there has been a significant increase in urbanization in critical areas such as Monte Sinaí, Villa Bonita, Villa Geranio 2, and Costa Sol. These areas have experienced continuous growth, mainly towards the peripheral boundaries of the consolidated urban area.

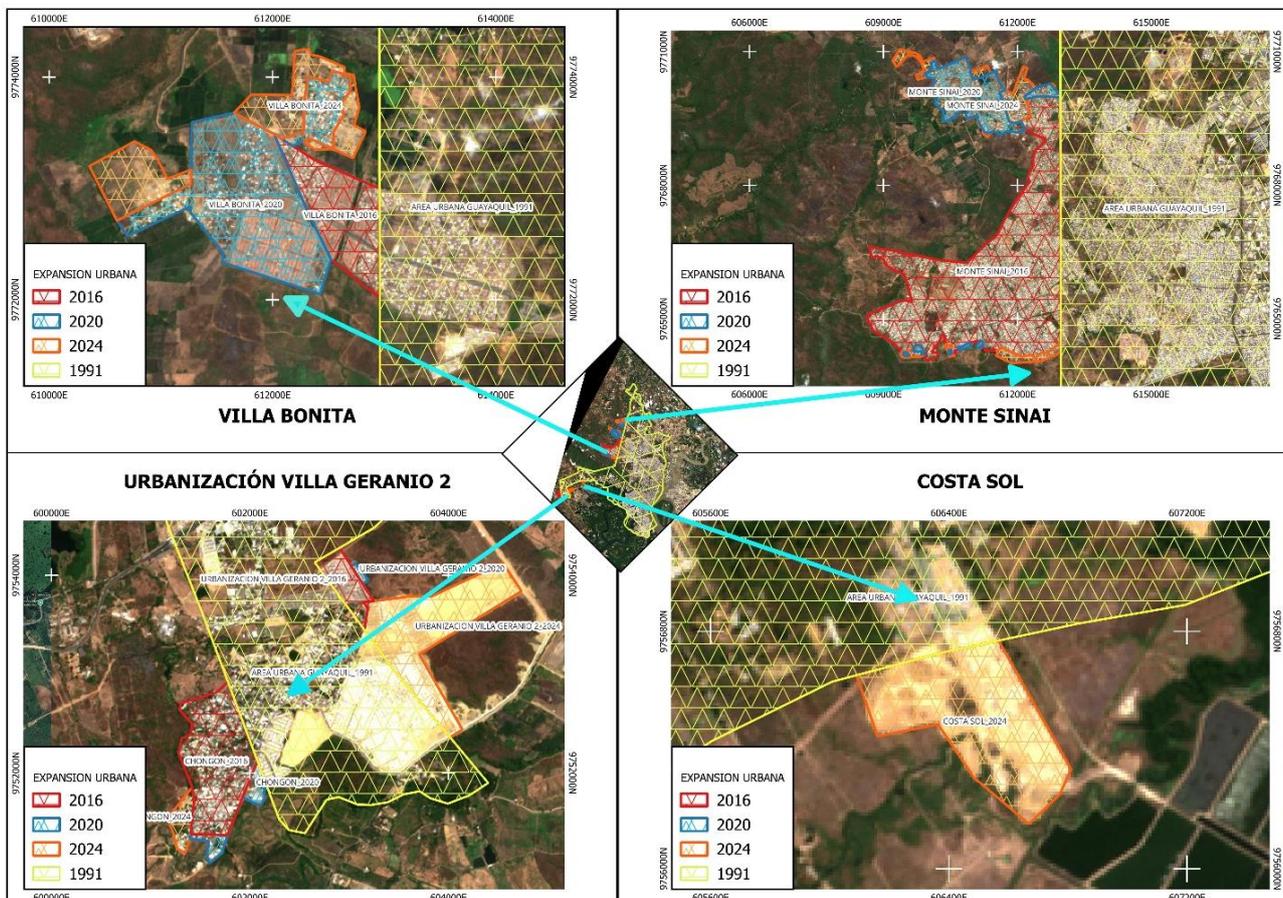


Fig 3. Spatiotemporal dynamics of urban expansion in Guayaquil (2016–2024) using Sentinel-2: identification of critical growth areas in Villa Bonita, Monte Sinaí, Villa Geranio 2, and Costa Sol.

Table 1 presents the evolution of the urbanized area in Guayaquil from 2016 to 2024. During this period, a total increase of 697.03 hectares was recorded. Despite an initial growth of 3.78% in 2016, the rate of expansion progressively slowed in the following years, reaching 1.13% in 2020 and 0.89% in 2024. This behavior suggests that the saturation of developable areas within the legal perimeter has begun to slow down growth, pushing expansion into unregulated and more distant areas from the urban core (Figure 3).

Table 1. Temporal evolution of the urbanized area and its percentage change in Guayaquil from 2016 to 2024, showing an increase of 697.03 hectares during the study period.

Year	Area (ha)	Δ percentage (%)
2016	35713,37	3,78
2020	36102,98	1,13
2024	36410,4	0,89

Growth by Zones

Table 2 details the evolution of urban expansion in different areas of Guayaquil between 2016 and 2024. Monte Sinai stood out as the area with the most significant growth, with 1,141.03 hectares incorporated in 2016, followed by a slowdown in the subsequent years. In comparison, areas like Villa Bonita showed more sustained growth, especially in 2020, with an increase of 163.84 hectares. On the other hand, Costa Sol displayed a more recent urbanization pattern, with an expansion of 21.92 hectares between 2020 and 2024, despite not recording any growth in the previous years. These results reflect a diverse pattern of expansion, varying in intensity and timing depending on the location.

Table 2. Evolution of urban growth by zones in Guayaquil (hectares) for the years 2016, 2020, and 2024, highlighting the expansion in Monte Sinai, Villa Bonita, and Costa Sol.

Zones	Years-ha		
	2016	2020	2024
Villa Bonita	60,96	163,84	73,01
Monte Sinai	1141,03	213,61	108,44
Chongón	99,42	12,16	104,05
Costa Sol	0	0	21,92
Total	1301,41	389,61	307,42

Access to Basic Services in Monte Sinai

One of the main findings of the analysis is the lack of access to basic services in the newly urbanized areas, especially in Monte Sinai. Table 3 shows that 57.63% of properties in this area lack access to electricity, drinking water, or a sewer system, highlighting a severe deficiency in the provision of basic infrastructure. Only 30.66% of the properties have access to electricity, and less than 10% have independent potable water or sewer coverage. Additionally, only 1.87% of the properties have both electricity and sewer services simultaneously, while merely 4.91% have both electricity and potable water. This disparity in access to essential services presents significant challenges to residents' quality of life and underscores the urgent need for improved urban planning and infrastructure provision in these peripheral areas.

Table 3. Access to basic services in Monte Sinai: Number and percentage of properties by type of coverage, highlighting the lack of essential services such as electricity, potable water, and sewage systems in the area.

	Number of Properties	Percentage of Properties (%)
No Service	28817	57,63
Electricity	15331	30,66
Potable water	5135	10,27
Sanitary sewer system	4111	8,22
Electricity and Sanitary sewer system	933	1,87
Electricity and Potable water	2456	4,91
Total Properties	50005	100,00

Spatial Distribution of Basic Services

Figure 4 illustrates the spatial distribution of basic service coverage in Monte Sinai. Fragmented and discontinuous coverage is observed, with areas lacking electricity predominating, represented in orange in the figure. Areas with access to potable water and sewer systems, represented in green and blue, are unevenly distributed, indicating inadequate planning and the need for intervention to improve the provision of these services in the expanding areas.

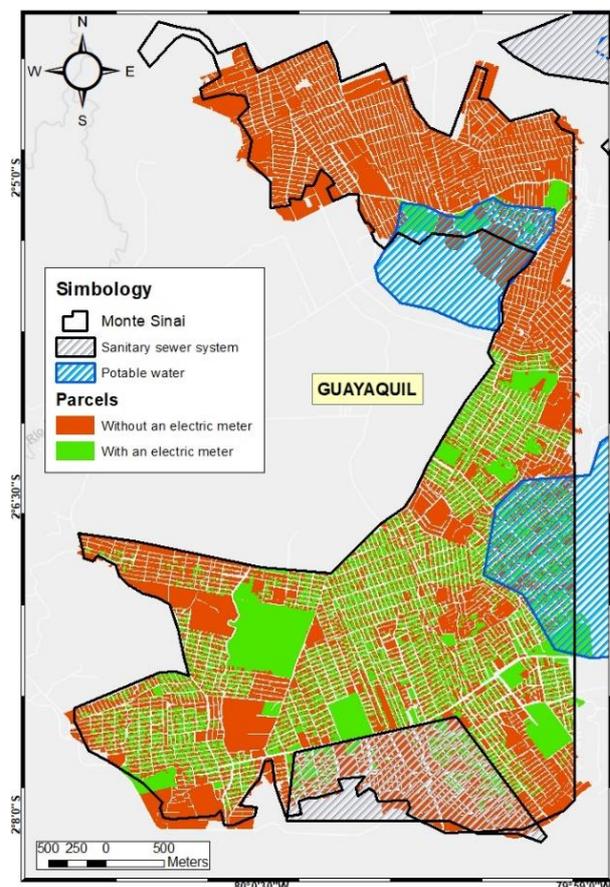


Fig 4. Spatial distribution of basic service coverage in Monte Sinai, showing areas with access to electricity, potable water, and

sanitary sewer systems, with discontinuous service coverage highlighting the challenges in infrastructure provision.

4. Discussion

The urban expansion in Guayaquil between 2016 and 2024, observed through Sentinel-2 satellite imagery and Geographic Information Systems (GIS), offer valuable insights into the spatial dynamics and challenges of urbanization. Throughout the analysis, a clear trend of expansion beyond the established urban boundaries was observed, especially in areas such as Monte Sinaí, Villa Bonita, and Costa Sol. This phenomenon reflects the common pattern of accelerated urbanization observed in many Latin American cities due to population growth and the expansion of economic activities (Espinoza Jaramillo, 2023). However, in Guayaquil, the expansion is marked by informality and a lack of adequate planning, a characteristic recurrent in developing countries (Metzger & Bermúdez, 1996). The increase in urbanized land by 697.03 hectares during the study period reflects the pressures cities face to accommodate a growing population, but the slowdown in the growth rate after 2016 could suggest the saturation of developable areas within the legal perimeter, which has driven expansion into unregulated sectors further away from the urban core (GAD Guayaquil, 2005).

The integration of satellite imagery with GIS tools has proven to be essential for quantifying and monitoring this expansion, allowing for precise detection of land-use changes (Gu & Zeng, 2023). The results reveal the heterogeneous nature of urban growth, with some areas, like Monte Sinaí, experiencing accelerated urbanization, while others, such as Villa Bonita, have shown more gradual growth. This heterogeneity highlights the complexity of expansion patterns and the need for urban planning strategies tailored to the specific characteristics of each area. Additionally, a common pattern of insufficient provision of basic services, such as electricity, potable water, and sewage, was identified, especially in Monte Sinaí, where more than half of the properties lack these essential services. This highlights a significant failure in urban planning, as the physical growth of the city has not been accompanied by the corresponding expansion of infrastructure, generating inequalities and affecting residents' quality of life (Yu et al., 2025).

The lack of basic services, especially in newly urbanized areas, presents a significant challenge for local authorities. If not properly addressed, this phenomenon may increase the social and environmental vulnerability of peri-urban areas, which are at risk of social exclusion and environmental degradation (Beuf, 2012). In this context, a recent study on recyclable waste collection in Guayaquil highlights the insufficient infrastructure to effectively manage waste, further exacerbating urban inequalities (J. Hidalgo-Crespo et al., 2023; J. A. Hidalgo-Crespo et al., 2024). The unequal distribution of services in Monte Sinaí, with areas lacking electricity predominating, underscores the need for more integrated urban planning that considers not only land use but also the development of infrastructure as part of the urbanization process (Yerkenhazi et al., 2025). This demands rapid and effective intervention to improve access to essential services in areas experiencing rapid expansion, such as Monte Sinaí, where the lack of basic infrastructure is a significant barrier to residents' well-being.

The results of this study highlight the urgency of adopting urban planning practices that integrate infrastructure development with urban growth. While urban expansion may bring economic and social benefits, as highlighted by (Roy et al., 2025), it must be managed in a way that ensures equitable access to services and

minimizes negative environmental impacts. The findings suggest that the expansion of Guayaquil has not been managed sustainably. The disconnect between the city's physical growth and the provision of basic services has increased social inequalities and put pressure on natural resources (Liang et al., 2025). It is necessary to strengthen coordination between local governments, service providers, and territorial planning agencies to ensure that urban growth aligns with the capacity of available infrastructure and services.

To address these challenges, public policies must be implemented that promote sustainable urban development, prioritizing the provision of basic services in expanding areas. Additionally, integrating tools such as satellite monitoring and GIS in urban planning can be crucial to detect growth patterns in real-time and ensure timely intervention (Chatrabhuj et al., 2024). In this regard, improving infrastructure in areas such as Monte Sinaí should be prioritized to ensure dignified living conditions for its inhabitants and reduce the territorial and social gap that currently exists.

In summary, this study provides a clear view of Guayaquil's urban expansion and its associated challenges, particularly in terms of infrastructure and inequality. The results highlight the need for coordinated urban planning that links physical growth with the expansion of services, ensuring that new urban areas are adequately equipped to support their growing populations. The use of satellite imagery and GIS tools has proven to be an effective method for monitoring urban dynamics, and the findings obtained should inform future urban planning strategies aimed at fostering sustainable and equitable development in Guayaquil.

5. Conclusions

The spatial and temporal analysis of urban expansion in Guayaquil between 2016 and 2024 revealed heterogeneous growth, predominantly concentrated in the peri-urban area of Monte Sinaí. This area exhibits an accelerated process of urbanization beyond the official perimeter, characterized by deficient and fragmented coverage of basic services such as electricity, potable water, and sanitary sewer systems, affecting 57.63% of properties. These conditions compromise habitability, territorial equity, and residents' quality of life, reflecting a structural disconnect between physical urban growth and the provision of basic infrastructure.

The lack of inter-institutional coordination and insufficient integrated planning are determining factors in the proliferation of this unregulated expansion, which increases the social and environmental vulnerability of peri-urban communities. The absence of adequate basic services generates health risks and limits access to minimum well-being conditions, perpetuating territorial and social inequalities.

The combined use of Sentinel-2 satellite imagery and Geographic Information Systems has proven to be a robust and efficient tool for monitoring and quantifying urban dynamics. It enables precise identification of critical expansion areas and their infrastructure deficiencies. However, these data must be complemented with socioeconomic and regulatory information for a comprehensive diagnosis that facilitates the formulation of effective public policies.

It is imperative to strengthen coordination among municipalities, service providers, and territorial planning agencies to implement strategies that regulate and organize urban growth, promoting sustainable and equitable territorial development. Expanding and

improving basic infrastructure in vulnerable areas such as Monte Sinaí should be prioritized to guarantee dignified living conditions and reduce socio-territorial gaps. This study provides an empirical basis for future research and management actions to foster resilient and sustainable urban models in Guayaquil.

6. References

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