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Digital image processing (DIP) applied to the analysis of the use and coverage of São Sebastião, federal district, Brazil

Summary

The article explores the application of Digital Image Processing (DIP) and Remote Sensing (RS) techniques in analyzing land use and land cover changes in the Administrative Region of São Sebastião, Federal District, Brazil. DIP plays a pivotal role in automated data analysis and interpretation, particularly in the context of RS, where it efficiently processes Earth's surface data collected by sensors on satellites, aircraft, and Unmanned Aerial Vehicles (UAVs). The study covers the period from 2000 to 2020, utilizing data from satellites such as Landsat to provide a continuous view of the region. The spatial and temporal analyses incorporate considerations of hypsometry, slope, and surface temperature, aiming to understand the dynamics of land use and its impact on the microclimate. The methodology involves a comprehensive literature review, acquisition of spatial data from government agencies, and the use of computational tools such as ArcGIS and ENVI. Classification of Landsat images employs false-color compositions and Maximum Likelihood Classification to identify urban areas, water bodies, vegetation, shrubland, and exposed soil. The analysis also includes generating land surface temperature maps. Results indicate significant urban expansion, particularly in the Southeast direction, with a concentration of urban activities. The study highlights a continuous growth trend over the years, emphasizing the importance of understanding and monitoring these transformations for sustainable planning. The article contributes to the field by providing valuable insights into the dynamics of urban growth, offering a clear spatial distribution of changes over time. The detailed methodology ensures the accuracy and reliability of the analysis, supporting informed decision-making in the context of environmental exploration and regional development planning.

Keywords: digital image processing, remote sensing, land use and land cover, urban expansion, spatial analysis

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Abbreviations: DIP, digital image processing; UAVs, unmanned aerial vehicles; NASA, national aeronautics and space administration; ESA, European space agency; CBERS, China-Brazil earth-resources satellite; RGB, red-green-blue; FD, federal district; RS, remote sensing; IBGE, Brazilian institute of geography and statistics; USGS, united states geological survey; DEM, digital elevation model; ALOS, advanced land observing satellite; PALSAR, phased array type L-band synthetic aperture radar; JAXA, administration of the Japan aerospace exploration Agency; ASF, Alaska satellite facility; ESRI, environmental systems research institute; ENVI, environment for visualizing images; TIFF, tag image file format; ST, surface temperature; °C, degrees celsius; K, Kelvin

Introduction

Digital Image Processing (DIP) is a fundamental technique in the automated analysis of information, playing a crucial role in enhancing the acquisition and interpretation of data extracted from images. When applied to Remote Sensing (RS), this set of tools enables the efficient identification and processing of Earth's surface data.[1] Currently, DIP encompasses a wide range of applications that extend to teleconferencing, geological image processing, analysis of radar and sonar data, and it significantly contributes to sectors such as digital cinema and digital television.[2] Sensors, housed in satellites, aircraft, and Unmanned Aerial Vehicles (UAVs), play a vital role in collecting surface information. These sensors can be categorized as passive, capturing the behavior of electromagnetic energy from external sources, such as the sun, or active, emitting and receiving their own electromagnetic waves.[3] The analysis of the spectral behavior of targets on the Earth's surface, characterizing them through the range of reflected waves, is a common practice. Images often present spectral information divided into "bands," corresponding to different ranges of the electromagnetic spectrum.[4] Notable examples include satellites such as Landsat from the National Aeronautics and Space Administration (NASA), Sentinel from the European Space Agency (ESA), and CBERS (China-Brazil Earth-Resources Satellite), which play crucial roles in Earth observation.

Satellites, like the Landsat series, offer a continuous view of the Earth's surface, allowing the assessment of target behavior over time. The division into bands facilitates RGB (Red-Green-Blue) compositions, highlighting specific elements such as vegetation or urban areas. Additionally, thermal sensors provide data on the atmospheric temperature of the captured scene. The image history provided by satellites such as Landsat is a valuable tool for analyzing the dynamics of land use and land cover. The combination of this information with computational data processing techniques enhances the efficiency and reliability of analyses, supporting studies on various aspects of environmental exploration activities. DIP enables the identification of patterns in scenes captured by sensors, representing distinct target configurations. Elements such as vegetation, urbanization, water bodies, and terrain elevation can be identified and analyzed. In this context, the present work aims to apply Remote Sensing and DIP techniques to classify land use and land cover in an administrative sector of the Federal District and its influence on the regional microclimate, which consequently affects aspects such as hydrology and surface runoff. The analysis will cover the period from 2000 to 2020, with five-year intervals, incorporating considerations about the terrain (hypsometry and slope) and its impact on surface temperature in these areas. This study will provide a comprehensive understanding of urban behavior and expansion over time, contextualizing relevant geographic and environmental factors.

Material and methods

This study was conducted in the Administrative Region of São Sebastião, located in the Federal District/FD, Brazil, as illustrated in Figure 1. The study area is delimited by Universal Transverse Mercator (UTM) coordinates: 8241518.84 S, 198071.58 E and 8224279.81 S, 220332.75 E, providing a specific geospatial perspective for the conducted analyses. To carry out this work, three methodological stages were adopted, as described in Figure 2. The methodology of this study was divided into carefully planned stages to provide a comprehensive and accurate analysis. Initially, a literature review was conducted, representing the first stage, allowing the examination of various approaches for obtaining products through Remote Sensing (RS). This facilitated the identification of the best strategies and methodologies employed in acquiring information through Digital Image Processing (DIP), highlighting the importance of classifying these products. To carry out this work, various spatial data were required, acquired freely from online platforms of various government agencies in Brazil and internationally. Given the data availability and in pursuit of the best results, a fifteen-year analysis interval was chosen, covering the period from 2005 to 2020, with analyses every five years (2005, 2010, 2015, 2020).

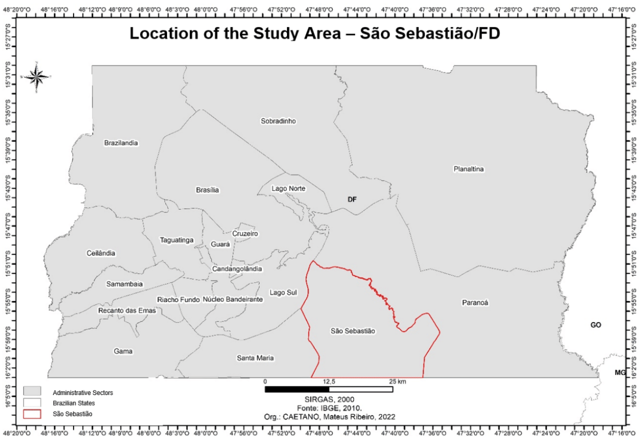

Figure 1 Location of the study area.

Source: The authors (2023).

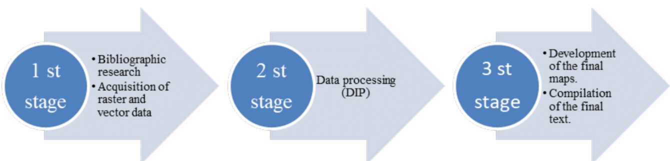

Figure 2 Schematic representation of the methodological stages.

Source: The authors (2023).

Vector data delineating territorial divisions were obtained through the Brazilian Institute of Geography and Statistics (IBGE), contributing to the precise delineation of the study area, covering the administrative sector of São Sebastião. Regarding DIP images, captures from Landsat 5 and Landsat 8 satellites were selected, whose operational range aligned with the temporal analysis. These data were acquired through the United States Geological Survey (USGS) database, selecting images corresponding to the months of July to October of each analyzed year, considering regional climatic conditions favorable with minimal cloud presence during these periods. To characterize the terrain relief, the Digital Elevation Model (DEM) from the Advanced Land Observing Satellite (ALOS), obtained by Phased Array type L-band Synthetic Aperture Radar (PALSAR), under the Administration of the Japan Aerospace Exploration Agency (JAXA) and made available by the Alaska Satellite Facility (ASF - managed by NASA), was used.

In the second stage of this study, various computational tools were employed, including ArcGIS 10.x software, developed by the Environmental Systems Research Institute (ESRI), and Environment for Visualizing Images (ENVI) 5.2, developed by L3Harris Geospatial. The classification of Landsat images involved the composition of RGB bands, using bands 5, 4, and 3 for Landsat-5 and 6, 5, and 4 for Landsat-8, resulting in false-color images. Urban area identification was performed by defining five main classes: vegetation, urban area, water body, shrubland, and exposed soil. Image classification was executed in ENVI, using the Maximum Likelihood Classification method. The resulting data were exported in Tag Image File Format (TIFF) format and manipulated in ArcGIS, where Rasters were converted into vector data. Refinement of these data occurred through the application of integration tools and manual analyses of image and vector overlay.

To generate the land surface temperature map, the band 10 of Landsat-8, corresponding to the thermal infrared range (10.6 μm – 11.19 μm), was employed. This specific analysis was conducted exclusively for the year 2020, using the raster calculator tool in ArcGIS and adopting the equation presented by Vale et al.[5] The formula used for calculating the land surface temperature (ST) in degrees Celsius (°C) from the thermal infrared band (Band-10.tif) of Landsat-8 is as follows in Equation 1:

$$ST(°C) = (K2 / Ln (K1 / (ML * \text{“Band-10.tif”} + AL) + 1)) - 273.15 \quad \text{(Eq. 1)}$$

Where:

ST(°C): Surface temperature at the satellite in Celsius (°C);

K2: Calibration constant 2 = 1,321.08 in Kelvin (K);

K1: Calibration constant 1 = 774.89 in Kelvin (K);

ML: Multiplicative rescaling factor for band 10 = $3.3420E^{-04}$;

AL: Additive rescaling factor specific to band 10 = 0.10000.

As for the terrain slope, data obtained from the Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) Digital Elevation Model (DEM) provide information on the hypsometric aspects of the landscape. By applying the slope tool in ArcGIS, the result is the terrain slope expressed in degrees. The adopted slope intervals were referenced in the work of Souza, et al.,[6] providing a consistent basis for analysis. The third phase of this study involved the creation of final maps, covering terrain aspects, urban expansion from 2005 to 2020, and, finally, the land surface temperature map. The results and detailed analyses of these maps are presented and discussed in the subsequent section.

Results and discussion

Since the 1990s, marked by the establishment of the administrative region of São Sebastião in 1993, until the year 2005, the land use and land cover classification reveal that this area experienced a substantial increase in urban coverage, totaling approximately 16 km² (Figure 3). This notable growth manifested predominantly in the South and Southeast directions, reflecting the distinctive pattern of urban expansion observed in the Federal District. Although expansion occurs in all directions, it demonstrates a more prominent trend towards the South, as identified by Oliveira and Maniçoba.[7] This evolution over time indicates not only the urban development of the region but also underscores the importance of understanding and monitoring these transformations for sustainable and efficient planning.

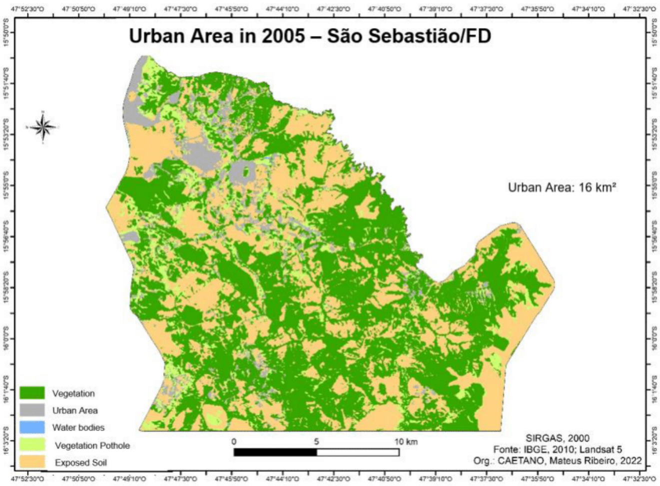

Figure 3 Urban Area for the year 2005, São Sebastião/FD.

Source: The authors (2023).

Continuing the temporal analysis, within a five-year interval, São Sebastião witnessed a significant increase in urban coverage, growing from approximately 16 km² to 18 km², reflecting an increase of approximately 11% compared to the year 2005. This advancement is evident in Figure 4, where in addition to the notable expansion, especially in the Southeast direction, there is also a densification of the urban area. This phenomenon suggests not only an increase in the occupied territorial extent but also a more concentrated intensity of urban activities, highlighting important aspects for understanding the dynamics of growth and planning in the region.

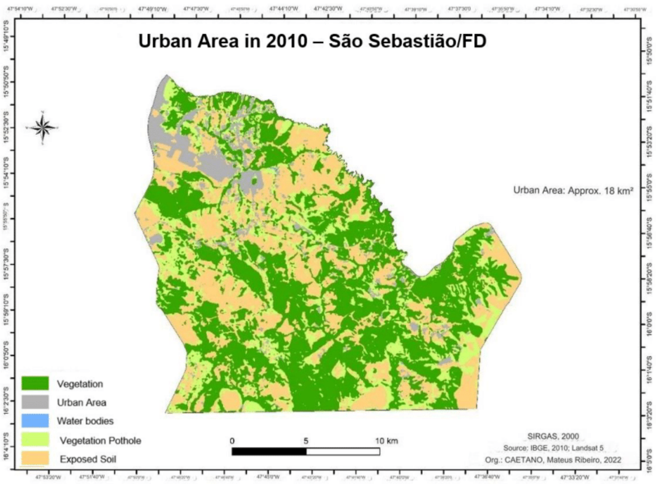

Figure 4 Urban Area for the year 2010, São Sebastião/FD.

Source: The authors (2023).

Like the previous records, the land use and land cover classification for the year 2015 reveals a continuation of the expansion pattern, both in terms of the direction of this phenomenon and its characteristics, notably the reduction of non-urbanized areas within and around the urban area. In the year 2015, the urban area identified by the classification reached approximately 21 km², representing an increase of about 31% compared to the year 2005. This data highlights a significant urban growth of 5 km² over a period of ten years. Between 2010 and 2015, the expansion reached 16%, surpassing the rate recorded between 2005 and 2010. This increase not only confirms the ongoing process of urban expansion but also indicates an intensification compared to the previously analyzed period.

The Figure 5 illustrates the configuration of the urban area in the year 2015, highlighting the locations of its predominance in the territory of the administrative region of São Sebastião. This visual representation offers a clear perspective on the extent and spatial distribution of urban growth, providing valuable insights for the understanding and planning of regional development. For the year 2020, the recorded urban area totaled approximately 25 km², representing an increase of about 56% compared to the year 2005. These data indicate continuous growth over the analyzed periods, characterized by a gradual evolution, with no evidence of pronounced expansions between these time intervals.

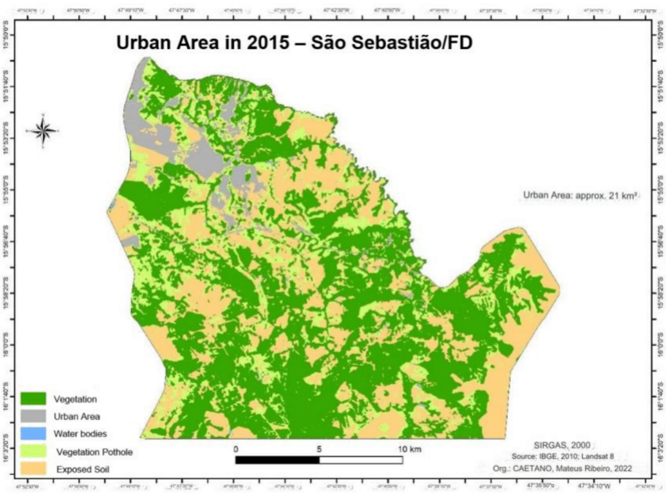

Figure 5 Urban Area for the year 2015, São Sebastião/FD.

Source: The authors (2023).

As observed earlier, the expansion of the urban area remains consolidated predominantly in the Southeast direction (Figure 6). In this regard, as previously noted, there is a noticeable densification in the vicinity of urbanized regions, corroborating with previous patterns. Despite the significant expansion around already urbanized areas, this phenomenon, while relevant, is less prominent when compared to the notable advancement in the Southeast direction. This subtle pattern of expansion towards already consolidated areas suggests a specific growth dynamic, deserving special attention for a more in-depth understanding of the factors and implications associated with this spatial distribution.

Among the various social, economic, and cultural factors influencing the urbanization process, a notably relevant aspect is related to the characteristics of the terrain. Regions with steep slopes, i.e., very steep terrains, tend to present limitations concerning urban development.

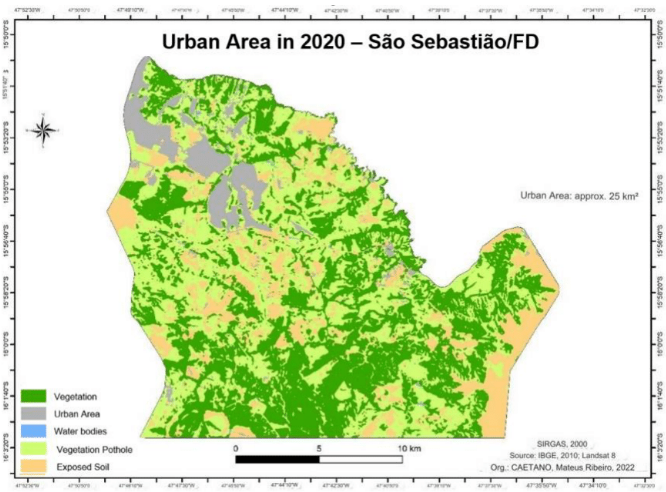

Figure 6 Urban Area for the year 2020, São Sebastião/FD.

Source: The authors (2023).

When examining the pattern of urban expansion, especially in its spatial dimension, it becomes possible to establish relationships that point to the underlying causes of these phenomena. As evidenced in the land use and land cover classification during the analyzed period, urban growth in São Sebastião occurs predominantly in the Southwest direction. The analysis of terrain relief aspects (Figure 7) allows observing a clear correlation between urbanized areas and the terrain slope. The study area is characterized by irregular terrain, ranging from 819 meters in the South to 1,161 meters in regions to the north and close to the Plano Piloto of Brasília. Lower regions exhibit distinctive characteristics influenced by drainage in the formation of topographic features (Figure 7A).

Regarding slope, most of the surface has a gently sloping relief, with degrees ranging from 0% to 15%. In contrast, more rugged regions demonstrate slopes between 15% and 30%, exceeding this scale (>30%) (Figure 7B). It is important to note that, in areas with a slope equal to or greater than 30%, Law No. 6,766 (Brazil, 1979)[8] imposes restrictions on land parceling. Urbanized areas are predominantly located on terrain with slopes between 0% and 15%, characterizing relatively flat relief regions. However, the presence of urban areas is also observed in locations where the slope exceeds 15%. This observation highlights the marked influence of topography on urban development, emphasizing the need for specific considerations related to relief in planning and urban expansion processes.

Another relevant aspect is not only linked to the phenomena that condition and shape urbanization but also to the effects triggered by this process in a specific region, such as temperature variations. Changes in the characteristics of a terrain, such as vegetation suppression and urbanization, result in an increase in the surface temperature in that specific area. As evidenced in Figure 8, regions with low or no vegetation cover, as well as urban areas, exhibit higher temperatures compared to areas that maintain vegetation on their surface. Although not explicitly delineated in the classifications due to the types of classes adopted, the land surface temperature map reveals points with high temperatures, exceeding 26 °C, outside urban areas, standing out from other regions on the image collection date. This behavior may be associated with areas affected by wildfires, where the surface has a significantly higher heat retention capacity due to the limitation in reflecting thermal radiation. This observation emphasizes the importance of considering not only the direct impacts of urbanization but also indirect effects, such as thermal variations, for a comprehensive assessment of urban development in a particular region.

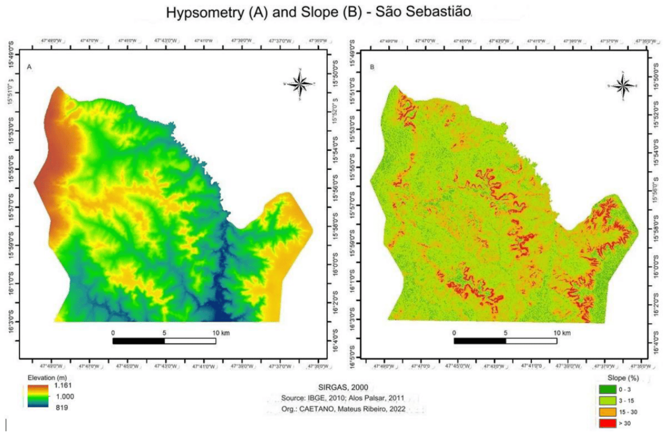

Figure 7 Hypsometry and Slope of the Administrative Region of São Sebastião/FD.

Source: The authors (2023).

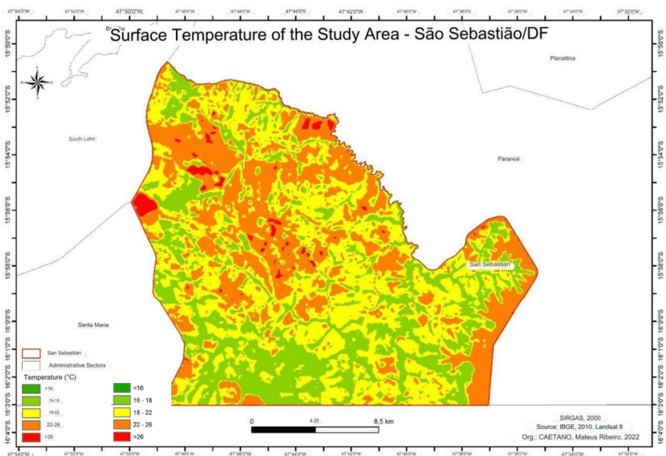

Figure 8 Land Surface Temperature for the year 2020, São Sebastião/FD.

Source: The authors (2023).

Conclusion

This study sought to highlight the potential of Digital Image Processing (DIP) when combined with other remote sensing and geoprocessing techniques, providing comprehensive analyses of the Earth's surface. This approach enhances the understanding of phenomena intrinsic to human activities and the processes derived from these activities. A crucial observation lies in the dynamic characteristics of land use and land cover, subject to annual and seasonal variations, which can be influenced by climatic conditions at the time of image acquisition. However, notably, urban areas demonstrate a consistent behavior over time, regardless of the weather conditions that may impact other areas, such as exposed soil areas. In the study area of this work, the application of the mentioned techniques enabled the acquisition of data revealing significant urban growth over a 15-year interval, totaling approximately 9 km². Additionally, identifying the predominant direction of this phenomenon and its correlation with terrain characteristics enriches the understanding of the underlying processes of urban development. The photointerpretation of the data highlights that factors such as terrain relief exert a direct influence on the occupation and configuration of urban areas, shaping the process

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of urbanization in specific regions. Furthermore, the observation that urban areas and areas devoid of vegetation cover tend to exhibit higher surface temperatures emphasizes the negative effects associated with vegetation suppression. This correlation between environmental elements and urban patterns underscores the need to consider not only quantitative expansion but also qualitative aspects of urban development for a more comprehensive and sustainable approach.

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Conflicts of interest

We declare that there is no conflict of interest in this research.

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