The Urbanization Process of São Carlos City between 1980 and 2016: Perspectives, Reflections and Environmental Impacts

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1. Introduction

In recent decades, medium-sized cities near Sao Paulo have become a destination not only for the population, but also for the new investments favored by the movement of economic and industrial devolution from São Paulo. In this way, they begin to play a new role in the territorial division and in the Brazilian urban network (GOMES, 2016).

Problems related to the environmental impacts of the urbanization process, and especially the rapid economic change of cities, especially in the countries whose development is delayed, affect the natural resources. Often, this predatory urban model is motivated by the private rather than the social interests, disrespecting the growth guidelines of the municipalities, allotment norms and the areas of permanent preservation (ROLNIK, 2009).

As a result of this context, over the last decades, medium-sized Brazilian cities (over 200 thousand inhabitants) have been presenting serious environmental problems. Most municipalities have shown similar characteristics with respect to the urbanization model, such as they are dispersed, fragmented, with social exclusion and spatial segregation, lacking infrastructure in certain areas to the detriment of others and intensive use of natural resources.

The intensification of the urbanization is considered as one of the major inducers of the current environmental problems, due to the diversification in the use of land and mainly, the saturation of the conditioning of the physical environment. The literature on the urban issue in Brazil indicates that the expansion of the peripheral areas is related to the demand for housing in areas with low land prices, which leads to the increase in the precarious occupations, such as the slums and the irregular allotments in areas without infrastructure which are exposed to risks and environmental degradation (BONDUKI & ROLNIK, 1982; MARICATO, 1996).

Urban sprawl has always had an extremely economic character due to ruling out the barriers and limitations of the physical environment. The characteristics that limit and prevent the city growth, should be directed to certain environmentally fragile and vulnerable areas and regions.

According to Santos (2004), the way the occupation of space is done has caused successive and numerous environmental problems, such as: the degradation of the vegetation cover; loss of the biodiversity; obstruction and alteration of the drainage network; transmission of the waterborne diseases; contamination and pollution of air; water and soil; loss of productive
land and erosion processes, among others. Milaré (2006) States that, since growth is imperative, it is necessary to discuss the instruments and mechanisms that could reconcile the developmental works and projects with the reduction of ecological impacts and also with the socioeconomic costs.

The analysis of the process and its consequences for understanding the factors that makes the urban growth a subject to create great impacts, when related to the aspects of population and infrastructure without proper planning of the areas, reach to directly affect the environment.

Thus, depending on the geological and relief characteristics, the form of the occupation of the territory may come to provoke risk situations. However, if the installation of the urban centers and the use of natural spaces are made after respecting the physical environment, the impacts are smaller and the risks can be minimized (PEJON; RODRIGUES; ZUQUETTE, 2009).

Among the existing impacts and which are already detected by different authors, there are several other problems, such as erosion, siltation, flooding in peripheral and central areas, lack of the green areas, soil degradation, visual pollution, air pollution and water body pollution, (rivers and streams) which among other factors, causes significant changes in the landscape, in addition to the loss of the citizen's quality of life.

In this sense, the availability of the satellite images taken from a particular region of Earth, spaced in time and the computational tools present in the Geographic Information System allows to make comparisons using the temporal dimension, quality of the data acquired at different times, and in qualifying the information obtained. This remote sensing function, intended for the analysis of the temporal phenomena, cyclic or non cyclic, is known for detecting changes in the land use and land cover or even in the temporal analysis (HUANG Et Al., 2000).

The present work was aimed to perform the multitemporal analysis of the growth of the urban area of the city of São Carlos / SP, using LANDSAT satellite images, with the purpose of reconstructing the dynamics of the landscape in the period of 1980, 1990, 2000, 2010 and 2016, in addition with studying the environmental impacts caused by the urbanization process over all these thirty-six years.

2. Characterization of the Study Area

São Carlos Municipality is located in the southeastern Brazil and central São Paulo State, between the parallels 22°00' and 22°30' S and 47°30' and 48°00' W. It lies approximately about 230 km northwest of the city of São Paulo. The area of the municipality is 1,140.92 km², whereas, its population in the last census in 2010 was about 221,950 inhabitants, which went to about 246,088 thousand inhabitants in 2017, of which 97% lived in the urban area, with the demographic density of 195.15 inhabitants per km² [10] (IBGE, 2017).

According to the Köppen classification, the climate type of the municipality is the Cwa, which covers the entire central part of the state of São Paulo and is characterized by the tropical
climate of altitude, which rains in the summer and drought in the winter with the average annual rainfall to be above 1,422 mm and the average temperature of the warmest month to be greater than 22°C [ (CEPAGRI, 2017).

Zuquette (1981) apud Gonçalves (1996) reports that the geology is represented almost entirely by the lithologies of the Sedimentary Basin of Parana, with a predominance of the Botucatu Formation. This formation has high permeability coefficients, and the infiltration basically happens in the area characterized by the region as an outcrop area, as the recharge of the Guarani Aquifer.

Much of the study area is formed by the deep soils composed of Deep Quartzous Sands overlying the geology of the Botucatu Formation, which enhances permeability (ZUQUETTE, 1981). In addition to the Red-Yellow Latosol, yellow refers to the Canchim unit, Coconut Palm unit and Dark Red Latosol, Limeira unit.

Henke-Oliveira (1996) warns that the local vegetation has been reduced to the forest fragments in the recent years, mainly due to the agribusiness and allotments. In a study conducted in the same region, found that much of the vegetation cover is being suppressed, related to the expansion related activities, growth, new areas and recent urbanization.

According to the data from IBGE (2017), the GDP of the municipality of São Carlos in 2015 reached up to 6.9 billion, which compared to the last projection, had an increase of 8.6%. Based on the performance of the industry and agriculture, the GDP per capita reached 40,994 thousand where the HDI (Municipal Human Development Index) came out to be 0.805. It has 98.4% of the housings with adequate sanitary sewage, 89.2% of the urban housings on public roads with afforestation and 34.2% of the urban housings on public roads with adequate urbanization - presence of manholes, sidewalks, pavements and curbs (IBGE, 2017).

3. Materials and Methods

The development of the work took place in a SIG environment, with georeferenced information about the region. For this purpose, all information such as: a topographic map of São Carlos (BRASIL - IBGE, 1971); a polygon of the municipality; the urban area in the period of 1980, 1990, 2000, 2010 and 2016 and hydrography and satellite images, was used in the scale of 1:50,000.

From the related information, the visual interpretation of the orbital images that referred to the urban area was performed, that is, the extraction of the information from the land surface targets was performed based on their spectral responses when observed in the image, which according to [17], uses some of the photo-interpretive elements employed in the aerial photography technique, such as the texture, shape, size, hue or color.

The multitemporal analysis was performed using a set of images from the LANDSAT 4, 5, 7 and 8 satellite, obtained free of charge through the website of the National Institute for Space Research - INPE and the National Aeronautics and Space Administration - NASA. The investigation was carried out over a period of 36 years, from 1980 to 2016. Table 1 characterizes the relationship and the main technical information obtained from the images.
Table 1. Relation of the LANDSAT satellite images used in the study.

| Date of the image | Satellite/Sensor | Spacial Resolution | Bands Used | Size of the Scene       |
|-------------------|------------------|--------------------|------------|-------------------------|
| 1984              | LANDSAT 4/TM/MSS | 30 metros          | 3, 4 e 5   | 170 km x 185 km         |
| 1990              | LANDSAT 5/TM/MSS | 30 metros          | 3, 4 e 5   | 170 km x 185 km         |
| 2000              | LANDSAT 7/ETM+   | 30 metros          | 3, 4 e 5   | 170 km x 185 km         |
| 2010              | LANDSAT 7/ETM+   | 30 metros          | 3, 4 e 5   | 170 km x 185 km         |
| 2016              | LANDSAT 8/OLI    | 30 metros          | 3, 4 e 5   | 185 km x 185 km         |

The LANDSAT satellite images obtained at different periods and by different sensors show variations in the: angles of solar incidence; in the atmospheric conditions; soil moisture and also in the calibration of the sensors that generated them. Considering that the images were obtained with significant differences between the periods - 1984, 1990, 2000, 2010 and 2016, the images underwent a treatment, which eliminated the radiometric errors and minimized the atmospheric influences (JENSEN, 1996, PONZONI & SHIMABUKURO, 2007).

In identifying and extracting the information contained in the images for further interpretation, necessary steps were required, such as removing or mitigating the degradations and distortions that limit the human visual capacity and the processing of large amounts of data.

Digital processing of Remote Sensing images was divided into: preprocessing; radiometric and geometric correction of the images; highlighting; applying contrast to the images; and classification, to perform the mapping using the pattern grouping algorithms. Figure 1 exemplifies the process of image processing, overlay and mosaic.
3.1. Processing of LANDSAT Images

Part of the methodological procedures was related to the processing of LANDSAT satellite images presented in Table 1, that focused on the georeferencing, registration and clipping of the study area. In this case, the boundary of the municipality, realized through the free software QGIS 2.18.0, came out to be the same as was used for the construction of the series of the temporal analysis. In the construction of the mosaic in all the series, the bands 3 (Red), 4 (Near Infrared) and 5 (Medium Infrared) were used, which were suitable for the construction of a false image, that involves the analysis of the urbanized area. Through these registration, clipping and mosaic steps it was possible to perform the supervised classification through the Semi – Automatic Classification Plugin (SCP).

The Images were recorded using the 2012 georeferenced image as a reference. The stage was performed with the marking of 10 control points. Finally, the availability of the boundary of the municipality of São Carlos allowed the creation of a mask to perform the clipping of the study area.

3.2. Mapping of Urbanized Areas

The characterization of the urbanized area was performed from the classification that was supervised in SIG. The corresponding red band was used to detect the sensitivity of the spectral curve, highlighting the urban areas in relation to the other bands and regions.
3.3. Supervised Classification

The atmospheric correction process of the images was built using the SCP plugin, in the pre and post processing. The plugin uses the Dark Object Subtraction (DOS) method, which is a correction procedure for the atmospheric scattering, in which the atmospheric interference is estimated directly from the digital numbers (ND) of the satellite images and hence the atmospheric absorption is ignored. Sanches (2011) reports that for the application of this technique there is no need to obtain weather data at the date when the images are obtained.

In the DOS method, it is assumed that there is a high probability of dark targets (pixels) in the images, such as the shadows caused by the topography or clouds, which should have a very low ND in the image, equivalent to the reflectance of about 1% (CHAVEZ, 1996). However, as a consequence of the atmospheric scattering these shaded pixels have higher than expected ND values in the images, and therefore these serve as a reference for the correction of the atmospheric scattering (SANCHES, 2011).

Importantly, atmospheric correction is a method of extreme necessity to obtain better results, both in the processing and classification of the images.

Once the atmospheric correction was made, the characterization of the spectral signature of the targets and the selection of the classes of use was made. Identification keys were established related to their reflectance and the close objects that could interfere with the results.

**Figure 2. Area of study**
4. Discussions and Results

The availability of free orbital sensors with different spatial, temporal and radiometric resolutions allow to access a reality that broadens the range of studies on the behavior and monitoring of the process of the urban growth of cities. It is possible to employ different compositions and sensors to obtain information with greater precision.

By evaluating the evolution of the urban area of the city of São Carlos / SP over the years, it is observed that the values related to the polygon of area referring the year 1980 increased significantly. Through the multitemporal series of images of the \textit{LANDSAT}, it was possible to materialize and characterize, by the process of sorting in terms of reflectance, the creation of maps demonstrating such growth. In this way, the information that gives support to the analysis and comparison of the changes in the scenario, as well as in the visualization of the period of 36 years, was conditioned.

During the work, the changes occurred were significant, especially with regard to the urbanized areas on the exposed soil, agricultural areas and vegetation. It was evidenced that the process of urbanization of the Municipality from the period 1980 to 2016, almost doubled the urban area of the Municipality. From the year 2000, with the intensification and massification of the condominiums and allotments of classes A and B, called "high standard" and "low standard".

The municipality in the 1980s had 37.74 km² of urban area, according to the data obtained through the satellite images and according to the IBGE census, where its population was about 119,535 thousand inhabitants. In the 1990s its urban area was 38.86 km² and its population was 158,221 thousand inhabitants, the urbanized area grew 11.21 km² and the population had an increase of 38,686 inhabitants. While the growth of the urbanized area during the period was just over 10%, the population grew almost 35%.

In the following decades, 2000 and 2010, the urbanized area had its highest growth rates, 60.01 km² and 80.82 km², respectively. The urban population in 2000 was 192,998 thousand inhabitants and in 2010 it reached to about 213,070 thousand inhabitants. Today the urban area of the Municipality is about 97.40 km².

Data from the IBGE demographic census reports that the degree of urbanization of the Municipality in 30 years increased from 92.21% in 1980 to 93.66% in 1990, to 95.04% in 2000 to 95.99% in 2010, respectively. Further analysis of the data and information is needed, as over a period of three decades the urbanized area of the municipality has more than doubled in its area, from 37.7 km² to 80.82 km². While the population has increased from 119,535 thousand inhabitants to about 213,070,000 inhabitants, nearly doubling in size, the degree of urbanization increased by little less than 3%.

The analysis of the growth process of the urban area indicates that prior to the decades analyzed, the bottoms of the valley of the streams such as the Tijuco Preto, Monjolinho and the Gregório, had their occupation process accelerated between the years 1940 to 1970, which increased gradually during the period from 1990 to 2010. This characterizes that the process of urban expansion continued to put pressure on the natural resources in all these years.

Mendes and Mediondo (2007) relate the process of occupation and growth of the
urbanized area and the process of quick waterproofing of the sub-basins of the Monjolinho and Gregório between the years 1940 to 2004, and their real consequences and relationships with the flooding in the urban area, mainly with the increase of the occurrences during the period analyzed. Gomes and Dantas-Ferreira (2012) state that the region drained by the micro basin of the Hot Water Stream suffered a strong occupation since the decade of 1980, where the neighborhoods Aracy and Antenor Garcia sprang up. Other works that have characterized the basin regarding its physical characteristics, report the fragility of the region, such as the presence of sandy soils from the Botucatu Formation and the characteristic rocky outcrops of the Guarani aquifer recharge areas.

Insufficient regulation in the recent decades has allowed the intense occupation of the floodplain, environmentally fragile and vulnerable areas. This occupation mainly occurred due to the implementation of the new housing developments and growth of the areas by waterproofing the soil.

This intense, fast and disordered process of urbanization, caused significant impacts for the municipality. Between the 1970s and 1980s there was a significant increase in flooding which arose due to the increase of waterproofed as well as the superficial runoff areas, which triggered the process of channeling some streams, such as Gregório in the central region of the city. Dupas (2001) considers that the municipality of São Carlos expanded its urbanized area (urban spot) without considering neither the environmental factors, such as the: geology; pedology; land use; erosion; siltation; urbanization, among others, nor the social factors, such as the interests of the population in the growth process.

Figure 3 presents the respective urban areas of 1980 and 2016 and their evolution over the analysis period, characterized by the polygon that demarcates the evolution of the urbanized area.
Molina Jr. (2005) states that between 1962 and 2002, the urbanized area of the Municipality expanded to the south and northwest, reaching the Monjolinho River and the Hot Water Stream. It eventually interfered and modified some sections of the water bodies, such as it gave rise to an increase in the channeling process, as well as the loss of springs and water eyes due to the burial and the implementation of allotments. Figures 4 and 5 show the growth of the urban area between 1980 and 2016.

According to Mota (1999), the process of rapid and intense urbanization can cause significant changes in the hydrological cycle, especially it can increase the precipitation, increase the amount of runoff, decrease the water infiltration due to the waterproofing and soil compaction, increase the consumption of surface and groundwater, enhance the soil erosion and consequently, increase in the process of siltation in the collections of surface water.

Such environmental problems have already been identified in the urban area of the municipality, in the studies conducted by Dias (2013), Guidolini (2013), Silva (2014) and Stanganini and Lollo (2016). Figure 4 characterizes the arborial covering of the municipality according to the São Paulo State Department of the Environment, based on the LANDSAT satellite images.
It is necessary to show the negative impacts of the urbanization process, especially on the environment that, directly or indirectly, affects the welfare, health and safety of the population. The Brazilian Forest Code 2012 (Law No. 12.651) (BRAZIL, 2012) and CONAMA Resolutions No. 302 and 303 of 2002 (CONAMA, 2002) and No. 369 of 2006 (CONAMA, 2006) established the cases in which the creation of Permanent Preservation Areas (APP) is necessary, where the delimitation criteria vary according to the characteristics of the site, such as its location and its area. The illustration (Figure 5) represents the suppression and the absence of vegetation (APP) around the rivers in the north of the city, a region that over the years has been consolidated by the presence of high standard condominiums and subdivisions.

Permanent preservation areas, as defined by the Forest Code, are the areas with an environmental function of preserving water resources, the landscape, geological stability, biodiversity and the gene flow of the flora and fauna, thus protecting the soil and ensuring better conditions of life for the population [30] (BRAZIL, 2012).
Figure 5. Area impacted by the vegetation suppression and by the absence of the areas of permanent preservation.

Noteworthy are the environmental impacts caused by the vegetation removal and the urban growth, as are highlighted such as the increased production of the domestic effluents, erosion due to the landscape alteration by the agricultural areas, alteration of the river channels and lakes by dikes, plumbing, drainage and flooding of the flooded areas, among others. The illustration (Figure 6) broadly demonstrates the situation of the land cover from the satellite data, featuring the shrubby herbaceous coverage as predominant.

It is noted that the regulation of the control instruments and mechanisms has been insufficient in the last decades, such as the lack of supervision, the institutionalization of the management tools, the implementation of the urban policies and the participation of the community in decisions, which made the intense occupation of floodplain, environmentally fragile and vulnerable areas possible, mainly through the implementation of the new housing developments.
The most significant urbanization process begins in the decade of 2000, with the considerable implementation of subdivisions and gated communities, diversifying and altering the process of verticalization of the central region; with the occupation mainly by the privileged location of the city and its infrastructure and urban equipment, two public universities, industries and technology companies; as well as the gradual increase of the urban population. The process of urban sprawl has often occurred in a disorderly manner, with striking progress over not only the unfavorable areas but which are even unfit for the human occupation. The illustrations (Figures 7 and 9) represent the evolution of the urban area over the decades of 1980 and 2016.
Figure 7. Growth of the urban area between years 1980, 1990 and 2000.

The population growth rate of the Municipality, from 2011 to 2017, was 5.80% per year, surpassing the growth rate recorded for the Metropolitan Region of São Paulo - RMSP, which was 4.53% per year in that period. The same can be observed with the growth of the urban population, where the Municipality presented a rate of 5.80% per year and the RMSP presented a rate of 4.56% per year.

The degree of urbanization of the Municipality in 2017 was 96%, while the geometric annual population growth rate in 2010 and 2017 was 0.96%, in the RMSP of 0.83%. These data exemplify the process that the Municipality has faced over the period and which it is still passing through. Table 2 represents the projection of the municipality's population between 2011 and 2050, and the Table 3 shows the projection of the number of urban dwellings throughout the 2011, with projection for the year 2050. The projections characterize that the growth process of the urban area tends to increase the possible environmental impacts. In this sense, it is necessary to create mechanisms to control the land use and occupation, with technical support especially in the management and planning instruments, to discipline, control and order the new developments that tend to emerge in the coming years.
Table 2. Population projection of Municipality of São Carlos / SP.

| Municipality | Year | Urban Population | Rural Population | Total Population |
|--------------|------|------------------|------------------|-----------------|
| São Carlos   | 2011 | 214.988          | 8.969            | 223.957         |
|              | 2017 | 227.468          | 9.490            | 236.958         |
|              | 2020 | 232.915          | 9.917            | 242.632         |
|              | 2030 | 243.767          | 10.170           | 253.937         |
|              | 2040 | 244.620          | 10.206           | 254.826         |
|              | 2050 | 237.241          | 9.898            | 247.139         |

Table 3. Projection of the number of urban dwellings in the Municipality of São Carlos / SP.

| Municipality | Year | Number of Urban Dwellings |
|--------------|------|---------------------------|
| São Carlos   | 2011 | 73.069                    |
|              | 2017 | 82.049                    |
|              | 2020 | 86.439                    |
|              | 2030 | 97.781                    |
|              | 2040 | 103.787                   |
|              | 2050 | 105.385                   |

Another preponderant factor that occurs in the process of growth of the urban area is the demographic density. Between 1980 and 2016 (Figure 8), the period relative to the decade of 1980 had the density of the Municipality higher than the region of the Government of São Carlos and, consequently, of the State of São Paulo. Noting that the urban growth of the Municipality had as a prerogative the practice of occupation by the condominiums, subdivisions and housing estates in horizontal, despite the other cities of the same size that opted for the vertical growth.
5. Conclusions

Since 1980 there has been a process of reduction of the areas of agricultural use and vegetation, having their use changed and being incorporated by the real estate sector in making the condominiums and subdivisions. In this way, demand for the housing increased over the
period, favoring the expansion and urban growth to be based on the disorder and the absence of mechanisms to protect the natural resources.

The impacts caused by the growth of the urban area were aggravated by the occupations of the urban sub-basins and, mainly, by the lack of the territorial planning in the environmentally fragile areas. Since the first studies on the growth of the urban area of São Carlos, dating from the 1930s, indicate that there were fragile areas that presented risks of environmental impacts, such as floods and erosions.

However, factors like the population densification, the real estate pressures and the urban occupation, led to the invasion of the floodplain areas by not considering the fragility of these locations, which caused the occupations of the bottom of the valley and the degradation of the areas of the permanent preservation.

The works of [24] Dupas (2001), [25] Molina Jr. (2005), [22] Mendes and Mediondo (2007), [23] Gomes and Dantas-Ferreira (2012), Vieira[32] and [14] Stanganini and Lollo (2016) already highlighted the need to look after the urbanization process, as well as the creation of the mechanisms that could assist in the making of decision and technical subsidies, especially related to the issues of flooding, soil degradation, loss and removal of the native vegetation, soil sealing, occupation of the floodplain, valley bottoms and the urban sub-basin areas. They also addressed how these issues influenced the process of expansion and the growth of the urbanized area.

Instruments, such as the Municipal Master Plan, are of paramount importance to evidence the need for the protection and restriction of the occupation near the environmentally degraded areas, as it is clear from the studies cited in the paper that urban sprawl goes to other regions and sub-basins, with great power to cause new environmental impacts, as well as the risk of degradation.

The perception and the alteration in the changes in the land use and occupation detected through remote sensing techniques allowed us to reconstruct the process by which the expansion of the urban area occurred, and thus it helped to understand the dynamics of the construction of this phenomenon.

If the current process of urban growth continues, the historical and temporal trend presented in the paper points out that the changes in the landscape, rivers and streams, and the sub-basins that supply the municipality are at the risk of major environmental impacts and probably in the near future, the vegetation areas will be extinct and will no longer compose the landscape of the city of São Carlos.

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